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\textit{\textbf{}}} submitted for the degree of \textit{\textbf{DOCTOR OF PHILOSOPHY}}

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DETERMINATION OF HUMAN BODY COMPOSITION

BY

JULIE A. PASCO  B.Sc.(Hons), Dip.Ed.

Being a thesis submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy

Section of Human Nutrition
School of Sciences
Deakin University.
March, 1987
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ACKNOWLEDGEMENTS

I would like to express my sincere thanks to my supervisors, Dr. R.S.D. Read and Mrs. I.H.E. Rutishauser, for their help and encouragement.

I would also like to thank Assoc. Prof. V.N. Tran and Mr. R.S. Whiteside for their electronics advice, Dr. M. Dove for assistance with deuterium analysis, and Mr. G.J. Ridgway for help with statistical analyses.

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# CONTENTS

## SUMMARY

Page 1

## CHAPTER 1

**INTRODUCTION AND LITERATURE REVIEW**

A. Background 4

B. Relative Weight and Weight-Height Indices 7
   1. Relative weight 7
   2. Weight-height indices 8

C. Direct Chemical Analysis 11

D. Indirect Methods 12
   1. Body density 14
   2. Body water 18
   3. Total body potassium 21
   4. Whole body impedance/conductivity 23
   5. Skinfold thickness 26
   6. Fat-soluble gases 28
   7. In Vivo Neutron activation analysis (IVNAA) 29
   8. Excretion of muscle metabolites 31
   9. Quantitative imagery 32

E. Aims Of This Project 35

## CHAPTER 2

**HYDROSTATIC DENSITOMETRY WITH LUNG VOLUME ESTIMATED BY HYDROGEN DILUTION AT THE TIME OF UNDERWATER WEIGHING**

A. Introduction 39

B. Methods 41
   1. Equipment for underwater weighing 41
   2. Closed-circuit rebreathing apparatus 42
3. Determination of minimum number of breaths
   needed for hydrogen equilibration 42
4. Procedure to determine underwater weight and
   lung volume at the time of underwater
   weighing 43
5. Accuracy 47
6. Reproducibility 48

C. Results 48
1. Hydrogen equilibration 48
2. Accuracy 51
3. Reproducibility 51

D. Discussion 52

CHAPTER 3
TOTAL BODY WATER ESTIMATED FROM DEUTERIUM OXIDE
DILUTION 54

A. Introduction 54

B. Methods 57
1. Administration of D₂O and collection of
   saliva 57
2. Extraction of H₂O-D₂O from saliva 58
3. D₂O assay 58

C. Results 61
1. Standard curve 61
2. Recovery of D₂O and reproducibility of D₂O
   measurements 64

D. Discussion 64
CHAPTER 4
ELECTROMAGNETIC DETERMINATION OF BODY COMPOSITION:
THEORY

A. Dielectric behaviour

B. Electrical behaviour of body tissues
   1. Water content
   2. Frequency
   3. Temperature
   4. Depth of penetration
   5. Reflection of energy incident at tissue interfaces

CHAPTER 5
BIOELECTRIC IMPEDANCE ANALYSIS

A. Introduction

B. Conditions affecting impedance values
   1. Methods
   2. Results

C. Validation of impedance measurements
   1. Methods
   2. Results

D. Discussion

CHAPTER 6
BODY FAT ESTIMATED FROM ANTHROPOMETRIC AND
BIOELECTRIC IMPEDANCE MEASUREMENTS

A. Introduction

B. Methods

C. Results
CHAPTER 7
DEVELOPMENT OF A TEST CAPACITOR SUITABLE FOR DETERMINING BODY COMPOSITION

A. Introduction
   1. Electrical theory

B. Development of capacitor design
   1. Model 1: Parallel-plate capacitor
   2. Model 2: Vertical rod or end-panel and parallel plates
   3. Model 3: Horizontal rod or panel and cylinder

C. Measurement of $\Delta Q$ caused by the introduction of a test subject into the test capacitors
   1. Methods
   2. Results

D. Measurement with graded amounts of absorbing materials
   1. Methods
   2. Results

E. Measurement of human subjects in the test capacitor
   1. Methods
   2. Results

F. Discussion
CHAPTER 8

DEVELOPMENT OF A RESONATING CHAMBER SUITABLE FOR DETERMINING BODY COMPOSITION 190

A. Introduction 190
1. Antenna function 190
2. Transmission lines 191
3. Standing wave patterns 192
4. Amplitude modulation 192

B. Equipment 194

C. Methods 201

D. Results 203
1. Effect on the electromagnetic field of changing the quantities and combinations of meat and fat in the chamber 203
2. Effect of subjects with different body composition on the electromagnetic field in the chamber: Preliminary study 210
3. Measurement of power density in the chamber 213
4. Effect of subjects with measured body composition on the electromagnetic field in the chamber 214
5. Reproducibility of electromagnetic field effect measurements 224

E. Discussion 225

CHAPTER 9

GENERAL DISCUSSION 231

A. The two-compartment body: errors in reference methods 231

B. Bioelectric impedance analysis 234

C. Measurement of electromagnetic field effects 236
APPENDICES

A. Information sheet for subjects participating in the human body composition study 242

B. Radiofrequency (0.3 – 300,000 MHz) safety standards 244

REFERENCES 245
<table>
<thead>
<tr>
<th>Plate</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>44</td>
</tr>
<tr>
<td>2.2</td>
<td>45</td>
</tr>
<tr>
<td>5.1</td>
<td>88</td>
</tr>
<tr>
<td>7.1</td>
<td>126</td>
</tr>
<tr>
<td>7.2</td>
<td>128</td>
</tr>
<tr>
<td>7.3</td>
<td>130</td>
</tr>
<tr>
<td>7.4</td>
<td>131</td>
</tr>
<tr>
<td>8.1</td>
<td>195</td>
</tr>
<tr>
<td>8.2</td>
<td>197</td>
</tr>
<tr>
<td>8.3</td>
<td>198</td>
</tr>
<tr>
<td>2.1 Underwater weighing: Subject in tank, rebreathing from respiratory bladder</td>
<td>44</td>
</tr>
<tr>
<td>2.2 Underwater weighing: Subject submerged in water</td>
<td>45</td>
</tr>
<tr>
<td>5.1 Measurement of bioelectric impedance</td>
<td>88</td>
</tr>
<tr>
<td>7.1 The parallel-plate test capacitor, model 1</td>
<td>126</td>
</tr>
<tr>
<td>7.2 Photograph of model 2 with an end-panel in front of the parallel plates</td>
<td>128</td>
</tr>
<tr>
<td>7.3 View of model 3 with the test capacitor open</td>
<td>130</td>
</tr>
<tr>
<td>7.4 The closed cylinder of the test capacitor of model 3</td>
<td>131</td>
</tr>
<tr>
<td>8.1 Photograph of model 4 with end-plates in position</td>
<td>195</td>
</tr>
<tr>
<td>8.2 Model 4: View of the chamber interior</td>
<td>197</td>
</tr>
<tr>
<td>8.3 Model 4: The trolley has been rolled out of the chamber and onto an external platform</td>
<td>198</td>
</tr>
</tbody>
</table>


### FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Hydrogen concentration in respiratory bladder</td>
<td>49</td>
</tr>
<tr>
<td>2.2 Hydrogen concentration corrected for endogenous hydrogen</td>
<td>50</td>
</tr>
<tr>
<td>3.1 Standard curve showing the relationship between absorbance and D$_2$O concentration</td>
<td>62</td>
</tr>
<tr>
<td>4.1 The frequency dependency of the permittivity for several tissues</td>
<td>71</td>
</tr>
<tr>
<td>4.2 The frequency dependency of the resistivity for several tissues</td>
<td>72</td>
</tr>
<tr>
<td>4.3 Equivalent circuit for biological tissue</td>
<td>74</td>
</tr>
<tr>
<td>4.4 The frequency variation of the permittivity of a typical biological tissue</td>
<td>76</td>
</tr>
<tr>
<td>5.1 Block diagram representing the tetrapolar bioelectric impedance analyser</td>
<td>86</td>
</tr>
<tr>
<td>5.2 Outline of experimental procedure for studies on the repeatability of bioelectric impedance measurements</td>
<td>89</td>
</tr>
<tr>
<td>5.3 Mean values of bioelectric impedance measurements for different electrode placements</td>
<td>94</td>
</tr>
<tr>
<td>5.4 Linear regression of fat-free weight from densitometry on height$^2$/resistance</td>
<td>107</td>
</tr>
<tr>
<td>5.5 Linear regression of total body water on height$^2$/resistance</td>
<td>108</td>
</tr>
</tbody>
</table>
6.1 Regression lines and equations for body fat estimated from body mass index and triceps skinfold for athletes and non-athletes

6.2 Regression lines and equations for body fat estimated from body mass index and the sum of four skinfold thicknesses for athletes and non-athletes

7.1 Basic circuitry of electrical equipment for measuring body composition: Models 1, 2 and 3

7.2 Relationship between change in $Q$ value and coil inductance for different plate separations: Model 1

7.3 Positions of the rod or end-panel relative to the parallel plates: Model 2

7.4 Effect on change in $Q$ value of changing rod or end-panel position in relation to the parallel plates: Model 2

7.5 The change in $Q$ with increasing volumes of saline, using a constant variable capacitance setting: Model 3 with the rod

7.6 The change in $Q$ with increasing volumes of saline, using a constant coil inductance: Model 3 with the rod

7.7 Relationship of change in $Q$ value per litre of saline: Model 3 with the rod

7.8 Variation of $Q$ with frequency: Model 3 with the rod

7.9 Relationship of the change in resonant frequency per litre of water with variable capacitance: Model 3 with the rod
7.10 Curve showing an increase in change in resonant frequency per litre of water with decreasing coil inductance: Model 3 with the rod: 159

7.11 Curves showing how Q varies with frequency: Model 3 with the rod: 160

7.12 The difference between change in resonant frequency values for two different arrangements of meat: Model 3: 164

7.13 The change in resonant frequency caused by increasing the amounts of meat or fat in model 3 with a panel: 166

7.14 The change in resonant frequency for different combinations of meat and fat placed in model 3 with a panel: 170

8.1 (a) Diagram of the enclosed resonating chamber of model 4: 193
(b) Standing wave patterns produced in the resonating chamber: 193

8.2 Block diagram of the equipment used in model 4: 199

8.3 The effect on the change in resonant frequency with increasing quantities of meat or fat in the chamber: Model 4: 206

8.4 The effect on the change in attenuation with increasing quantities of meat or fat in the chamber: Model 4: 207

8.5 Relationship between the change in resonant frequency and weight of meat for different combinations of meat and fat: Model 4: 208
8.6 Relationship between the change in attenuation and weight of meat for different combinations of meat and fat: Model 4
# TABLES

## Table

| 1.1 | Applications of studies on human body composition | 5 |
| 1.2 | Physiological events measured by electrical impedance | 24 |
| 3.1 | Reproducibility of D$_2$O concentration - absorbance standard curve | 63 |
| 4.1 | Dielectric constant and conductivity of biological tissues | 70 |
| 4.2 | Penetration depth as a function of frequency | 78 |
| 5.1 | Age and anthropometric characteristics of subjects in repeatability studies of bioelectric impedance measurements | 84 |
| 5.2 | Mean paired differences for repeated resistance and reactance measurements | 91 |
| 5.3 | Reproducibility of resistance measurements | 93 |
| 5.4 | Mean paired differences for resistance and reactance measurements before and after lunch | 96 |
| 5.5 | Mean paired differences for resistance and reactance measurements before and after fluid intake | 98 |
| 5.6 | Mean paired differences for resistance and reactance measurements before and after passing urine | 99 |
5.7 Age and physical characteristics of subjects in reliability studies of bioelectric impedance measurements

5.8 Correlation matrix of variables related to measurements of bioelectric impedance and estimates of body composition

6.1 Age and anthropometric characteristics of athletes and non-athletes

6.2 Estimates of body fat from anthropometric and bioelectric impedance measurements

7.1 Maximum change in $Q$ value for a variety of inductor coils: Model 1

7.2 Maximum change in $Q$ value for a variety of inductor coils: Model 2 with the rod

7.3 Maximum change in $Q$ value for a variety of inductor coils: Model 2 with end-panels

7.4 Effect of end-panel dimension on change in $Q$: Model 2

7.5 Maximum change in $Q$ for a variety of inductor coils: Model 3

7.6 Effect of panel dimension on change in $Q$: Model 3

7.7 Effect of panel width on change in resonant frequency per kilogram of meat: Model 3

7.8 Meat/fat ratios of change in resonant frequency value for different weights of meat and fat placed in model 3 with a panel

7.9 The composition of various combinations of meat and fat placed in model 3
7.10 Age and physical characteristic of subjects in the study of the effect of human bodies on the electromagnetic field in model 3 172

7.11 Correlation matrix of variables related to measurements of electromagnetic field effects (model 3 with a panel) and estimates of body composition 174

7.12 Stepwise regression of fat-free weight on five predictor variables from measurements of electromagnetic field effects (model 3 with a panel), height and weight 175

7.13 Regression equations for predicting fat-free weight from measurements of electromagnetic field effects (model 3 with a panel), height and weight 176

7.14 Correlation matrix of variables related to measurements of electromagnetic field effects (model 3 with a rod) and estimates of body composition 178

7.15 Stepwise regression of fat-free weight on six predictor variables from measurements of electromagnetic field effects (model 3 with a rod), height and weight 179

7.16 Regression equations for predicting fat-free weight from measurements of electromagnetic field effects (model 3 with a rod), height and weight 180

7.17 Predicted fat-free weights together with 95% confidence intervals for the mean and the individual: Model 3 with a rod 182

7.18 Correlation matrix for calculated fat-free weights based on electromagnetic field effects (model 3 with a rod), densitometry and anthropometry 183
7.19 Summary of conditions resulting in largest maximum values of change in \( Q \) for a subject in each test capacitor

8.1 The composition of various combinations of meat and fat placed in the chamber of model 4

8.2 Age and anthropometric characteristics of subjects in a preliminary study on the effect of human bodies on the electromagnetic field in model 4

8.3 Correlation matrix for variables related to measurements of electromagnetic field effects (model 4) and anthropometry

8.4 Correlation matrix for variables related to measurements of electromagnetic field effects (model 4) and estimates of body composition based on measurements of body density and total body water

8.5 Stepwise regression of (a) fat-free weight, and (b) fat weight, on eight predictor variables from measurements of electromagnetic field effects (model 4), height and weight

8.6 Stepwise regression of fat weight on eight predictor variables from measurements of electromagnetic field effects (model 4), height and weight

8.7 Stepwise regression of fat weight on eight predictor variables from measurements of electromagnetic field effects (model 4), height and weight

8.8 Predicted fat weight values together with 95\% confidence intervals for the mean and the individual: model 4
8.9 Correlation matrix relating various estimates of fat-free weight, total body water and height\(^2\) resistance

8.10 Mean paired differences for repeated measurements of subjects in model 4

8.11 Reproducibility of measurements of electromagnetic field effects for 20 L saline measured daily in model 4
SUMMARY

This thesis deals with two electrical methods designed to enable rapid, safe and noninvasive measurement of body composition, both for clinical and community use.

The first section provides a review of the literature related to measurement of body composition in humans and outlines the approach of the research project. The second section deals with established methods of determining body composition, the two most important being hydrostatic densitometry and deuterium oxide dilution. In this part of the report, a novel method for measuring lung volume by hydrogen dilution at the time of underwater weighing is described.

The main findings of the thesis are contained in the third section which deals with the assessment of body composition by electrical means. There are two components to this part of the study. The first involved the testing of a commercially available bioelectric impedance analyser (BIA) which measures impedance to a flow of current through the body. Studies on the reproducibility and reliability of measurements were performed. Results showed the importance of correct electrode placement and revealed that subjects can consume a light meal and a drink before being measured with the BIA without adversely affecting impedance readings. Results suggested, however, that subjects empty their bladders before measurements are made. Strong correlations were found between height^2/resistance and measurements of total body water (r = 0.839) and fat-free weight derived from densitometry (r = 0.821). Moderate correlations (r = 0.6 to 0.7) were
also found when height\(^2\)/resistance was related to fat-free weight derived from anthropometric measurements.

The second and major component of the third section deals with the development of a method based on the absorption of energy from a weak electromagnetic field established in a capacitor or chamber large enough to accommodate an adult human subject. The method involves measurement of the effect of the body on the electromagnetic field, and is based on differential absorption of energy by body fat and fat-free tissues. Regression equations were developed for predicting the weight of fat and fat-free tissue in the body from measurement of electromagnetic field effects in a test capacitor and in a resonating chamber.

The test capacitor comprised a large aluminium cylinder with a copper rod as a central conductor. The following equation was derived for the relationship of fat-free weight (FFW) based on body density, with measurements of change in resonant frequency (\(\Delta f_R\)), height (H) and weight (W):

\[
FFW = -4.39 + 0.690 W + 19.9 H + 37.6 \Delta f_R
\]

In a study of 17 subjects, a value of 0.891 was found for \(R^2\), and S.E.E. was 1.63.

The resonating chamber consisted of a large enclosed aluminium cylinder with a copper rod as a central conductor. The following equation was derived for the relationship of fat weight (FW) based on the mean of estimates from body density and total body water, with
measurements of change in signal attenuation ($\Delta A$), change in resonant frequency ($\Delta f_R$), and height (H) and weight (W):

$$FW = 73.48 + 0.291 \frac{(W/\sqrt{A})}{\Delta A} - 49.2 \ H - 0.53 \ \Delta f_R$$

In a study of 27 subjects, a value of 0.956 was found for $R^2$, and S.E.E. was 1.97. In these equations, variables were measured in the following units: $FFW$, $FW$ and $W$ (kg), $\Delta f_R$ (MHz) and $H$ (m).
CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

A. BACKGROUND

Quantification of the composition of the human body is necessary in a broad range of fields including clinical nutrition, applied physiology and medicine. Such information is of importance for studies of the nature and therapy of obesity, changes taking place during growth and ageing, nutritional status of the hospitalized and infirm, changes which occur during pregnancy, elite athletes, effects of sports training, and effects of weightlessness experienced by astronauts in space (Table 1.1).

Measures of body fat are of particular interest to human nutritionists because triglyceride is the major energy store of the body. Human beings carry a relatively high proportion of body fat compared with other mammals of corresponding weight (Bray 1973). Obesity, which may be defined as 'an excess of body fat frequently resulting in a significant impairment of health' (Burton et al. 1985), is a public health problem that Australia shares with other Western countries where highly industrialised and automated societies are associated with inactivity and overnutrition.

Excessive accumulation of body fat is undesirable and considered a risk factor in a number of diseases, including hypertension, heart disease, gout, diabetes mellitus, gall bladder disease, impaired fat metabolism and in the development of psychiatric and social
Table 1.1
Applications of studies on human body composition.

Studies and authors

Nature and therapy of obesity:

Changes taking place during growth and ageing:

Nutritional status of the hospitalised and infirm:

Changes which occur during pregnancy:
Emerton et al. 1975; Pipe et al. 1979; Seitchik 1967.

Elite athletes:

Effects of sports training:
Cumming et al. 1973; Parizkova 1963.

Effects of weightlessness experienced by astronauts in space:

Obesity results from an energy imbalance; if energy intake exceeds energy expenditure, energy balance is positive and the excess is stored mostly as fat (Bray 1983; Garrow 1981). During weight reduction programmes, the balance between energy intake and expenditure is designed to be negative, forcing energy stores in the body to be metabolized to supply energy needs. This goal can be reached by altering exercise and/or dietary habits, each having a different effect on the composition of the weight lost (Behnke and Wilmore 1974).

The aim in the treatment of obesity is to reduce body fat to normal levels without loss of too much lean tissue, which may involve muscle wasting and increased susceptibility to infection (Alexander 1974; Chandra 1976). If drastic measures are used to aid weight loss, such as starvation, diuresis, drug therapy and ketogenic or other unbalanced dietary regimes, seriously high losses of body water and body protein may occur (Pierson et al. 1976).

Brozek et al. (1963) calculated that the composition of the difference between the obese body and the lean body, based on the differences between low-density and high-density young men of similar heights and ages, was 73% fat, 7% extracellular water and 20% cell residue. Webster et al. (1984) concluded that differences in weight between women matched for height comprised tissue which was 70-78% fat and 22-30% lean, and they advise that no more than 22% of the weight loss should be lean tissue.
Studies on the relative contribution of fat, water and lean tissues to total weight loss are important in the evaluation of weight reduction regimes because measurements of body weight alone cannot provide information about compositional changes.

B. RELATIVE WEIGHT AND WEIGHT-HEIGHT INDICES

1. Relative Weight

Reports on the incidence of obesity are usually based on measurements of body weight and deviations from an arbitrary standard are often expressed as percent overweight. Traditionally, the standards for desirable or ideal body weights have been drawn from tables relating weight to height, sex, age and, sometimes, frame-size.

The widely publicised 1959 weight-height tables developed by the American Metropolitan Life Insurance Company (1959), based on actuarial analyses, indicate the range of body weights associated with the greatest longevity for each height category of policy holders. Some of the weights were self-reported and the tables make a distinction between small, medium and large frames, based on three even subdivisions of the weights within each height category, so the somewhat arbitrary divisions were not based on any defined anthropometric parameters. Another problem with these tables is that confusion often arises regarding allowances for shoe heel height and clothing weight.

More recently, models have been proposed for defining frame-size by bone diameter or breadth measurements (Frisancho and Flegel 1983; Garn

It has been suggested, however, that there is little benefit in categorizing weight-height data according to frame-size (Baecke et al. 1982; Katch and Freedson 1982; McKay et al. 1983; Rookus et al. 1985), and it is this view which has led to revised tables such as the one recommended at the Fogarty Conference in 1973 which gives a central weight and range of acceptable weights (Bray 1973). This table is similar to the Metropolitan Life Insurance tables, but weights are given without clothes, and heights without shoes.

In Australia, height-weight data from actuarial records of the 1930’s were used to compile early Australian tables which were based on a small insured population (NH and MRC 1957). More recently, average height-weight data has been compiled from population studies on a national basis (Nat. Heart Found. 1980 and 1985), from a country town (Stenhouse 1979) and from health screening programmes (Sodgwick et al. 1979; Simons and Jones 1978; Wood and Dai 1984), however, national anthropometric reference standards are not currently available (Wood and Dai 1984).

2. Weight-Height Indices

Standard tables are population specific and do not necessarily represent average weights for height found in other populations. Various numerical relationships of weight to height have been
suggested in search of an optimal 'obesity' index which is highly correlated with measures of body fat, but independent of height. The more commonly suggested indices include the simple ratio \( W/H \), Quetelet's index \( W/H^2 \), the ponderal index \( W^{0.33}/H \) and the similar Rohrrez index \( W/H^3 \). The indices involving the cube root of the weight or the third power of the height are based on the erroneous assumption that body volume is proportional to the third power of body length (Keys 1973) and furthermore they are height biased so are not independent measures of relative weight (Billewicz et al. 1962; Keys 1973).

Last century Quetelet found that \( W/H^2 \), often known as the body mass index (BMI) (Keys et al. 1972), shows only a small correlation with height (Billewicz et al. 1962; Goldboult and Medalie 1974; Norgan and Ferro-Luzzi 1982; Womersley and Durnin 1977) and a good correlation \((r > 0.7)\) with estimates of body fat based on body density (Norgan and Ferro-Luzzi 1982; Womersley and Durnin 1977) and on a combination of measurements of body density, total body water and total body potassium (Garro and Webster 1985; Webstor et al. 1984). In other surveys, however, the correlation with measurements of skinfold thickness (Florely 1970; Goldboult and Medalie 1974) and body density (Brockett et al. 1956) measurements were poorer \((r < 0.7)\), which may indicate that estimates of body fat from height and weight leave a considerable amount of uncertainty.

Another proposed index is the Benn index, \( W/H^D \), where \( p \) is calculated for the group to be studied, so that \( W/H^D \) is unrelated to height (Benn 1971; Lee et al. 1981). Because the value of \( p \) is close to 2 for most adult populations (Baecke et al. 1982; Goldboult and Medalie 1974; Keys et al. 1972) and \( W/H^D \) exhibits similar correlations with skinfold
thickness as $W/H^2$ (Baekke et al. 1982; Lee et al. 1981 and 1982), $W/H^2$ is often the preferred index in practice (Baekke et al. 1982; Garrow and Webster 1985).

Classification of obesity for clinical purposes based on Quetelet’s index involves several different arbitrary cut-off points. Recent studies (Andres 1980; Keys 1980) indicate that there is little increase in mortality until $W/H^2$ exceeds 30 and this is often used as the cut-off for obesity. The (Australian) National Heart Foundation Risk Factor Prevalence Study (1985) adopted the following classification, as described by Bray (1978):

<table>
<thead>
<tr>
<th>Classification</th>
<th>Women</th>
<th>Men</th>
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<tr>
<td>Underweight</td>
<td>$\leq 18$</td>
<td>$\leq 19$</td>
</tr>
<tr>
<td>Acceptable weight</td>
<td>19-24</td>
<td>20-25</td>
</tr>
<tr>
<td>Overweight</td>
<td>25-30</td>
<td>26-30</td>
</tr>
<tr>
<td>Obese</td>
<td>$&gt; 30$</td>
<td>$&gt; 30$</td>
</tr>
</tbody>
</table>

Use of relative weight, or weight corrected for height, as a measure of body fatness has been criticized because it fails to make any distinction between differences in body composition (Brozek and Keys 1951; Clark et al. 1977; Edmonds et al. 1975; Lesser et al. 1971; Morgan and Ferro-Luzzi 1982; Pollack et al. 1980; Seltzer and Mayer 1965; Welham and Behnke 1942; Wright and Wilmore 1974) and this leads to inaccurate estimations in special groups such as old people or muscular athletes (Garrow and Webster 1985; Morgan and Ferro-Luzzi 1982).
In the 1940's, Welham and Behnke (1942) found that, of 25 professional football players, 17 were classified as too fat based on relative weight standards set by the military. Subsequent body composition determinations revealed that most of the overweight footballers actually carried only a small percentage of body fat and their excess weight was due to well-developed musculature. In this instance, reducing body weight to within the acceptable range would have involved loss of fat-free tissue. In contrast, a sedentary person whose body weight is within acceptable limits may, because of body type, be carrying excess body fat but would not be considered 'obese' (Seltzer and Mayer 1965; Wright and Wilmore 1974). To overcome such anomalies, it is desirable to set classification criteria on the basis of body fat content instead of body weight.

C. DIRECT CHEMICAL ANALYSIS

Of the limited number of cadavers which have been analysed for water, fat, nitrogen, calcium and other chemical constituents (Camerer and Soldner 1900; Camerer et al. 1902; Forbes et al. 1953; Forbes and Lewis 1956; Forbes et al. 1956; Mitchell et al. 1945; Widdowson 1950; Widdowson et al. 1951), few can be considered to have been normal at the time of death. Consequently there are no absolute values available for comparison, and results from one indirect method of determining body composition are usually validated by comparison with one or more other indirect methods.

The direct chemical analyses have revealed, however, that changes occur in body composition during growth from the foetus and newborn through to the adult. On the basis of fat-free weight, these changes
include a decrease in water, a decrease in sodium and chloride contents and an increase in nitrogen, calcium, potassium, magnesium and phosphorus (Forbes 1962).

Analyses of six adult cadavers (Forbes et al. 1953; Forbes and Lewis 1956; Forbes et al. 1956; Mitchell et al. 1945; Widdowson et al. 1951) revealed little variation in the weight of the dry fat-free skeletons and more variation in the amounts of skeletal muscle. The most variable component was body fat, ranging from 4 to 28% of total body weight. Water and potassium contents of the fat-free tissues remained fairly consistent, water contents ranging from 67.4 to 77.5%, giving an average value of 72.4%, and the potassium contents ranging from 66.6 to 73.0 mmol/kg, with an average of 69.4 mmol/kg.

D. INDIRECT METHODS

Because the need for measurement of body composition ranges from assessment of the individual in a clinical setting, to broader based studies in which large segments of the population are screened, a number of factors affect the choice of technique. These include availability of time, equipment and trained investigators, together with consideration of an acceptable level of subject co-operation. The human body is a complex mixture of many components and since direct chemical analyses cannot be performed under normal circumstances, methods for determining the composition of a living human body must be, to varying extents, indirect.

There are three commonly used laboratory techniques for measuring human body composition; these are based on determination of body
density, total body water and total body potassium. All three methods involve calculation of the size of two compartments within the body: fat and fat-free. It is assumed that the density of fat is constant, that the overall density of the fat-free tissues is constant, also that fat is anhydrous and contains no potassium, and that both water and potassium are present in fixed proportions in the fat-free body. Where fat-free body weight is estimated from total body water or total body potassium, the weight of fat is calculated as the difference between total body weight and fat-free weight.

Confusion has arisen with the indiscriminate interchange of the terms "fat-free weight" (FFW) and "lean body mass" (LBM). Fat is defined as pure triglyceride which is chemically extractable with solvents such as ether, and the fat-free component is the difference between total body weight and fat weight. In man there appears to be a minimum body weight, below which satisfactory health is not maintained, and this functional lower limit was referred to as the LBM by Behnke (Behnke 1941-42; Behnke et al. 1942; Behnke et al. 1953) who proposed that body fat accounted for body weight in excess of LBM. Essential membrane lipids, such as lecithin and phospholipids, are included in LBM (Behnke et al. 1953) and this differs from FFW which excludes all lipid (Keys and Brozek 1953).

A further confounding factor arises when fat is equated with adipose tissue because adipose tissue in the adult comprises approximately 83% fat, the remainder being 15% water and 2% protein (Garrow 1978). In lean individuals the difference between LBM and FFW is small, but it becomes exaggerated when there is a large amount of adipose tissue, because the presence of non-fat adipose components becomes
significant. Therefore the difference between FFW and LBM becomes marked in the very obese (Garrow 1982b).

The concepts of the reference man and obesity tissue were introduced by Keys and Brozek (1953) such that obesity tissue, comprising fat, extracellular water and cell residue, accounts for the difference in body composition between the reference man and a given individual. The composition of the reference man was calculated as the mean of the bodies of clinically healthy young men and was regarded as a standard body against which others could be compared. The fat content of the reference man (14% fat, body density $= 1.063 \times 10^3$ kg/m$^3$) was later revised and the new standard body was termed the reference body (15.3% fat, body density $= 1.064 \times 10^3$ kg/m$^3$) (Brozek et al. 1963).

1. Body Density

The measurement of body density for the assessment of body composition was pioneered by Behnke (Behnke et al. 1942). This technique is based on the concept of weight per unit volume, first proposed by Archimedes about 2000 years ago in his work on floating objects.

There are two experimental approaches for determining body density using Archimedes' principle. In both, body weight is easily measured by weighing the person in air, but the methods differ in the technique for determining body volume.

One method involves measurement of the volume of water displaced when the body is submerged (Allen 1963; Garn and Nolan 1963). Accurate measurements are usually made by detecting the rise of water in a thin
tubo attached to the side of a tank. The other method involves weighing the subject in air and then again when completely submerged under water (Akers and Buskirk 1969; Behnke et al. 1942; Goldman and Buskirk 1961; Harsha et al. 1978; Katch et al. 1967). The apparent loss of weight is equivalent to the weight of the water displaced. It is necessary to correct for the buoyancy effect of gas trapped in the lungs and gastrointestinal tract in order to calculate the true volume of the body tissues.

Attempts have been made to avoid complete submersion of the subject in water. Helium dilution (Siri 1961b) has been utilized to measure the volume around a human body sealed in a gas-tight chamber, and techniques using a plethysmograph have been developed (Garrow et al. 1979) which require the subject to be immersed to the neck in water while the air space around the head is measured by a pneumatic principle. The advantage in using this technique is that no correction is necessary for the volume of gas in the lungs and gastrointestinal tract.

From the experimentally determined body density it is possible to calculate the relative percentage of fat in the body if constant values for the densities of fat and fat-free tissues are assumed.

If $F$ and $N$ represent the proportions of fat and non-fat (fat-free) components, each with densities $f$ and $n$ respectively, then the density of the whole body ($D_B$) is:

$$D_B = \frac{F + N}{(F/f) + (N/n)}$$

As the density of the whole body equals the sum of its constituents, $F + N = 1$. Substitution in the previous equation gives:
\[
D_B = \frac{1}{(f/f) + (N/n)}
\]

Therefore, on rearranging the terms,

\[
F = \frac{1}{D_B} \times \frac{f \times n}{(n - f)} - \frac{f}{(n - f)}
\]

The fat-free body is a mixture of water, protein and mineral which have densities of approximately \(0.993 \times 10^3\), \(1.34 \times 10^3\) and \(3.00 \times 10^3\) kg/m³ respectively, at body temperature (Brozek et al. 1963). The density of the fat-free body for an individual will depend on the proportions of these constituents and it is an average combined density value which is usually used.

The Siri equation (Siri 1961a) assumes that, at body temperature, human fat has a density of \(0.900 \times 10^3\) kg/m³ and the average density of the fat-free tissues is \(1.10 \times 10^3\) kg/m³. Percentage body fat (\(\%F\)) is then calculated from:

\[
\%F = \left(\frac{4.950}{D_B} - 4.500\right) 100
\]

Brozek et al. (1963) avoided estimating the density of the fat-free tissues and instead they used data relating to the composition of the reference man \((D_B = 1.064 \times 10^3\) kg/m³ and \(\%F = 15.3\)) to develop the following equation:

\[
\%F = \left(\frac{4.570}{D_B} - 4.142\right) 100
\]
The subject's density is therefore compared with that of the reference man.

A provisional equation for human bodies was derived by Rathbun and Pace (1945) following studies made on guinea pigs. In their equation

$$\%F = \left(\frac{5.548}{\text{sp.gr.}} - 5.044\right) 100$$

sp.gr. refers to body specific gravity. The values of $1.10 \times 10^3$ and $0.918 \times 10^3$ kg/m$^3$ have been used for the densities of fat-free tissues and fat, but as the latter relates to the density at room temperature rather than at body temperature, this equation has not been widely used.

Using a sample of 54 college-age males, Wilmore and Behnke (1968) reported an intercorrelation of 0.995 to 0.999 between percent body fat values derived from the Siri, Brozek et al., and Rathbun and Pace equations. Their data suggested that for a constant body density, the Rathbun and Pace equation produced the highest $%F$ value, the Brozek et al. equation yielded the lowest $%F$ value, while the Siri equation gave an intermediate value.

For subjects whose body densities lie between $1.03 \times 10^3$ and $1.09 \times 10^3$ kg/m$^3$, body fat values agree to within 1% fat when the Siri and the Brozek et al. equations are used (Lohman 1981). However, for subjects who exceed 30% fat, the Siri equation gives increasingly higher estimates.
Having determined a value for percent body fat, the absolute value for fat weight can be calculated from the following relationship:

\[
\text{body fat weight} = \text{body weight} \times \frac{\%F}{100}
\]

Apart from experimental errors in measuring body density, the accuracy of the estimated values for the weight of fat and fat-free tissues are limited by the assumptions concerning the constancy of the densities of each compartment in the two-compartment body. Wilmore (1983) and Womersley et al. (1976) suggest that the value \(0.9000 \times 10^3 \text{ kg/m}^3\) is a reasonable estimate for the mean density of body fat at 37°C. This figure is independent of age, sex or location within the body. Greater variations are more likely to occur in the fat-free compartment, where there are inter-individual differences in bone mineral and water contents (Baikser and Stuikenkamp 1977; Siri 1956; Wedgwood 1963). Siri (1961a) estimated that, in the absence of experimental error, the standard deviation for the determination of relative body fat by densitometry, is 3.8%.

2. Body Water

Measurements of the amount of water in the body were made in the nineteenth century by means of desiccation (Bezold 1857), a direct method that is still being used on cadavers today.

Indirect measurements of total body water in the living human body are based on the principle of dilution (Edelman et al. 1952; Moore 1946; Moore et al. 1963; Novak 1967). A tracer substance is either ingested
or injected and, after it has equilibrated with the water pool in the body, the concentration of the tracer and therefore its volume distribution can be calculated following analysis of some body fluid such as blood, urine or saliva. An ideal tracer is one which distributes rapidly throughout the fluid compartments of the body, reaching a uniform equilibrium at which its concentration can be accurately measured. It should be non-toxic and not selectively stored, secreted or metabolized.

Numerous water-soluble tracers such as urea (Bradbury 1961; Srikanthia and Gopalan 1957), antipyrine (Mendelsohn and Levin 1960; Soberman et al. 1949) and ethanol (Loeppky et al. 1977) have been utilized, but because they are either bound to proteins, rapidly metabolized and excreted or are incompletely diffused to all fluid compartments, questions are raised about their suitability as tracers (Novak 1967; Schloerb et al. 1950).

An isotopically-labelled water which is completely exchangeable with non-labelled water would be more appropriate (Moore 1946; Siri 1956). Deuterium oxide, also known as deuterated or heavy water, (Bencsath et al. 1983; Halliday and Miller 1977; Lukaski and Johnson 1985; Mendez et al. 1970; Moore 1946; Nielsen et al. 1971; Schloerb et al. 1950; Solomon et al. 1950; Stansell and Hyder 1976; Wang et al. 1973), and tritiated water (Hume and Weyers 1971; Moore et al. 1963; Szaluga et al. 1984) have been widely used. Tritium is radioactive, with a physical half-life of 12 years (Nagy and Costa 1980; Novak 1967; Schloerb et al. 1950), so its use with humans is subject to ethical considerations (Pinson 1952). However, tritium is often chosen as the tracer because it is easily detected with a liquid scintillation counter (Langham et al. 1956; Leibman et al. 1960). With the recent
renewed interest in stable isotopically-labelled tracers (Bier 1982) there is extensive use of deuterium despite the difficulties involved in its measurement (Cheek 1980; Leibman et al. 1960).

Recently H$_2$O has been tested as a tracer water (Schoeller et al. 1980; Schoeller et al. 1982). It contains only stable isotopes, as does deuterium oxide, but has the advantage of avoiding loss of tracer from the water pool, which occurs by exchange of deuterium with nonaqueous hydrogen in the body (Culebras et al. 1977; Culebras and Moore 1977; Pinson 1952; Schloerb et al. 1950; Sheng and Huggins 1979).

The volume of total body water, calculated from the dilution of a tracer, can be converted to a corresponding fat-free body weight, using an estimate of the water content of the fat-free tissues. Mean results from desiccation analyses on adult human cadavers (Forbes 1962; Garrow 1978; Sheng and Huggins 1979) show that water comprises about 73% - 74% of the fat-free weight and this compares favourably with carcass analyses of other mammals, such as guinea pigs (Pace and Rathbun 1945) and rats (Cheek et al. 1955).

Assuming a constant water content of 73.2 g per 100 g fat-free tissue, (which is a widely-used mammalian constant) (Pace and Rathbun 1945), body fat is calculated from the expression:

$$\text{body fat weight} = \text{body weight} - \frac{\text{body water weight}}{0.732}$$

The accuracy of this method is dependent on the accuracy of the body water estimation and the error in using a mean value for the water
content of the fat-free tissues. Several studies have shown that the hydration of fat-free tissue in obese subjects is increased (Garrow 1978; Halliday et al. 1979; Pierson et al. 1976; Wang and Pierson 1976). Strong correlations (r > 0.9) have been reported (Garrow et al. 1979; Segal et al. 1985) between body fat estimates based on measurements of body density and total body water.

Total body water can be divided into two components: extracellular and intracellular water. The extracellular water encompasses all the water outside cells and includes plasma water, interstitial and lymph fluid, bone, cartilage and connective tissue, and transcellular fluid which includes fluid in the gastrointestinal tract, the central nervous system, the eye and the joints (Cheek 1961; Edelman et al. 1952). Extracellular water volume can be measured using electrolytes such as bromide, chloride, sodium, thiocyanate, sulfate and thiosulfate ions, and non-electrolytes such as sucrose, imulin and mannitol (Novak 1967). Intracellular water volume is often calculated as the difference between total body water and extracellular volumes, but more directly it can be determined from potassium measurements (Novak 1967; Wang and Pierson 1976) assuming a constant intracellular concentration, and that most of the potassium resides inside the cells.

3. Total Body Potassium

In nature, potassium exists labelled with approximately 0.0118\% $^{40}$K, a radioactive isotopic form which emits a high energy gamma-ray. With the development of gamma spectrometers, which use liquid scintillants or sodium iodide crystal detectors, it is possible to estimate the
fat-free compartment of the body by whole body counting (Anderson et al., 1956; Smith and Cronquist 1977; Smith et al., 1979).

The equipment is large and expensive because it must be large enough to contain a human subject and because it needs to be shielded from external radiation by heavy screens of lead or steel in order to reliably measure the low concentration of $^{40}K$ in the body.

Difficulties arise in calibrating the whole body counter to allow for differences in body shape and build. Phantoms are used, or the subject is given a measured dose of the radioactive isotope $^{42}K$, so that calibration can be achieved allowing for absorption of radiation by the tissues of the body. The standard error of an estimate of total body potassium of 140 g (typical for a 70 kg subject) is in the range of 3.0 - 3.4% (Smith and Cronquist, 1977; Smith et al., 1979).

In estimating fat-free weight from total body potassium measurements, it is assumed that potassium is present only in the fat-free tissues and in known concentrations. Indirect estimates of the potassium content of adult fat-free tissues range from 62 to 66 mmol/kg for men and 54 to 60 mmol/kg for women (Boddy et al., 1972; Delwaide and Crenier 1973; Edmonds et al., 1975; Pierson et al., 1974) and it has been shown that this concentration decreases with increasing obesity (Colt et al., 1981; Pierson et al., 1974) and decreases with increasing age (Anderson and Langham 1959; Edmonds et al., 1975; Pierson et al., 1974; Pierson et al., 1982; Womersley et al., 1976). Therefore the use of a constant value of potassium per unit fat-free weight is an assumption which has serious limitations.
The calculation of fat-free weight is similar to that used for total body water, namely,

$$\text{FTW} = \frac{\text{total K content}}{\text{concentration of K per kg of FTW}}$$

Strong correlations ($r > 0.9$) have been reported (Garrow et al. 1979; Segal et al. 1985) between body fat estimates based on body density and those based on measurement of total body potassium.

4. Whole Body Impedance/Conductivity

The principle of using electrical methods for determining body composition is based on the different electrical conductivity and dielectric properties of various components of the body (Pethig 1979). The fat-free tissues are perfused with an electrolyte solution and are good conductors, whereas fat does not contain any water or electrolytes and is an insulator. Therefore, fat has a much lower electrical conductivity and a much lower dielectric constant than fat-free tissues at the same frequency (Johnson and Guy 1972; Pethig 1979).

The method for determining body impedance involves injection of a weak, constant current into the deep tissues by means of surface, subcutaneous or implanted electrodes, and the measurement of impedance to the spread of current. Electrical impedance has been used for many years for various kinds of physiological measurements (Table 1.2).

Using a two-terminal system, Thomsett (1962) was the first to predict total body water in man with whole body impedance measurements. Since
Table 1.2
Physiological events measured by electrical impedance.

Events and authors

Patterns of respiration:
Geddes et al. 1962a; Goldonsohn and Zablow 1959; Robins and Marko 1962.

Uterine activity during labour:
Komnnesser and Nyboer 1962.

Contraction of skeletal muscle:
Geddes et al. 1962b.

Cardiac, pulmonary and systemic pulsatile flow volumes:
Bonjer et al. 1952; Jenkner 1959 and 1962; Kubicek et al. 1974;
Nyboer 1944 and 1972; Nyboer et al. 1940; Polzer et al. 1960;
Rushmer et al. 1953; Stewart 1897; White 1947.

Heart sounds:
Groom and Silvonen 1957.

Eye position:
Sullivan and Weltman 1963.

Fluid-volume changes during haemodialysis:

The wound-healing process:
Adam et al. 1983.

Deep vein thrombosis:
then, four-terminal impedance methods have been used and good correlations ($r > 0.89$) between whole body electrical impedance (corrected for height) and total body water (Hoffer et al. 1969; Hoffer et al. 1970; Lukaski et al. 1985; Segal et al. 1985), lean body mass based on body density, and total body potassium (Lukaski et al. 1985; Segal et al. 1985) have been reported.

A more recent development in the determination of body composition by electrical means is the electronic meat monitoring equipment (EMME) developed by Marker (1973), which is used to predict the composition of live or slaughtered animals. The EMME consists of a fibreglass tunnel surrounded by an energized solenoid which creates an electromagnetic field in the tunnel. The addition of a magnetic core (the animal or carcass) into this field alters the field characteristics, the size of the disturbance being proportional to the conductivity and dimensions of the core.

This technique has been shown to be a useful indicator of the lean composition of live pigs (Domecuth et al. 1976; Freden et al. 1979) and beef carcasses (Koch and Varnadore 1976), but measurements performed on live lambs (Jones et al. 1983) and pig carcasses (Jones and Haworth 1983) suggest that EMME numbers are more related to total body or carcass weight than to lean weight.

The EMME has now been adapted for use with humans (Harrison and Van Itallie 1982; Klish et al. 1984; Presta et al. 1983a; Presta et al. 1983b) and has been called TOBEC, an acronym for total body electrical conductivity. Reports have been made of strong correlations ($r > 0.84$) between total body electrical conductivity, or total body electrical conductivity corrected for height, and lean body mass based
on body density (Presta et al. 1983a; Segal et al. 1985), total body
water and total body potassium (Presta et al. 1983b; Segal et al.
1985).

The advantage of these new electrical methods lies in the ease of
measurement, but accuracy is still being determined and research to
date has been criticized because most of the studies have been
performed exclusively on young healthy subjects (Cohn 1985), the
question of the subject’s state of hydration has not yet been
addressed (Cohn 1985 and 1986; Nash 1985), and in the measurement of
body conductivity, the received signal depends on the shape and size
of the body (Harrison and Van Itallie 1982; Segal et al. 1985; Van
Itallie 1984).

5. Skinfold Thickness

Single or multiple skinfold thicknesses, measured with calipers, can
be used to provide an estimate of total body fat. The skin is fairly
constant in thickness, and the differences in thicknesses of skinfold
measurements is chiefly a reflection of the thickness of the
subcutaneous fat layer.

One of the earliest equations relating skinfold thicknesses to total
body fat was established by Matiegka (1921). He calculated body fat
from surface area and the average of six skinfold thicknesses. Brozek
and Keys (1951) published the first equation for men based on the
relationship between skinfold thickness and body density. Since then
many linear regression equations have been derived for predicting body
density, and hence body fat, from anthropometric measurements such as
circumferences, diameters and/or skinfolds (Behnke and Wilmore 1974; Forsyth and Sinning 1973; Katch and McArdle 1973; Parizkova 1961; Pollock et al. 1976; Pollock et al. 1975; Sinning 1978; Sloan 1967; Sloan et al. 1962; Wilmore and Behnke 1970). The use of these equations is limited because they have been developed from relatively small, homogeneous samples and some have been shown to be population specific by cross-validation studies on new groups of subjects (Flint et al. 1977; Jackson and Pollock 1977; Katch and Michael 1969; Lohman 1981; Mayhew et al. 1981; Pollock et al. 1977; Pollock et al. 1976; Pollock et al. 1975; Spurr et al. 1981; Wilmore and Behnke 1970).

Research has demonstrated that a non-linear relationship exists between skinfold thickness and body density (Chien et al. 1975; Durnin and Womersley 1974; Jackson and Pollock 1978; Jackson et al. 1980) and that age is independently related to body composition (Durnin and Womersley 1974; Jackson and Pollock 1978; Jackson et al. 1980). As the proportion of subcutaneous fat to internal fat is higher in females than in males and tends to diminish with age (Pollack et al. 1980), prediction equations should accommodate these differences.

Durnin and Womersley (1974) found a curvilinear relationship between the log of multiple skinfold thicknesses and body density, and separate equations were derived for five different age groupings within each sex.

Newer, ‘generalized’ prediction equations have since been developed on large heterogeneous samples of both sexes, based on the quadratic relationship of body density with skinfold thickness, with age being incorporated as an independent variable (Jackson and Pollock 1978; Jackson et al. 1980; Lohman 1981). The generalized equations are
purportedly useful because they replace several population-specific
equations without loss of accuracy for adults varying in age and body
fatness (Jackson and Pollock 1985), however, caution is advised for
their use with individuals whose ages are not within the range 18 - 61
years (Jackson and Pollock 1985). Cross-validation studies of the
generalized equations with particular populations of athletes (Sinning
et al. 1985; Sinning and Wilson 1984; Thorland et al. 1984)
demonstrated variable accuracy in the estimation of body density.

Caliper measurement of skinfold thickness offers a simple method for
the estimation of body composition for mass testing, but its accuracy
has been questioned (Brozek 1963; Grande 1973). Problems with
skinfold measurements relate mainly to inter- and intra-observer
variation, differences in skinfold compressibility, and difficulty in
locating the fat-muscle interface, and in the very obese it is
difficult, if not impossible, to obtain meaningful skinfold
measurements (Booth et al. 1966; Garrow 1982a and 1982b; Garrow and
Webster 1985; Ruiz et al. 1971). There are also ethnic differences in
subcutaneous fat distribution (Dugdale et al. 1980; Jones et al.
1976).

6. Fat-Soluble Gases

A theoretically attractive technique has been described (Hytten et al.
1966; Lessor et al. 1971) using a dilution principle based on the high
solubility of some anaesthetic and inert gases, such as cyclopropane,
krypton and xenon, in fat as compared to water. Unfortunately it
involves rebreathing through a mask for several hours to enable the
gas to equilibrate, and the uptake curve is not smooth because depot
fat is unevenly perfused (Garrow 1982b and 1983). This technique makes no assumptions about adipose tissue composition and provides an independent measure of body fat (Lesser et al. 1971).

7. **In vivo Neutron Activation Analysis (IVNAA)**

Radiative neutron capture by the body results in the emission of gamma-rays with energies characteristic of the capturing nuclei (Vartsky et al. 1979). Elemental analysis is dependent on the energy of the neutrons and on the type of gamma-emission obtained (prompt or delayed). Using this technique, the elements able to be measured include: nitrogen, calcium, sodium, chlorine, carbon, hydrogen, phosphorus, and also the toxic elements cadmium and lead.

When used in conjunction with the measurement of the naturally-occurring gamma-emission of potassium and, perhaps, total body water by an isotopic dilution technique, in vivo neutron activation analysis (IVNAA) can be used to measure the following aspects of body composition:

(a) the amount of body protein, calculated from total body nitrogen (TBN)

(b) skeletal mass, calculated from total body calcium (TBCa)

(c) extracellular water volume, calculated from total body chloride (TBCI)

(d) total body energy, calculated from total body carbon (TBC).

This involves calculation of total body fat from the relationship:

\[
\text{body fat} = (\text{TBC} - \text{TBN}) - (\text{TBCa} + \text{TBCI} + \text{TBK}).
\]
Intracellular water volume can be calculated as the difference between total body water and extracellular water volumes, or from potassium measurements, assuming that most of the potassium resides inside the cells at a constant concentration.

Cohn et al. (1980) proposed that estimates of the amounts of muscle and non-muscle fat-free tissues could be made from a combination of nitrogen and potassium measurements, providing the ratio of nitrogen and potassium in these tissues is known. However, the nitrogen/potassium ratio varies with age and illness, and for different tissues of the fat-free body (Cohn et al. 1983; Garrow 1982b; Lukaski et al. 1981).

The major problem with IVNAA has been to calibrate the body elemental analysis so measured by the technique. IVNAA is a growing field and at present its use in estimating body fat is more expensive and appears to have little advantage in terms of accuracy over measures of body fat based on densitometry, total body water and total body potassium (Lukaski et al. 1981). The method has also been criticized because it is difficult to activate calcium uniformly (Spinks 1979). IVNAA does, however, offer a means of measuring different components within the body, and thus avoids some of the assumptions regarding the uniformity of fat-free tissue composition, which are inherent in methods such as densitometry, total body water and total body potassium. IVNAA involves radiation exposure which is undesirable (Preston et al. 1985) and therefore not suitable for multiple body composition analyses.
8. Excretion of Muscle Metabolites

Creatine and phosphocreatine in muscle are converted to the waste-product creatinine, which is excreted in the urine (Webster and Garrow 1985). 3-Methyl histidine is another muscle metabolite, released after the breakdown of myofibrillar protein in muscle (Buskirk and Mendez 1984; Garrow 1982b). Daily urinary excretion of these metabolites should yield an estimate of the weight of muscle, providing that a 24-hour urine sample is accurately and completely collected and that no meat is eaten for two to three days prior to the test (Buskirk and Mendez 1984; Garrow 1982b).

Creatinine excretion is affected by dietary creatine and creatinine from meat and fish, dietary restriction and intensive exercise (Buskirk and Mendez 1984). Urinary levels have been shown to fluctuate, with measured coefficients of variation within the same individual over short periods of time, ranging from 2 to 30% (Boileau et al. 1972) and 8.7 to 34.4% (Webster and Garrow 1985). Moderate correlations ($r = 0.56$ to $0.91$) have been reported for the relationship of creatinine excretion with estimates of fat-free body weight based on measurements such as body density, total body water and total body potassium (Boileau et al. 1972).

Although fat-free weight correlates better with urinary 3-methyl histidine than with creatinine levels (Lukaski and Mendez 1980), excretion rates are affected by variations in muscle turnover rates (McKean et al. 1978) and uncertainties with the use of 3-methyl histidine arise because it can also be derived from sources other than skeletal muscle (Buskirk and Mendez 1984).
9. Quantitative Imagery

(a) Soft-tissue radiography
The thickness of the adipose layer over the body surface can be measured at selected sites using soft-tissue radiography (Cumming et al. 1973; Katch and Behnke 1984; Sidhu et al. 1975) because on the X-ray picture, shadows corresponding to subcutaneous fat can be analysed in terms of thickness or cross-sectional areas (Brozek 1963). Good correlations (usually \( r > 0.8 \)) are reported for the relationship of X-ray density with subcutaneous fat measured by calipers, but there are problems with distortion (Brozek 1963) and radiation exposure (Bullen et al. 1965; Haynes et al. 1976; Weiss and Clark 1985).

A recent technique using computed tomography (CT) has been described (Borkan et al. 1982; Kvist et al. 1986). As CT scans are thin cross-sectional radiographic images which can be taken at any position through the body, differentiation between intra-abdominal and subcutaneous fat is possible. The method has only limited potential because of the radiation exposure involved.

(b) Nuclear magnetic resonance tomography (NMR)
Recently nuclear magnetic resonance (NMR) imaging has been used for estimating body composition. The method is noninvasive, does not use ionizing radiation and is apparently without hazard (Andrew 1980).

Internal images are obtained by exposing the tissues to non-uniform magnetic fields producing recognizably different NMR frequencies from different nuclei. In contrast to the narrow X-ray beam used in CT scanning, the whole object within the NMR probe coil is irradiated,
and following complex computing, two- or three-dimensional images can be produced.

Using NMR images of living pigs, Foster et al. (1984) found marked contrast (6:1) between fat and muscle, and the interfaces in the images were found to correspond with those in the animal (Fuller et al. 1985) by measuring frozen tissue slices with a planimeter.

Even though NMR tomography has provided mainly proton images to date, allowing contrast between fat and muscle, it has the potential for measuring the density distribution of other nuclei.

(c) Ultrasonography

Ultrasound, which is a sound frequency greater than 20,000 Hz, will penetrate soft tissues and be reflected back at tissue interfaces, such as the junction between fat and muscle. A-mode (linear) (Booth et al. 1966; Bullen et al. 1965; Haymes et al. 1976) or the more sophisticated B-mode (brightness-mode) (Weiss and Clark 1985) can be used to measure subcutaneous fat thickness. The A-mode provides a one-dimensional linear array to represent the depth between different interfaces, while the B-mode provides a two-dimensional image of internal tissues (Weiss and Clark 1985).

Ultrasonography measurements have been found to have strong correlations with actual measurements of subcutaneous fat thickness \( r = 0.98 \) to \( 0.99 \) measured both \textit{in vivo} in abdominal operations and at post-mortem (Balta et al. 1981; Sanchez and Jacobson 1978). Strong correlations have also been found with electrical conductivity
measurements of subcutaneous abdominal adipose tissue \((r = 0.98)\) (Booth et al. 1966), needle puncture measurements of abdominal fat \((r = 0.98)\) (Bullen et al. 1965) and soft-tissue radiographs over the triceps \((r = 0.88)\) and supra-iliac \((r = 0.78)\) sites (Haymes et al. 1976). Although there is no substantial improvement of ultrasonic measurements over caliper measurements of subcutaneous fat (Booth et al. 1966; Bullen et al. 1965; Fanelli and Kuczmarski 1984; Sloan 1967; Weiss and Clark 1985), the ultrasonic technique is potentially superior for use with very obese subjects (Balta et al. 1981; Haymes et al. 1976).

(d) Stereophotogrammetry

Surface area and volume of the body, and cross-sections of body segments, can be calculated from stereophotographs. The process requires at least two overlapping photographs of the subject, and the end-result is a contour map of the body (Pierson 1963). If total body volume is to be measured, in order to determine body density, the volume of gas in the lungs and gastrointestinal tract must be estimated by other methods. This is because only the volume encompassed by the skin is measured by stereophotogrammetry. The technique, however, can be applied to individual body segments without such considerations. This method has been used to study body composition of astronauts and the changes produced by exposure to weightlessness (Whittle 1978 and 1979; Whittle et al. 1976).
E. AIMS OF THIS PROJECT

Despite the existence of a variety of techniques for the estimation of body composition, there is still a need for one which is closer to the ideal. Such a method would employ measurement techniques which are rapid, safe, noninvasive, accurate and convenient. The equipment required should be of low capital and recurrent cost, and should be operable by unskilled personnel and suitable for use in the clinic and in the field.

Most of the current laboratory methods are time-consuming and demand a high level of subject co-operation, making them unsuitable for use with the sick, elderly and very young. Ethical problems arise if the methods involve exposure to ionizing radiation, injection or ingestion of radioactive tracers or sampling of blood. Some of the more sophisticated methods are limited in their usefulness because the equipment is extremely expensive and the operators need to be highly skilled. In contrast to many of these laboratory methods, the simpler field techniques generally lack the necessary accuracy.

The main aim of this project was to develop an electrical method for determining human body composition. The method should fulfill the ideal criteria listed earlier, thereby providing nutritionists, clinicians and epidemiologists with an effective tool for monitoring body composition in individuals of differing age, sex and physical condition.

The electrical method developed is based on the markedly different electrical properties of fat and fat-free tissues in the body. The equipment was designed to measure the effect of the whole body on a
weak electromagnetic field, producing information which can be used in conjunction with the subject's body weight to calculate the proportions of fat and fat-free tissues.

In developing this equipment, it was necessary to design and test several prototypes in the process of optimizing field characteristics for both sensitivity and precision. It was also important that the equipment design should allow for subject comfort, including easy access and brief measurement time. The equipment should be sufficiently portable to permit its use in the field and provide measurement data of acceptable accuracy.

Another aspect of this research was to evaluate the usefulness of a commercially available bioelectric impedance analyser (RJL Systems, Model 101, Detroit, U.S.A.) as an instrument for measuring human body composition. This method is also based on the different electrical properties of fat and fat-free tissues, and involved the transmission of a 50 kHz current into the tissues of the body. The equipment is portable and easily operated, and in evaluating this method both the repeatability and reliability of the measurements were tested.

In order to calibrate the new equipment developed and to test the reliability of bioelectric impedance measurements, it was necessary to have estimates of fat and fat-free tissue weights of subjects based on other, indirect methods. Therefore a subsidiary aim of the project was to establish methods for estimating body composition by hydrostatic densitometry and deuterium oxide dilution. This involved setting up appropriate equipment and apparatus, which included construction of a water tank with associated filtering and heating
facilities and the development of a method for estimating lung volume at the time of underwater weighing.

The aims of the project are summarized below, in the order of presentation in the following text:

1. To set up methods for estimating body composition based on hydrostatic densitometry and deuterium oxide dilution.

2. To develop a method for estimating lung volume using hydrogen dilution at the time of underwater weighing.

3. To evaluate the usefulness, in terms of repeatability and reliability, of a bioelectric impedance analyser as an instrument for determining human body composition.

4. To develop electrical equipment suitable for determining human body composition.

5. To test the response of the equipment to different quantities and combinations of absorbing materials such as lean meat and fat.

6. To employ multiple regression analysis to develop equations for predicting the weights of fat and fat-free tissue in the body from measurements of body weight and the change in electromagnetic field characteristics caused by the body.

The subjects who volunteered to participate in these studies were from the University, local community and local slimming groups. Written,
informed consent was obtained from the subjects and the studies were approved by the University Ethics Committee.
CHAPTER 2

HYDROSTATIC DENSITOMETRY WITH LUNG VOLUME ESTIMATED BY
HYDROGEN DILUTION AT THE TIME OF UNDERWATER WEIGHING

A. INTRODUCTION

When a body is immersed in water, the weight of the displaced water is equal to the difference between the weight of the body in air \( (M_A) \) and the weight when completely submerged \( (M_W) \). Therefore, the conventional equation for the density of water \( (D_W) \)

\[
D_W = \frac{M}{V}
\]

where \( M = \text{mass} \) and \( V = \text{volume} \), becomes

\[
D_W = \frac{(M_A - M_W)}{V}
\]

or

\[
V = \frac{(M_A - M_W)}{D_W}
\]

As body volume is equal to the volume of displaced water, body density \( (D_B) \) is then

\[
D_B = \frac{M_A}{V} = \frac{M_A}{\left(\frac{M_A - M_W}{D_W}\right)}
\]

The volume of water displaced by the body includes the volume of gas trapped in the lungs and in the gastrointestinal tract at the time of underwater weighing.
Using a plethysmographic method, Blair et al. (1947) determined the average volume of gas in the gastrointestinal tract to be approximately 1 L. Bedell et al. (1956) used an improved plethysmographic method and reported a gas volume of approximately 100 mL. Corrections for this gas volume have been largely ignored because the volume was considered to be relatively small and variable (Goldman and Buskirk 1961), but others (Ross and Marfell-Jones 1982) consider it customary to allow 100 mL for gastrointestinal gas.

Lung volumes, however, which can range between residual volumes of about 1 L to total lung capacities of about 6 L (Timson and Coffman 1984), represent a large and measurable volume. Numerous methods have been employed to measure lung volume accurately; these include closed-circuit dilution and equilibration of indicator gases such as hydrogen (Birath 1944; Christie 1932; von Dobeln 1956), helium (Katch et al. 1967; Motley 1957), nitrogen (Rahn et al. 1949) and oxygen (Wilmore 1979), and the nitrogen washout open-circuit method (Darling et al. 1940).

As residual volume is the most consistent lung volume to measure, both in and out of the water, most investigators have chosen this as the volume at which the underwater weight is to be observed and often this volume is estimated before or after submersion.

Since it is desirable to measure lung volume at the time of underwater weighing, a simple, rapid method of doing this using a closed-circuit hydrogen rebreathing system was developed and is described in this chapter. Body density is determined at approximately 50% of total lung capacity thereby improving both subject comfort and co-operation.
and avoiding the problems associated with maintaining residual lung volume while under water.

In developing this method, it was necessary to establish the minimum number of breaths required to equilibrate the tracer hydrogen in the rebreathing system with the air in the lungs, and the method for doing this is described.

As hydrogen is produced endogenously from the fermentation of fibre in the lower intestine (Calloway 1966), it is necessary to correct for the contribution of endogenous hydrogen to the total hydrogen in the rebreathing system, and this chapter also describes a method for doing this.

B. METHODS

1. Equipment for Underwater Weighing

A corrugated-iron tank, measuring 1.50 m high with a diameter of 1.33 m, was used for underwater weighing. In preparation for use, the water in the tank was chlorinated (Filtrite, Clark Rubber Wholesale Pty. Ltd.), filtered (Filtrite Cartridge Filter 2400) and warmed to 30 - 36°C with immersion heaters (G3 LN Products Pty. Ltd). Access and egress was assisted by a ladder which was removed from the tank during the underwater weighing procedure. The subject’s chair, constructed of rigid PVC tubing, was attached to a set of overhead suspension scales (Salter spring balance No. 236T) via a chain, enabling adjustment of chair height.
2. Closed-Circuit Rebreathing Apparatus

The apparatus consisted of a standard respiratory mouthpiece fitted to a three-way valve attached to a 2 L neoprene respiratory bladder containing an accurately measured volume (2.026 L, which was 2 L plus the dead-space between the valve and the bladder) of a mixture of hydrogen in air (approximately 220 ppm or ×L/L). The valve was arranged so that the subject could breathe room air or be switched to rebreathing from the bladder. The collar to which the bag was attached had a small hole covered with a band of rubber through which gas samples (20 mL) could be extracted with a hypodermic syringe and later analysed for hydrogen concentration to an accuracy of ± 1 ppm (Exhaled Hydrogen Monitor, GMT Medical Ltd., Renfrew). The breathing apparatus had a very small total dead-space and was easily supported in the subject’s hands.

3. Determination of Minimum Number of Breaths Needed for Hydrogen Equilibration

In order to determine the minimum number of breaths needed for hydrogen equilibration, 10 subjects each rebreathed the hydrogen-air mixture from the closed-circuit rebreathing system for a total of 10 breaths. Near the end of each exhalation a 20 mL gas sample was withdrawn as previously described and analysed for hydrogen concentration.

Endogenous hydrogen concentration was similarly determined except that the subjects rebreathed air from the closed-circuit rebreathing system.
4. Procedure to Determine Underwater Weight and Lung Volume at the Time of Underwater Weighing

In this procedure a sample was first withdrawn from the hydrogen-air mixture in the bladder and analysed later for initial hydrogen concentration. After showering and climbing into the tank, the subject removed any air bubbles adhering to skin, bothers or hair, sat in the chair and was weighed down by a diver’s belt. Chair height was adjusted so that the water was at chin level. With the nose-clip, mouthpiece and respiratory bladder in place, the subject exhaled comfortably to near residual volume and the valve was turned to enable the subject to breathe slowly five times from the bladder. Plate 2.1 shows a subject who is in the tank and breathing from the bladder.

After the fifth inhalation and while still connected to the bladder, the subject leant forward into the water until totally submerged, taking the collapsed bladder under the water for several seconds while the underwater weight was recorded. Plate 2.2 shows the underwater weighing procedure in progress. On a signal from the investigator, the subject raised his/her head above the water and exhaled into the bladder. The valve to the bladder was then closed to trap the rebreathed gas mixture in the bladder and a final sample of gas was then withdrawn from the collar for analysis so that hydrogen dilution could be calculated.

To determine endogenous hydrogen concentration, the subject, with nose-clip and mouthpiece in place, breathed five times from the closed-circuit rebreathing system containing air. A gas sample from this system was withdrawn and later analysed.
Plate 2.1

Underwater weighing: The subject is sitting on a chair suspended from scales while rebreathing a hydrogen-air mixture from a respiratory bladder.
Plate 2.2

Underwater weighing: The subject has leaned forward into the water to become completely submerged while the underwater weight is determined.
Ambient temperature, water temperature and atmospheric pressure were recorded.

The volume of gas in the lungs, anatomical dead-space and the breathing apparatus at the time of underwater weighing was calculated using the following relationship:

$$V_G = \frac{C_I \times 2.025}{C_F - C_E}$$

where

- $V_G$ = gas volume in the lungs and breathing apparatus (L)
- $C_I$ = initial hydrogen concentration (ppm)
- $C_F$ = final adjusted hydrogen concentration (ppm)
- $C_E$ = endogenous hydrogen concentration (ppm)

The calculated lung volume, $V_G$, was corrected to body temperature and pressure and saturation with water vapour (BTPS) using standard correction factors (Diam and Lentner 1970).

Finally, the hydrostatic pressure ($P_H$), which reduced the volume of gas in the lungs while the subject was underwater, was calculated from

$$P_H = h \times d \times g$$

where

- $P_H$ = hydrostatic pressure (N/m$^2$)
- $h$ = estimated distance of the centre of volume of the lungs from the surface of the water (m)
- $d$ = density of water (kg/m$^3$)
- $g$ = 9.81 (m/s$^2$)
and the reduction in lung volume was calculated using the General Law of Gases.

These procedures yielded the data needed to calculate body density from the following equation:

\[
D = \frac{W_A}{B} \left( \frac{W_A}{W_A - W_W} - V \right) \frac{1}{D_W}
\]

where \(D_B\) = body density \((\text{kg/dm}^3)\),

\(W_A\) = weight in air \((\text{kg})\),

\(W_W\) = weight underwater \((\text{kg})\) corrected for tare weight

\(D_W\) = density of water at temperature of water during weighing

\(V\) = \(V_G\) \((\text{L})\), after correction for DIPSS and hydrostatic pressure.

5. Accuracy

To test the accuracy of the method, a model lung was connected to the respiratory bladder via a three-way valve. The model lung, another respiratory bladder \((2 \text{ L capacity})\), was filled with an accurately measured volume of air \((1.00 \text{ L})\), and connected to the 2L-respiratory bladder by an assembly of two collars and a three-way tap. Before the connecting valve was opened, 2.026 L of air, containing hydrogen at 220 ppm, was delivered into the second bladder and a 20 mL sample withdrawn for analysis. The valve was opened and the gases mixed by alternately depressing each bladder so that the gas mixture was forced from one bladder to the next through the connecting tap assembly.
After equilibration in this way, a second gas sample was withdrawn. The volume of the dead-space in the connecting assembly was determined by filling with water and weighing. The volume of air in the model lung was determined 10 times.

6. Reproducibility

The body density of a healthy 21-year-old female subject was determined five times on the same day by underwater weighing, with lung volume at the time of weighing, measured by the closed-circuit hydrogen rebreathing method described. The coefficient of variation of the computed densities was then calculated.

C. RESULTS

1. Hydrogen Equilibration

Figure 2.1 shows the measured concentration of hydrogen in the gas mixture in the bladder after each breath during rebreathing from a respiratory bladder initially containing air with hydrogen added to 220 ppm, allowing for the reduction in volume due to sampling. After the initial mixing period, the hydrogen concentration continued to rise in some subjects and this was attributed to the addition of the endogenous hydrogen to the gas mixture. To correct for this, the measured concentration of endogenous hydrogen was subtracted from the total hydrogen concentration, and these adjusted values are shown in Figure 2.2. Equilibration of lung gas with the gas mixture in the bladder had been reached by the fourth of fifth breath in all
Figure 2.1

Hydrogen concentration in the respiratory bladder after each breath in males and females.
Figure 2.2
Hydrogen concentration corrected for endogenous hydrogen production for males and females.
subjects. Following equilibration, the slight negative slopes of the graphs indicate the rate at which hydrogen was absorbed into the body through the lungs. After five breaths, the mean loss of hydrogen was $4.1 \pm 1.6 \, \text{ppm} \, (\pm \text{s.d.})$. For routine calculation of lung volume during underwater weighing, this small loss of hydrogen by absorption can be neglected. In more accurate studies this loss can be accounted for by adding 4 ppm to the hydrogen concentration in the final gas sample taken from the respiratory bladder after the five-breath equilibration period.

2. Accuracy

The mean measured volume of air in the artificial lung was estimated as $1000.2 \pm 31.9 \, \text{mL} \, (\pm \text{s.d.})$, i.e. a coefficient of variation of 3.2%. If this was the only error in the determination of body density, the 95% confidence limits for a single determination of body density in a subject with an actual body density of $1.0300 \, \text{kg/dm}^3$ would be between 1.0288 and 1.0312 kg/dm$^3$.

3. Reproducibility

The body density of a single subject was measured in four sets of five determinations on the same day, using the lung volume technique described. The resulting coefficients of variation ranged from 0.16% to 0.31%, for five determinations, with a mean value of 0.23%.
D. DISCUSSION

The method for underwater weight determination, which involves soating the subject so he/she is immersed to chin level and then bending forward for complete submersion, was described by Goldman and Buskirk (1961) and differed from earlier methods which had the subject lowered into the water. There are advantages in the Goldman and Buskirk submersion technique. The subject is in control during the submersion process and, because most of the body is already under the water, the head can be bent forward with only small disturbance of the water, which minimizes scale oscillations thus reducing the necessary submersion time.

Lung volume can be determined by the technique described with an accuracy and reproducibility which lie within acceptable limits. The main advantage of the present method is that it provides a simple and relatively inexpensive method for determining lung volume at the time of underwater weighing. Hydrogen, although used as an indicator gas in the past, Christie (1932), fell into disuse because of the potential explosiveness of hydrogen-air mixtures. In the present method a very low and non-combustible concentration of hydrogen in air has been used and this has been made possible by the sensitivity of the hydrogen monitor which can detect hydrogen concentrations in the range 1 to 250 ppm (± 1 ppm). The minimum combustible concentration of hydrogen in air is 40,000 ppm at atmospheric pressure and room temperature (Weast 1974). The concentration of hydrogen used here (220 ppm) is therefore safe.

Unlike methods which measure lung volume before or after underwater weighing, it is not necessary with this method to ensure that the
subject reaches the same lung volume (usually either residual or maximal) during each underwater weighing since the amount of air in the lungs at the time of each underwater weighing is determined. This approach enables subjects to have a comfortable amount of air in the lungs when submerged and makes the procedure more acceptable to them. The effect of hydrostatic pressure on the volume of air in the lungs during underwater weighing can be allowed for.

The accuracy of any protocol for determining body composition by underwater weighing is limited by the current inability to measure the volume of gas in the gastrointestinal tract. To minimize this error, it is desirable to have the subjects fast for twelve hours and empty bladder and bowels, if possible, before being weighed underwater. A possible added advantage of using hydrogen for lung volume determination is that the level of production of endogenous hydrogen provides an indication of the volume of gas in the large intestine and its consequent buoyancy effect. The presence of significant endogenous hydrogen indicates a probable underestimate of body density.
CHAPTER 3

TOTAL BODY WATER ESTIMATED FROM DEUTERIUM OXIDE DILUTION

A. INTRODUCTION

Total body water estimates based on deuterium dilution were first reported by Hovey and Hofer (1934). Deuterium, with a relative atomic mass of 2, is the heavy stable isotope of hydrogen. The natural abundance of deuterium in tap water is about 150 ppm (Halliday and Miller 1977) and it is non-toxic in concentrations less than 25% (Novak 1967). Reported estimates for the half-time of deuterium in the adult human body range from 9 - 11 days (Hovey and Hofer 1934; Mendez et al. 1970; Schloerb et al. 1950).

The substitution of hydrogen by deuterium in water results in changes in physical properties. Heavy water, D₂O, is about 10% heavier, 25% more viscous, and has 8.8% lower vapour pressure at 20°C than ordinary water (Kirshenbaum 1951; Robertson 1949). The melting and boiling points of D₂O are higher than those of H₂O, and the temperature of maximum density is markedly higher in D₂O, indicating that hydrogen bonding is more extensive in D₂O than in H₂O (Katz 1960).

Procedures for quantitating D₂O in biological fluids are based on physical differences such as those listed above and include the falling drop method (Schloerb et al. 1951), freezing point elevation (Garry et al. 1968), gas chromatography (Arnett and Duggleby 1963; Mendez et al. 1970; Nielsen et al. 1971), mass spectrometry (Halliday...

The preparation of body fluids such as plasma, urine and saliva, for deuterium analysis can be complex and may require treatments such as: (a) precipitation of interfering proteins with copper sulfate (Turner \textit{et al.} 1960)

(b) filtration through charcoal (Wang \textit{et al.} 1973)

(c) dialysis (Robbins 1969)

(d) vacuum distillation (Schloerb \textit{et al.} 1950; Turner \textit{et al.} 1960; Wentzel \textit{et al.} 1958)

(e) vacuum sublimation or lyophilization (Bencsath \textit{et al.} 1983; Byers 1979; Lukaski and Johnson 1985; Schoeller \textit{et al.} 1980)

(f) reduction of water from the sample to hydrogen gas (Halliday and Miller 1977; Schloerb \textit{et al.} 1950; Schoeller \textit{et al.} 1980; Solomon \textit{et al.} 1950)

(g) conversion by chemical ionization (Bencsath \textit{et al.} 1983; Munson and Field 1966)

(h) gamma irradiation (Stansell and Hyder 1976).

$D_2O$ is considered a useful tracer for body water because it forms an ideal solution with water (Longsworth 1937; Swift 1939). The metabolism of $D_2O$ is essentially identical to that of water (Pinson 1952) and the body does not concentrate deuterium in the various water pools (Mendez \textit{et al.} 1970; Wang \textit{et al.} 1973).
The volume of equilibrium dilution of $D_2O$ has been shown to represent closely the total body water volume in desiccation studies in animals (Moore 1946; Soberman et al. 1949). However in more recent studies with several mammalian species, including rats (Culebras et al. 1977; Tisavipat et al. 1974), dogs (Shang and Huggins 1971), pigs (Kay et al. 1966), sheep (Cowan et al. 1980; Foot and Greenhalgh 1970), goats (Panaretto 1963), cattle (Carnegie and Tulloch 1968; Odwongo et al. 1984) and humans (Halliday and Miller 1977; Schoellor et al. 1980), the deuterium space, or the similar tritium space (Wang et al. 1973), has reportedly overestimated total body water.

The main source of error arises from the exchange of deuterium or tritium with labile hydrogen atoms in protein and, to a lesser extent, carbohydrate (Culebras and Moore 1977). The result is that the calculated deuterium or tritium space appears larger than the actual total water volume. Culebras and Moore (1977) theoretically calculated that the maximum amount of nonaqueous exchangeable hydrogen by weight in the human body is 5.2% of the total exchangeable hydrogen. Schloerb et al. (1950) calculated the error to have a water equivalent of 0.5 - 2.0% of body weight in healthy subjects, which is in agreement with Pinson's (1952) estimate of 1 - 2%. It has been suggested (Halliday and Miller 1977) that for short term studies, errors arising from exchange reactions are of negligible consequence.

Of practical concern is the choice of body fluid used for analysis and the time allowed for $D_2O$ equilibration. A report by Taggart and Hytten (1959), that salivary glands could concentrate deuterium above the level in serum 3 hr after ingestion of $D_2O$ by pregnant women,
caused some confusion. Coppen and Gibbons (1960), however, questioned this after finding a rapid equilibration of ingested tritium in plasma and saliva. More recently, rapid equilibration of D$_2$O in plasma, saliva and urine has been demonstrated (Mendez et al. 1970). Schloerb et al. (1950) reported that deuterium took 3 hr to equilibrate with the body water pool after ingestion or injection of D$_2$O. However, equilibration data since then (Lukaski and Johnson 1985; Mendez et al. 1970; Nielsen et al. 1971) have shown that there is a peak of D$_2$O concentration in plasma and saliva about 2 hr after D$_2$O administration.

In this chapter, a method for estimating total body water is described in which D$_2$O dilution is determined by measuring the infrared absorption of saliva sublimates.

B. METHODS

1. Administration of D$_2$O and Collection of Saliva

An estimate of the subject's total body water was made after calculating fat content from body mass index (weight/height$^2$) as described by Womersley and Durnin (1977). The D$_2$O dose was calculated so that its concentration in the body water compartment would be approximately 0.1% (w/v). An accurately weighed dose of D$_2$O (99.75%, Australian Institute of Nuclear Science and Engineering) was ingested and the container was rinsed with distilled water so that the total volume of liquid consumed was approximately 300 mL.
After a 2 hr equilibration period, the subject collected a 10 mL saliva sample by expectorating into a clean, dry screw-top plastic tube; salivation was stimulated by chewing parafilm or rubber. Saliva samples were frozen until required for further treatment.

2. Extraction of H$_2$O-D$_2$O From Saliva

Water and D$_2$O were isolated from saliva using vacuum sublimation. Saliva samples (5 mL) were shell-frozen in round-bottom flasks in liquid nitrogen. Six cold finger condensers were positioned in a liquid nitrogen bath and cotton wool pads were used as insulating covers. Vacuum was supplied with a pump, reducing the pressure to approximately 300 Pa.

The sublimation process continued for about 3.5 - 4.0 hr to ensure complete removal of H$_2$O-D$_2$O. This was an important step because of the small differential in H$_2$O and D$_2$O vapour pressures (Robertson 1949). If the samples were not sublimed to dryness, the recovery of D$_2$O would be incomplete. Isolated H$_2$O-D$_2$O sublimates were stored in screw-top plastic tubes and frozen for later analysis.

3. D$_2$O Assay

(a) Equipment

In dilute D$_2$O solutions, essentially two molecular species, H$_2$O and DKO, exist because of the following equilibration:
\[ \text{H}_2\text{O} + \text{D}_2\text{O} \rightarrow 2 \text{DHO} \]

Spectroscopic analysis is based on the O-D vibrational band at 2500 cm\(^{-1}\). At this frequency there is a maximum absorbance for D\(_2\)O coinciding with a minimum absorbance of H\(_2\)O. Infrared analysis actually measures the molecular species DHO, but the term D\(_2\)O concentration is used because it is based on prepared D\(_2\)O-H\(_2\)O (w/v) standards used.

Absorbance was measured at 2500 cm\(^{-1}\) using a fixed filter (4.0 μm) single beam infrared analyser (Foxboro Analytical MIRAN-1, South Norwalk, Conn.) with a sealed calcium fluoride cell and 0.2 mm pathlength.

(b) Standard curve

Standards were prepared by weighing amounts of D\(_2\)O and diluting them to 100 mL with distilled water in volumetric flasks. Concentrations of the prepared standards ranged from 0.02 - 0.20% (w/v).

The baseline value of the analyser was adjusted with the cell filled with distilled water, and using 1 mL syringes, 0.8 mL of each sample was injected in order of increasing concentration into the inlet port of the cell. Air bubbles were excluded from the system.

With the introduction of each sample there was an immediate increase in absorbance (a boundary effect) followed by a decline which became linear with time, the gradient being similar for each sample tested. This was caused by a rise in sample temperature in the cell, as the
O-D resonance band is temperature dependent (Lukaski and Johnson 1985). To overcome this problem, absorbance was taken at a fixed time interval, 2.00 min, after sample injection.

To measure the reproducibility of the standard curve, absorbance values for the standards were measured four times over two days, and mean absorbance, together with standard deviation and coefficient of variation, were calculated for each standard.

(c) Analysis of saliva samples
The samples were brought to room temperature prior to analysis. As the approximate D$_2$O concentration in the saliva sublimates was 0.1%, aliquots of the 0.1% standard solution were measured in the analyser before the sublimates were assayed, and then after every fourth sample to test for instrument drift.

(d) Determination of total body water
The percent (w/v) concentration of D$_2$O in saliva sublimates was determined from the standard curve, and total body water (TBW) was calculated from the following equation:

$$\text{TBW (L)} = \frac{\text{mass D}_2\text{O administered (g)}}{\% \text{ D}_2\text{O (g/100 mL)} \times 10}$$

There is a minor error in the method because of the continuous accumulation of urine in the bladder. The concentration of D$_2$O in this urine rises with time after the ingestion of D$_2$O, but will not reach equilibrium with that of the rest of the body water because of limited exchange of water across the bladder wall.
(e) Recovery of D$_2$O and reproducibility of D$_2$O measurements

Duplicate 5 mL aliquots of 0.08%, 0.10% and 0.12% standard solutions were treated by vacuum sublimation and analysed for D$_2$O concentration.

Recovery of D$_2$O was calculated by comparing absorbance readings of the sublimates with absorbance readings for corresponding untreated standards. Significance levels for accuracy were determined using a chi-square test.

Reproducibility was calculated by comparing absorbance readings of duplicate samples which had been separately vacuum sublimed, and significance levels for differences were determined using a 2-tailed paired t-test.

C. RESULTS

1. Standard Curve

Figure 3.1 shows a typical standard curve, illustrating the linear relationship between absorbance and D$_2$O concentration.

The reproducibility of the standard curve is shown in Table 3.1 in which values for absorbance are the means of four determinations carried out over two days.
Figure 3.1

Standard curve showing the relationship between absorbance and $D_2O$ concentration.
Table 3.1.
The reproducibility of the standard curve. The values for absorbance are the means of four determinations carried out over two days.

<table>
<thead>
<tr>
<th>% D₂O (w/v)</th>
<th>Absorbance</th>
<th>± s.d.</th>
<th>coefficient of variation (%)</th>
</tr>
</thead>
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<td>0.02</td>
<td>0.021</td>
<td>0.0028</td>
<td>13.6</td>
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<td>0.0010</td>
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<td>0.16</td>
<td>0.170</td>
<td>0.0048</td>
<td>2.8</td>
</tr>
<tr>
<td>0.20</td>
<td>0.220</td>
<td>0.0019</td>
<td>0.9</td>
</tr>
</tbody>
</table>
2. Recovery of D₂O and Reproducibility of D₂O Measurements

For the six samples tested, D₂O recoveries ranged from 98.3 - 101.1%, with a mean recovery (± S.D.) of 99.7 ± 1.2%.

There was no significant difference (P > 0.25) in absorbance values between standards which had been treated by vacuum sublimation and the corresponding untreated standards, indicating that the measured concentration of D₂O in a sublimate was an accurate measure of D₂O concentration in the untreated sample.

There was no significant difference (P > 0.10) between duplicate samples which had been separately vacuum sublimed, indicating that the technique was highly reproducible.

D. DISCUSSION

The method for analysing D₂O concentrations in saliva proved to be rapid, noninvasive and precise. Other body fluids, such as plasma or urine, could have been used, but there were advantages in using saliva as the sampling fluid. Unlike plasma collection, it was noninvasive and therefore appeared more acceptable to many subjects, while the collection of urine samples can be personally embarrassing to some people.

Although analytical accuracy can be improved by giving large amounts of D₂O (Nielsen et al. 1971; Schloerb et al. 1950; Wentzel et al. 1958), it is desirable to keep administered quantities low. In this method, the amount of D₂O given to subjects resulted in a D₂O
concentration of approximately 0.1% (w/v). This was a dose within the
range of those reported for infrared absorption analysis. A D₂Ο dose
of 1 g/kg body weight (approximately 50 – 70 g), resulting in D₂Ο
concentrations of 0.05 – 0.5% (w/v), has been widely used (Graystone
et al. 1967; Mendez et al. 1970; Schutte 1980; Turner et al. 1960;
Wang et al. 1973). Smaller D₂Ο doses, such as 10 g resulting in D₂Ο
concentrations of about 0.005 – 0.04% (w/v) (Lukaski and Johnson 1985)
and 0.25 g/kg body weight (Byers 1979), have been successfully
quantitated.

Although longer times have been used (Schloerb et al. 1950), a 2 hr
equilibration period was chosen because it has been shown to be
adequate (Lukaski and Johnson 1985; Mendez et al. 1970; Nielsen et al.
1971). Using a 2 hr D₂Ο equilibration time, Lukaski and Johnson
(1985) calculated that 74.0 ± 1.6% of the fat-free weight was water, a
figure which is similar to the accepted mammalian value of 73.2% (Pace
and Rathbun 1945). They suggested that by using a 2 hr equilibration
time the error in overestimating the total body water volume due to
exchange of isotopic hydrogen could be reduced.
CHAPTER 4

ELECTROMAGNETIC DETERMINATION OF BODY COMPOSITION: THEORY

A. DIELECTRIC BEHAVIOUR

The effect of a human body on an electromagnetic field depends on the electromagnetic field induced within the body by the incident electromagnetic field. The characteristics of the human body which are important in this regard include the physical shape, dimensions, and dielectric permittivity.

The dielectric permittivity is defined as:

\[ \varepsilon = \varepsilon_0 (\varepsilon' - j\varepsilon'') \]

and the loss tangent as

\[ \tan \delta = \varepsilon''/\varepsilon' \]

where \( \varepsilon_0 \) = permittivity of vacuum

\( \varepsilon' \) = relative dielectric constant

\( \varepsilon'' \) = relative loss factor.

The dielectric constant (\( \varepsilon' \)) is related to the medium's ability to store electric energy, while the loss factor (\( \varepsilon'' \)) involves the amount of energy the medium dissipates as heat (Tinga and Nelson 1973).
The dielectric constant is a measure of the extent to which localized charge distributions can be distorted through polarization or charge storage, by an external electric field. Ackmann and Seitz (1984) describe the most important polarization mechanisms in biological systems as follows:

a) **Electronic polarization** which occurs when the negative charge associated with the electron cloud is displaced from the positive charge of the nucleus.

b) **Dipole polarization** which occurs when polar molecules, which possess a permanent electric dipole moment, align themselves with an applied field.

c) **Interfacial polarization** which occurs in heterogeneous materials where areas of high conductivity exist within a matrix of low conductivity. This situation arises in biological materials where intracellular contents of high conductivity are separated by cell membranes which are relatively insulating.

d) **Space charge polarization** (and Faradaic polarization) which occur where interfacial layers with high resistivity block the movement of charge-carriers, resulting in a build-up of charge.

To orientate themselves in an applied electric field, dipoles move away from an equilibrium position and store the energy used for this as potential energy. Removal of the field causes the dipoles to restore the equilibrium and the energy thus released is dissipated as heat.
If the polarity of an applied field reverses, the dipoles rotate, although the random motion of the molecules prevents perfect realignment. The degree of orientation is limited by frictional forces that are dependent on the rate of molecular rotation, and by the relaxation time, which is dependent on solvent viscosity, dipole size and shape, and solute-solvent bonding (Stuchly 1979).

As frequency increases, \( \varepsilon' \) decreases as the mass and inertia of the dipoles prevent them from keeping up with the changes in direction of the alternating electric field. Accompanying this fall in dielectric constant there is an absorption of energy from the field by the medium. This phenomenon, referred to as dielectric relaxation, or dispersion, can occur at low frequencies of approximately \( 10^{-1} \) Hz for bulky macromolecules, to frequencies approaching \( 10^{12} \) Hz for small molecules (Pethig 1979).

The effective conductivity \( (\sigma) \) of a material results from both the DC conductivity, which is governed by the movement of delocalized electric charge, as well as that resulting from polarization of the material under the influence of an alternating electric field. The conductivity and the loss factor are interrelated (Stuchly 1979; Stuchly and Stuchly 1980) in the following way:

\[
\sigma = 2nf_\varepsilon \varepsilon''
\]

where \( \sigma \) = conductivity

\( f \) = frequency

\( \varepsilon_0 \) = permittivity of vacuum

\( \varepsilon'' \) = relative loss factor.
B. ELECTRICAL BEHAVIOUR OF BODY TISSUES

The human body is a complex electrical medium because of its irregularity of shape and the heterogeneity of the properties of the tissues. The basis of electrical methods for determining body composition lies in the difference in electric properties of the various body tissues.

1. Water Content

Table 4.1 shows the permittivity of two groups of tissues: those with high water contents, such as muscle and skin, and those with low water contents, such as fat and bone. The dielectric constants and conductivities of high water content tissues are greater than those of low water content tissues. Similarly, tissues with low water contents have greater resistivities. Figures 4.1 and 4.2 show the average dielectric properties of several tissues over the frequency range 1 MHz – 10 GHz, at 37°C (Pethig 1979).

Pure water has large dielectric values because the water molecules are strongly polar. The dielectric properties of water at 37°C are \( \varepsilon' = 74 \) and \( \varepsilon'' = 0.003 \) at 1 MHz, and \( \varepsilon' = 74 \) and \( \varepsilon'' = 0.9 \) at 300 MHz (V.N. Tran, personal communication). Therefore water is a good energy absorber in this frequency range, and in the presence of electrolytes \( \varepsilon'' \) will increase because of the associated increase in conductivity. This explains the strong dependence of the dielectric properties of tissues on their water content.
Table 4.1

Dielectric constant and conductivity of biological tissues (adapted from Johnson and Guy 1972). Tissues with high water contents include muscle and skin; tissues with low water contents include fat and bone.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Wavelength (cm)</th>
<th>High water content tissues</th>
<th>Low water content tissue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(\varepsilon')</td>
<td>(\sigma(S/m))</td>
</tr>
<tr>
<td>1</td>
<td>30000</td>
<td>2000</td>
<td>0.400</td>
</tr>
<tr>
<td>10</td>
<td>3000</td>
<td>160</td>
<td>0.625</td>
</tr>
<tr>
<td>27.12</td>
<td>1106</td>
<td>113</td>
<td>0.612</td>
</tr>
<tr>
<td>40.68</td>
<td>738</td>
<td>97.3</td>
<td>0.693</td>
</tr>
<tr>
<td>100</td>
<td>300</td>
<td>71.7</td>
<td>0.889</td>
</tr>
<tr>
<td>200</td>
<td>150</td>
<td>56.5</td>
<td>1.28</td>
</tr>
<tr>
<td>300</td>
<td>100</td>
<td>54</td>
<td>1.37</td>
</tr>
<tr>
<td>915</td>
<td>32.8</td>
<td>51</td>
<td>1.60</td>
</tr>
<tr>
<td>2420</td>
<td>12.2</td>
<td>47</td>
<td>2.21</td>
</tr>
<tr>
<td>3000</td>
<td>10</td>
<td>46</td>
<td>2.26</td>
</tr>
<tr>
<td>5000</td>
<td>6</td>
<td>44</td>
<td>3.92</td>
</tr>
<tr>
<td>10000</td>
<td>3</td>
<td>39.9</td>
<td>10.3</td>
</tr>
</tbody>
</table>
Figure 4.1

The frequency dependency of the permittivity (ε) for several tissues (adapted from Pethig 1979).
Figure 4.2
The frequency dependency of the resistivity ($\rho$) for several tissues (adapted from Pethig 1979).
Water contained in biological tissue exists in two forms, called free water and bound water. Bound water has various definitions which arise from the different experimental techniques used to investigate it. The structure of bound water lies between that of ice and normal water (Schwan 1965 and 1977) and is generally described as molecules held in nonrandom orientations at or near a macromolecular surface (Stuchly 1979). Therefore the properties of bound water depend on the presence of solvated ions and large molecules such as proteins. Dielectric measurements indicate that bound water comprises only two molecular hydration layers (Grant et al. 1978) and that most tissue water is dielectrically similar to pure water (Foster et al. 1980; Schwan 1977; Schwan and Foster 1977). However, nuclear magnetic resonance evidence suggests that the bound water layer extends further so that all cellular water is, to some extent, affected (Hazlewood 1977). Bound water has larger dielectric and conductivity values than free water (Joines 1984), since the relaxation frequency of bound water lies within the 100 - 1000 MHz range, while for free water, it is approximately 25 GHz at 37°C (Grant et al. 1978; Stuchly 1979).

2. Frequency

Mammalian tissue comprises a matrix of cells bathed by tissue fluids. The intracellular and extracellular fluids, which are separated by thin membranes, contain dissolved salts and polar protein and water molecules. Tissues can be ideally represented by an equivalent circuit shown in Figure 4.3 (Ackmann and Seitz 1984).
$R_m$ = membrane resistance
$C_m$ = membrane capacitance
$R_i$ = intracellular resistance
$R_p$ = DC parallel path through extracellular space.

Figure 4.3
Equivalent circuit for biological tissue (Ackmann and Seitz 1984).
There is a decrease in dielectric constant and an increase in conductivity of tissues as frequency is increased. At frequencies less than about 100 MHz, cell membranes, which have a capacitance of approximately 1 μF/cm² (Ackmann and Seitz 1984; Cole 1933), behave as insulating layers so that currents are conducted only via the extracellular fluid space (Rp). At higher frequencies, the capacitive reactance of the cellular membrane is decreased (Ackmann and Seitz 1984; Geddes and Baker 1975; Johnson and Guy 1972) resulting in increasing current in the intracellular fluid, which causes an increase in the total conductivity of the tissue. This means that for frequencies above about 100 MHz, the cell membrane capacitive reactance is low enough for the cells to be short-circuited, enabling an even spread of current throughout the tissue.

Figure 4.4 shows the typical variation of the permittivity (ε) with frequency in biological tissue (Pethig 1979). There are three regions where the permittivity changes rapidly with frequency. The change which occurs with low frequencies, in region 1, reflects dielectric dispersions associated with interfacial phenomena. In region 2, the change is governed by the capacitance of cell membranes. The effect of the membrane capacitance diminishes as frequency is increased until frequencies of about 100 MHz are reached. As described above, intracellular and extracellular fluids then affect the dielectric properties of the tissue. In the frequency range 100 - 3000 MHz, there is relatively little change in permittivity value which is essentially governed by the water content of the tissue.
Figure 4.4

The frequency variation of the permittivity ($\varepsilon$) of a typical biological tissue (Fethig 1979).
3. Temperature

In tissues with low water contents, most of the water is bound, and the loss factor tends to increase with temperature. This may be due to a reduction in binding force, enabling the water and other polar molecules to reorientate more freely in an alternating field. In tissues with high water contents, there is an abundance of free water, and the loss factor tends to decrease with temperature. This is due principally to changes in hydration shells as well as a variety of other chemical reactions.

4. Depth of Penetration

As an electromagnetic wave penetrates the body tissues, it is attenuated as a result of absorption of the power density of the wave. The wavelength of the propagating wave in tissue is markedly lower than when transmitted through air because of the higher permittivity of the tissue (Pethig 1979). The depth of penetration, defined as the distance the propagating wave travels before the power density decreases by a factor of $e^{-2}$, corresponding to a power reduction of 86.5\%, (Johnson and Guy 1972; Pethig 1979), is determined by the permittivity of the tissues and the frequency of the applied field (Johnson and Guy 1972; Pethig 1979; Stuchly 1979). Table 4.2 shows that for a given tissue, penetration depth decreases with increasing frequency, and penetration depth is greater in tissues with low water contents than it is in those with high water contents at the same frequency.
Table 4.2

Penetration depth as a function of frequency (adapted from Johnson and Guy 1972). Tissues with high water contents include muscle and skin; tissues with low water contents include fat and bone.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Penetration Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High water content tissues</td>
</tr>
<tr>
<td>1</td>
<td>91.3</td>
</tr>
<tr>
<td>10</td>
<td>21.6</td>
</tr>
<tr>
<td>27.12</td>
<td>14.3</td>
</tr>
<tr>
<td>40.68</td>
<td>11.2</td>
</tr>
<tr>
<td>100</td>
<td>6.66</td>
</tr>
<tr>
<td>200</td>
<td>4.79</td>
</tr>
<tr>
<td>300</td>
<td>3.89</td>
</tr>
<tr>
<td>915</td>
<td>3.04</td>
</tr>
<tr>
<td>2450</td>
<td>1.70</td>
</tr>
<tr>
<td>3000</td>
<td>1.61</td>
</tr>
<tr>
<td>5000</td>
<td>0.788</td>
</tr>
<tr>
<td>10000</td>
<td>0.343</td>
</tr>
</tbody>
</table>
5. Reflection of Energy Incident at Tissue Interfaces

As a result of various interfaces between body tissues of different complex permittivities, there will be reflections of energy incident at such interfaces. When a wave in a tissue of low water content reaches a tissue of high water content of sufficient thickness (exceeding the depth of penetration), the reflected wave, which is almost $180^\circ$ out of phase with the incident wave, creates a standing wave with an intensity minimum at the interface. In contrast, a reflected wave produced by power being propagated initially through tissue of high water content and joining low water content tissue will be in phase with the incident wave, resulting in an intensity maximum near the interface. Where there are several layers of different types of tissues with thicknesses less than the penetration depths, the patterns of reflected energy and standing waves are governed by the layer thicknesses and the various wave impedances. The reflection coefficients for air-fat, air-muscle and fat-muscle interfaces in the MHz range have been tabulated by Johnson and Guy (1972).
CHAPTER 5

BIOELECTRIC IMPEDANCE ANALYSIS

A. INTRODUCTION

One approach which has been used to measure body composition related to differences in electrical properties of the body tissues, is to measure the impedance to the transmission of electric current through the body.

Electrical impedance, which is the total effective AC resistance of a component or circuit, is a combination of reactance (inductive and/or capacitive) and DC resistance. It is frequency-dependent and vectorially partitioned into reactive ($X$) and resistive ($R$) components such that

$$Z = \sqrt{R^2 + X^2}$$

where $Z$ is the impedance if $X$ and $R$ are series-connected (Nyboer 1970 and 1972).

In general, the capacitive reactive component ($X_C$) of impedance is related to the dielectric or nonconductor space within the field, while the resistive component ($R$) is related to the ionic conductor volume (Nyboer 1972).
The impedance of a geometrical system of constant configuration at a
constant signal frequency (Hoffer et al. 1969 and 1970) obeys the
relationship:

\[ Z = \rho L/A \]

where
- \( Z \) = impedance (ohm)
- \( \rho \) = resistivity (ohm.cm)
- \( L \) = conductor length (cm)
- \( A \) = cross-sectional area (cm^2).

Therefore, using a fixed signal frequency and a constant conductor
configuration, the impedance is governed by the length and cross-
sectional area of the conductor.

In biological tissues, \( R \) is better than \( X_c \) as a predictor of \( Z \)
(Iwakaski et al. 1985) and the resistance is related to the conductor
volume (Gessert et al. 1969) by the following relationship:

\[ R = \rho L/A \]

Substituting \( V \) (volume) for \( AL \), and rearranging gives:

\[ V = \rho L^2/R \]

This 'electrical volume' is by definition the same as the physical
space occupied by an electrical conductor (Nyboer 1970). Despite the
complex geometry of the human body, this relationship can be viewed as
the principle underlying the empirically derived relationships for
total body water estimates based on impedance measurements.
The main fraction of the current flowing through the body is conducted through the tissues with higher water and electrolyte content. Fat, which is amongst the poorest conductors in the body (Geddes and Baker 1967), has a much lower electrical conductivity than lean tissue, and this difference is much greater than differences in conductivities between the various lean tissues (Pethtig 1979; Schwan 1963). The electric current, therefore, spreads essentially through the fat-free body compartment, the volume of which corresponds to the conductor volume already mentioned.

In early work by Thomasset (1962) a two-electrode (bipolar) system was used where stainless steel needles were inserted subcutaneously. The major disadvantage of this, and other bipolar systems, is that the measured values are the combined effects of the sample plus the electrode polarization impedance (Ackmann and Seitz 1984; Gessert et al. 1969; Nyboer and Khalafalla 1970). If the impedance is measured with zero current, electrode polarization impedance is eliminated and this can be accomplished by using a four-electrode (tetrapolar) system (Ackmann and Seitz 1984; Gessert et al. 1969). The constant excitation current is applied to the subject by one electrode pair, while the potential is measured by a second electrode pair. If the input impedance of the circuit which measures the potential is very high, it prevents current flowing in the potential electrodes, thus eliminating electrode polarization. This means that the observed voltage is independent of changes which may occur in impedance at the potential electrode-skin boundaries. Today, the technique is commonly applied using a phase-sensitive impedance detector (Nyboer et al. 1943), but bridge methods (Perris 1974; Gessert et al. 1970; Horton 1936; Horton et al. 1935) can also be employed.
Recently a portable bioelectric impedance analyser (BIA), which measures the impedance to the spread of current through the tissues of the body, has become available. Initially this analyser was tested to determine its response under a variety of conditions.

B. CONDITIONS AFFECTING IMPEDANCE VALUES

1. Methods

The purpose of the studies in this section was to assess:

(a) the reproducibility of impedance measurements
(b) the effects of electrode placement
(c) the effects of intake of a light meal
(d) the effects of fluid intake
(e) the effects of the menstrual cycle in impedance measurements in females.

(a) Subjects

For this study subjects were volunteers from the University staff and student populations. The ages and anthropometric data of the 20 subjects (10 female and 10 male) are listed in Table 5.1. It was desirable to have a wide range of ages represented in each sex, however all the subjects were adults.

(b) Measurement technique

Height and weight were measured to the nearest 0.1 cm and 100 g respectively. Triceps, biceps, subscapular and supra-iliac skinfold
Table 5.1
Mean, standard deviation and range for age and anthropometric data of subjects in repeatability studies of bioelectric impedance measurements.

<table>
<thead>
<tr>
<th></th>
<th>Females (n=10)</th>
<th></th>
<th>Males (n=10)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± s.d.</td>
<td>Range</td>
<td>Mean ± s.d.</td>
<td>Range</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>28.9 ± 9.8</td>
<td>21 - 46</td>
<td>28.3 ± 9.6</td>
<td>20 - 48</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.638 ± 0.089</td>
<td>1.488 - 1.780</td>
<td>1.750 ± 0.065</td>
<td>1.602 - 1.850</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>57.8 ± 6.7</td>
<td>45.7 - 67.8</td>
<td>70.2 ± 9.1</td>
<td>57.7 - 85.0</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>27.0 ± 4.6</td>
<td>21.8 - 37.3</td>
<td>18.1 ± 3.1</td>
<td>13.7 - 22.7</td>
</tr>
</tbody>
</table>

* from sum of four skinfolds (Durnin and Womersley 1974).
measurements were made to the nearest 0.1 mm with Harpenden calipers on the right side of the subject according to the techniques described by Weiner and Lourie (1969), except that the supra-iliac skinfold was taken at an angle of 45° from the vertical. Body fat was predicted from the sum of four skinfold measurements as described by Dummin and Womersley (1974).

Impedance measurements were made by means of a tetrapolar impedance plethysmograph, or bioelectric impedance analyser (BIA) (RJL Systems Model 101, Detroit, U.S.A.). Subjects removed shoes and socks, but otherwise remained clothed, and rested supine on a bed. After the skin contact areas were cleaned with 1:1 (v/v) alcohol - acetone mixture, a thin layer of electrode cream (Medi-trace EKG sol; Graphic Controls Corp., Medical Products Div. Buffalo, New York) was applied to the exposed foil strip along the tape electrodes (CP Brand No. M6001; Contact Products Inc., Dallas, Texas) which were then applied to the dorsal surfaces of the hands and feet. The source electrodes were placed at the distal metacarpals and metatarsals, and the detector (potential) electrodes at the wrist and ankle, between the distal prominences of the radius and ulna and between the medial and lateral malleoli (Figure 5.1).

The distal electrodes were fed by a constant current (I) of 800 µA at 50 kHz, and the voltage drop (E) was measured over the proximal sites via two high-impedance electrodes.

The subjects could not detect the current which provided the electric field in the body. To avoid capacitive shunting (Nybøer and Khalafalla 1970), the subject’s hands were positioned away from the body, and legs were spread apart so that no body parts were in contact
Figure 5.1

Block diagram representing the tetrapolar bioelectric impedance analyser (BIA). Distal electrodes were fed by a constant current (I) of 800 μA at 50 kHz; voltage drop (E) was measured over the proximal sites via two high-impedance electrodes.
during the test. Plate 5.1 shows a recumbent subject with electrodes from the BIA in place.

By using phase-sensitive electronics the resistive (R) and capacitive reactive ($X_C$) components of impedance (Z) were quantitated and displayed by digital read-out.

(c) Protocol

Subjects came to the laboratory on the same day of the week for three or more consecutive weeks, at least 3 hr after consuming a light breakfast. Figure 5.2 outlines the experimental procedures over the three-week period.

At each visit before lunch, subjects were weighed after passing urine, and measurements of skinfold thicknesses, R and $X_C$ were made with electrodes placed on the right side of the body.

At the first visit, subjects reported again 1 hr after consuming a light lunch and measurements of R and $X_C$ were made with electrodes placed in the following four location combinations: $R_{H_F}$, $R_{H_L}$, $R_{H_L}$, and $R_{H_F}$, where $R_H = $ right hand, $R_F = $ right foot, $L_H = $ left hand and $L_F = $ left foot. These measurements were made to assess the effect of electrode placement on impedance values.

At the second visit, subjects reported again after a light lunch and two independent measurements of R and $X_C$ were taken with electrodes placed on the right side of the body, to test the reproducibility of impedance values. New electrodes were used for the second readings.
Plate 5.1

Measurement of bioelectric impedance. The recumbent subject has electrodes from a bioelectric impedance analyser (BIA) connected to the right side of the body.
Measurements
before lunch:
  height
  weight
  skinfolds
  R and $X_C^*$

Measurements
after lunch:
  weight
  R and $X_C^*$

Measurements
before liquid:
  weight
  skinfolds
  R and $X_C^*$

Measurements
after liquid:
  weight
  R and $X_C^*$

(repeated readings)
(before and after passing urine)

* electrodes placed on the right side of the body
# electrodes placed in different location combinations

Figure 5.2
Outline of experimental procedure for studies on the repeatability of bioelectric impedance measurements.
The following week the subjects reported again 1 hr after drinking 1 L liquid (water and/or fruit juice), and \( R \) and \( X_C \) were determined with electrodes placed on the right side of the body, to assess the effect of fluid intake. With electrodes still in place, subjects passed urine, and \( R \) and \( X_C \) were measured for the third time that day.

To assess the effect of the menstrual cycle, females reported to the laboratory on several other occasions; \( R \), \( X_C \) and weight were measured and the date of the last menstrual period recorded.

In analysing the data, two-tailed paired t-tests were used to determine if observed differences were significant.

2. Results

(a) Reproducibility of impedance measurements

The following two approaches were used to assess the reproducibility of impedance measurements:

(i) \( R \) and \( X_C \) measurements were made twice at week 2, with new electrodes used for the second reading which immediately followed the first.

(ii) three \( R \) and \( X_C \) readings were made in the same individuals at weekly intervals.

Table 5.2 lists the mean paired differences in repeated \( R \) and \( X_C \) measurements at week 2 for females and males. Repeating the measurement of resistance after replacement of electrodes produced a slight increase in \( R \) value in most subjects. This difference was not significant in males (\( P > 0.20 \)), but just statistically significant in
Table 5.2

Mean paired differences ± s.d. for repeated resistance (R) and reactance (X_C) measurements at week 2 in females and males. Electrodes were placed on the right side of the body.

<table>
<thead>
<tr>
<th></th>
<th>Females (n=10)</th>
<th>Males (n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (ohm)</td>
<td>2.5 ± 3.4</td>
<td>0.3 ± 3.1</td>
</tr>
<tr>
<td>X_C (ohm)</td>
<td>-0.2 ± 0.8</td>
<td>-0.2 ± 0.9</td>
</tr>
</tbody>
</table>
females ($P < 0.05$). A difference of 2 - 3 ohm in approximately 550 ohm does not have any practical significance and may have been due to replacing the electrodes which caused localized irritation and redening of the skin at contact areas. Irritation of the skin does not happen under normal circumstances.

Table 5.3 lists the $R$ values which were determined on three consecutive weeks with electrodes placed on the right side of the body. The coefficients of variation for $R$ values determined in individuals on three consecutive weeks ranged from 0.4 - 4.0% for females and 0.2 - 2.9% for males, and the mean coefficients of variation were 1.8% and 2.0% respectively. This is in close agreement with data reported by Lukaski et al. (1985) who found that the individual coefficients of variation for $R$ values measured in 37 men on five successive days ranged from 0.9 - 3.4%, the average coefficient of variation being 2%.

(b) Effects of electrode placement

Values of $R$ and $X_C$ were obtained for the subjects using the four different combinations of electrode placement shown in Figure 5.3. Electrode placement did affect the $R$ but not the $X_C$ values. For both sexes, $R$ values with electrodes placed on the right side of the body were significantly different from, and lower than, $R$ values observed with electrodes placed on the left side of the body ($P < 0.01$). To determine if changing the electrodes from one foot to the other altered $R$, hand electrodes were attached to the right side, and $R$ was measured with electrodes on the left foot and then with them placed on the right foot. Significant differences ($P < 0.02$) were observed for both sexes, the lower value corresponding to electrode placement on the right foot.
Table 5.3

Reproducibility of resistance (ohm) measurements in 10 females and 10 males on three consecutive weeks. Electrodes were placed on the right side of the body.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>mean ± s.d.</th>
<th>C.V.*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Females (n=10)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>606</td>
<td>569</td>
<td>599</td>
<td>591 ± 20</td>
<td>3.3</td>
</tr>
<tr>
<td>B</td>
<td>578</td>
<td>585</td>
<td>582</td>
<td>582 ± 4</td>
<td>0.6</td>
</tr>
<tr>
<td>C</td>
<td>539</td>
<td>539</td>
<td>543</td>
<td>540 ± 2</td>
<td>0.4</td>
</tr>
<tr>
<td>D</td>
<td>502</td>
<td>492</td>
<td>499</td>
<td>498 ± 5</td>
<td>1.0</td>
</tr>
<tr>
<td>E</td>
<td>533</td>
<td>510</td>
<td>525</td>
<td>523 ± 12</td>
<td>2.2</td>
</tr>
<tr>
<td>F</td>
<td>663</td>
<td>667</td>
<td>712</td>
<td>681 ± 27</td>
<td>4.0</td>
</tr>
<tr>
<td>G</td>
<td>568</td>
<td>572</td>
<td>576</td>
<td>572 ± 4</td>
<td>0.7</td>
</tr>
<tr>
<td>H</td>
<td>538</td>
<td>514</td>
<td>535</td>
<td>529 ± 13</td>
<td>2.5</td>
</tr>
<tr>
<td>I</td>
<td>530</td>
<td>547</td>
<td>551</td>
<td>543 ± 11</td>
<td>2.1</td>
</tr>
<tr>
<td>J</td>
<td>507</td>
<td>500</td>
<td>515</td>
<td>507 ± 8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

| mean   | 556| 550| 564| 1.8         |       |
| ± s.d. | 49 | 52 | 61 | 1.2         |       |

| **Males (n=10)** |    |    |    |             |       |
| A      | 430| 437| 438| 435 ± 4     | 1.0   |
| B      | 509| 492| 494| 498 ± 9     | 1.9   |
| C      | 411| 392| 411| 405 ± 11    | 2.7   |
| D      | 470| 470| 494| 478 ± 14    | 2.9   |
| E      | 479| 489| 467| 478 ± 11    | 2.3   |
| F      | 597| 587| 584| 589 ± 7     | 1.2   |
| G      | 576| 572| 549| 566 ± 15    | 2.6   |
| H      | 409| 407| 408| 408 ± 1     | 0.2   |
| I      | 494| 493| 474| 487 ± 11    | 2.3   |
| J      | 477| 495| 472| 481 ± 12    | 2.5   |

| mean   | 485| 483| 479| 2.0         |       |
| ± s.d. | 63 | 63 | 56 | 0.9         |       |

* C.V. = (s.d./mean) 100%
(a) RESISTANCE (ohm)

Females (n=10)

\[ 555 \pm 50 \]
\[ 562 \pm 46 \]
\[ 566 \pm 48 \]

Males (n=10)

\[ 483 \pm 60 \]
\[ 499 \pm 65 \]
\[ 488 \pm 57 \]

(b) REACTANCE (ohm)

Females (n=10)

\[ 61 \pm 5 \]
\[ 61 \pm 6 \]
\[ 61 \pm 56 \]
\[ 61 \pm 53 \]

Males (n=10)

\[ 62 \pm 9 \]
\[ 62 \pm 9 \]
\[ 62 \pm 9 \]
\[ 62 \pm 9 \]

\( R_F \) = right foot, \( R_H \) = right hand, \( L_F \) = left foot and \( L_H \) = left hand.

Figure 5.3
Mean values \( \pm \) s.d. of (a) resistance and (b) reactance in 10 female and 10 male subjects for the four combinations of electrode placement: \( R_H R_F, L_H R_F, L_H L_F \) and \( R_H L_F \).
A similar effect was observed in males when the positioning of electrodes on the right and left hands was tested. With foot electrodes attached to the right side, R was measured with electrodes on the left hand and then on the right hand. A significant difference ($P < 0.001$) was observed, the lower value corresponding to electrode placement on the right hand. In females there was no significant difference ($P > 0.05$) in R values when the hand electrodes were swapped from the left to the right sides.

To determine if changing the diagonal placement of electrodes affected R, electrodes were placed on the right hand and left foot ($R_{HF}$) and then on the left hand and right foot ($L_{HF}$). A significant difference ($P < 0.01$) was observed again for males, the lower R value obtained for $R_{HF}$ combination. No significant difference ($P > 0.2$) was observed in females.

Results from the male subjects support those reported by Lukaski et al. (1985) who measured R and $X_C$ in 37 men, using the same four combinations of electrode placement. They found that electrode placement using the right arm had significantly lower ($P < 0.05$) R values than did placements using the left arm and they suggested that these differences reflected differences in muscle mass in the transmission pathways.

(C) The effects of intake of a light meal.

Table 5.4 lists the mean paired differences in R and $X_C$ readings for females and males, before and after a light lunch measured at weeks 1 and 2. The consumption of a light meal did not influence the observed
Table 5.4

Mean paired differences ± s.d. for resistance (R) and reactance ($X_C$) values measured on weeks 1 and 2, before and after a light lunch. Electrodes were placed on the right side of the body.

<table>
<thead>
<tr>
<th></th>
<th>Females (n=10)</th>
<th>Males (n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>week 1</td>
<td>week 2</td>
</tr>
<tr>
<td>$R$ (ohm)</td>
<td>-1.8 ± 10.8</td>
<td>-3.8 ± 10.3</td>
</tr>
<tr>
<td>$X_C$ (ohm)</td>
<td>0.1 ± 1.7</td>
<td>-0.2 ± 2.7</td>
</tr>
</tbody>
</table>
R and \( X_c \) values significantly (\( P > 0.2 \)) in both sexes, but the trend was for R to decrease after a light meal.

(d) The effects of fluid intake followed by passing urine

In Table 5.5 are listed the mean paired differences in R and \( X_c \) values taken before and after the consumption of 1 L fluid. There was no significant difference in measured R or \( X_c \) (\( P > 0.05 \)) values after fluid intake in both sexes.

Results presented in Tables 5.4 and 5.5 indicate that subjects need not be restricted in terms of consuming a light meal or having a drink before impedance measurements are made.

As an extension to this test, the R and \( X_c \) values were also measured after the subjects passed urine, following the fluid loading during the previous hour. Table 5.6 lists the mean paired differences for R and \( X_c \) before and after passing urine. Results from both sexes showed a trend in an increase in R value after urine was passed. This increase was not significant in females (\( P > 0.20 \)), but it was significant (\( P < 0.01 \)) in males. Once again \( X_c \) values were not affected significantly (\( P > 0.20 \)).

The effects of passing urine were tested after the subjects were loaded with 1 L fluid during a 1 hr period. As they had emptied their bladders before receiving the fluid loading, urine accumulation in the bladder had occurred for only 1 hr. On passing urine, the mean weight loss for the group was 0.2 kg, indicating only small urine losses. Under general testing conditions it is possible that larger volumes of urine would accumulate in the bladder, as several hours may have
Table 5.5
Mean paired differences ± s.d. for resistance (R) and reactance ($X_C$) values measured before and after the intake of 1 L fluid, during a 1 hr period. Electrodes were placed on the right side of the body.

<table>
<thead>
<tr>
<th></th>
<th>Females (n=10)</th>
<th>Males (n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (ohm)</td>
<td>-0.6 ± 8.5</td>
<td>3.3 ± 11.8</td>
</tr>
<tr>
<td>$X_C$ (ohm)</td>
<td>-1.7 ± 5.7</td>
<td>0.2 ± 1.6</td>
</tr>
</tbody>
</table>
Table 5.6
Mean paired differences ± s.d. for resistance (R) and reactance ($X_C$) values measured before and after passing urine, following a 1 L fluid load during the preceding hour. Electrodes were placed on the right side of the body.

<table>
<thead>
<tr>
<th></th>
<th>Females (n=10)</th>
<th>Males (n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ (ohm)</td>
<td>0.8 ± 4.9</td>
<td>2.6 ± 2.6</td>
</tr>
<tr>
<td>$X_C$ (ohm)</td>
<td>0.3 ± 1.5</td>
<td>0.3 ± 2.2</td>
</tr>
</tbody>
</table>
elapsed since urine was passed. It is therefore recommended that subjects empty their bladders before impedance measurements are taken.

(e) Effects of the menstrual cycle on impedance measurements in females

Of the 10 female subjects studied, one had previously undergone hysterectomy, two were measured over one menstrual cycle, and seven over two consecutive cycles.

Regular patterns in changes in body weight and R values did not emerge when measurements from the nine subjects were compared, and often a trend shown in one menstrual cycle was not repeated in the next. Week-to-week fluctuations in body weight were generally less than 1 kg and none of the subjects suffered from obvious premenstrual oedema.

There is great interindividual variability with regard to fluctuation in daily body weights for females. While there are reports of weight peaks often occurring at or before the onset of menstruation (Sweeney 1934; Thomas 1953; Thorm et al. 1938), others report no such changes (Taggart 1962) or conclude that menstrual weight peaks could be explained by chance alone (Chesley and Hellman 1957). The major cause of short-term changes in body weight is considered to be fluctuation in water balance (Taggart 1962) which is in a constant state of flux, and attributed to true differences in body hydration and fluctuations of water in the gut lumen, including water associated with residues from recent food intake.

Of the subjects tested, there was an increase in body weight, reflected by a decrease in R value (indicating a rise in total body
water) in five subjects at or before the onset of menstruation, but in only one subject was this pattern repeated during another cycle. Results from one other subject indicated a loss of body weight and an increase in R value during menstruation.

This picture, however, was confused by opposing trends in other subjects, leading to the conclusion that in this group, no regular changes in body weight or impedance values could be attributed to menstruation. This does not mean that such cyclical variations were completely non-existent, however, if they were present they were masked by other factors. It may be necessary to study a larger population of women over a longer period of time before conclusive findings emerge.

C. VALIDATION OF IMPEDANCE MEASUREMENTS

1. Methods

In this section of the work the reliability of the BIA was assessed. Impedance measurements on a group of normal individuals were compared with body composition estimates based on anthropometry, body density and total body water measurements.

(a) Subjects

Table 5.7 lists the ages and physical characteristics of the 27 healthy female volunteers who were mainly University staff and students, and members of the local community.
Table 5.7
Mean, standard deviation and range for age and physical characteristics of the 27 female subjects in reliability studies of bioelectric impedance measurements.

<table>
<thead>
<tr>
<th></th>
<th>Mean ± s.d.</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>29.4 ± 12.2</td>
<td>18 - 56</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.631 ± 0.047</td>
<td>1.544 - 1.706</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>63.3 ± 12.16</td>
<td>43.8 - 97.7</td>
</tr>
<tr>
<td>W/H² (kg/m²)</td>
<td>23.7 ± 4.17</td>
<td>16.9 - 33.9</td>
</tr>
<tr>
<td>Body fat (%) derived from:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>densitometry</td>
<td>32.3 ± 8.00</td>
<td>19.7 - 47.7</td>
</tr>
<tr>
<td>D₂O dilution</td>
<td>30.2 ± 7.04</td>
<td>19.9 - 45.1</td>
</tr>
<tr>
<td>sum four skinfolds *</td>
<td>30.9 ± 6.33</td>
<td>21.1 - 44.3</td>
</tr>
<tr>
<td>W/H² **</td>
<td>28.8 ± 6.25</td>
<td>20.9 - 42.2</td>
</tr>
<tr>
<td>Fat-free weight (kg) from densitometry</td>
<td>42.1 ± 4.98</td>
<td>29.7 - 51.1</td>
</tr>
<tr>
<td>Total body water (L)</td>
<td>31.8 ± 3.57</td>
<td>24.2 - 39.3</td>
</tr>
</tbody>
</table>

* Durnin and Womersley (1974)

** Womersley and Durnin (1977)
(b) Protocol

On the morning of the test, subjects were allowed a light breakfast at least 2 hr before participating in the study. After passing urine, subjects received an accurately weighed, pre-determined dose of D₂O which was washed down with distilled water. During the D₂O equilibration period the subjects were measured in a variety of ways. Height, weight, skinfold thicknesses and bioelectric impedance were measured as described in section B. Electrodes from the BIA were attached to the right side of the body. Subjects were also tested in an electrical resonating chamber and these results are presented and discussed in chapter 8. Body density was determined five times, with lung volumes estimated by the hydrogen dilution method discussed in detail in chapter 2. Saliva samples were collected 2 hr after D₂O administration and stored frozen for later analysis. The method for calculating total body water volume from D₂O dilution is described in chapter 3.

Appendix A contains a copy of the information sheet given to the volunteers several days before the testing period.

2. RESULTS

A correlation matrix relating impedance readings to various measures of body composition is shown in Table 5.8. The following abbreviations have been used: W = weight, H = height, FFW(D) and FW(D) = fat-free weight and fat weight respectively, based on densitometry, FFW(Skf) and FW(Skf) = fat-free weight and fat weight respectively, derived from the sum of four skinfolds (Durnin and Womersley 1974), FFW(W/H²) and FW(W/H²) = fat-free weight and fat weight respectively,
Table 5.8
Correlation matrix of variables related to measurements of bioelectric impedance and estimates of body composition for 27 female subjects.

<table>
<thead>
<tr>
<th></th>
<th>FTW(D)</th>
<th>FW(D)</th>
<th>Density</th>
<th>TBW</th>
<th>FTW(Skf)</th>
<th>FW(Skf)</th>
<th>FW(W/H²)</th>
<th>FW(W/H²)</th>
<th>R</th>
<th>Xc</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW(D)</td>
<td>0.433</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>-0.093</td>
<td>-0.921#</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TBW</td>
<td>0.945*</td>
<td></td>
<td>0.602*</td>
<td>0.305</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FTW(Skf)</td>
<td>0.877#</td>
<td>0.691#</td>
<td>-0.401</td>
<td>0.914#</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FW(Skf)</td>
<td>0.484</td>
<td>0.965#</td>
<td>-0.877#</td>
<td>0.632*</td>
<td>0.617*</td>
<td>0.950#</td>
<td>0.708#</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FTW(W/H²)</td>
<td>0.866#</td>
<td>0.730#</td>
<td>-0.488</td>
<td>0.913#</td>
<td>0.940#</td>
<td>0.740#</td>
<td>0.971#</td>
<td>0.745#</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FW(W/H²)</td>
<td>0.562</td>
<td>0.968#</td>
<td>-0.823#</td>
<td>0.696#</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>-0.635*</td>
<td>-0.285</td>
<td>0.048</td>
<td>-0.666*</td>
<td>-0.484</td>
<td>-0.378</td>
<td>-0.414</td>
<td>-0.455</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xc</td>
<td>-0.265</td>
<td>-0.332</td>
<td>0.203</td>
<td>-0.340</td>
<td>-0.257</td>
<td>-0.377</td>
<td>-0.136</td>
<td>-0.462</td>
<td>0.734#</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>-0.632*</td>
<td>-0.287</td>
<td>0.051</td>
<td>-0.666*</td>
<td>-0.483</td>
<td>-0.380</td>
<td>-0.412</td>
<td>-0.458</td>
<td>0.999#</td>
<td>0.741#</td>
<td></td>
</tr>
<tr>
<td>H²/R</td>
<td>0.821#</td>
<td>0.334</td>
<td>-0.025</td>
<td>0.839#</td>
<td>0.695*</td>
<td>0.390</td>
<td>0.612*</td>
<td>0.479</td>
<td>-0.881#</td>
<td>-0.585</td>
<td>-0.880#</td>
</tr>
</tbody>
</table>

* P < 0.001, # P < 0.0001

W = weight (kg); H = height (m); FTW(D) and FW(D) = fat-free weight (kg) and fat weight (kg) respectively, based on densitometry; Density (kg/dm³) is based on densitometry; TBW = total body water (L) estimated from D₂O dilution; FTW(Skf) and FW(Skf) = fat-free weight (kg) and fat weight (kg) respectively, derived from sum four skinfolds (Durnin and Womersley 1974); FTW(W/H²) and FW(W/H²) = fat-free weight (kg) and fat weight (kg) respectively, derived from W/H² (kg/m²) (Womersley and Durnin 1977); R = resistance (ohm); Xc = reactance (ohm); Z = impedance (ohm) where Z = √R² + Xc².
derived from $W/H^2$ (Womersley and Durnin 1977), and TBW = total body water.

The significant ($P < 0.001$) inverse relationships found between $R$ and FFW, and $R$ and TBW, also existed between $Z$ and these variables. The correlation coefficients were the same whether $R$ or $Z$ values were used in the calculations. Considerably lower correlation coefficients were obtained where $X_C$ was related to FFW(D) or TBW. The correlation between $R$ and $Z$ values ($r = 0.999$) was significantly greater ($P < 0.001$) than that relating $X_C$ with $Z$ values ($r = 0.741$), indicating that $R$ (the resistive component) is the better predictor of $Z$. These data support those of Lukaski et al. (1985) who subsequently used $R$ values as measures of bioelectric impedance.

Whether $R$ was related to FFW, TBW, FFW(Skf) or FFW($W/H^2$), there was a marked increase in correlation coefficient when these measures were related to $H^2/R$. Hoffer et al. (1969) demonstrated that the impedance value was related to the conducting volume of the human body and the square of the conductor's length, by observing that TBW and TBM were strongly correlated ($r > 0.9$) with $H^2/Z$. More recent reports (Lukaski et al. 1985; Segal et al. 1985), as well as the data presented in Table 5.8, support this finding.

Although there was little difference between correlation coefficients for the relationships between $H^2/R$ and TBW, and $H^2/R$ and FFW(D), the strongest correlation ($r = 0.839$) was observed for $H^2/R$ with TBW, which is the most direct measure of the conducting body compartment. Significant correlations ($P < 0.001$) were also observed between $H^2/R$ and FFW(Skf), and between $H^2/R$ and FFW($W/H^2$), but as these values were derived indirectly from anthropometric measurements, i.e. skinfold
thicknesses, and body mass index \((W/H^2)\), it is not surprising that the correlations were not as strong \((r = 0.695\) and \(0.642\) for FFW(SkI) and FFW\((W/H^2)\), respectively).

The data indicated poor relationships \((r < 0.5)\) between \(R\), or \(R\) corrected for height, and values of body density or body fat calculated from density, skinfold thicknesses or body mass index \((W/H^2)\).

Graphical relationships of \(H^2/R\) with fat-free weight from densitometry, and total body water from \(D_2O\) dilution are illustrated in Figures 5.4 and 5.5, respectively.

D. DISCUSSION

The bioelectric impedance analyser is portable, safe and noninvasive, and imposes minimal inconvenience on the subject. It provides readings which are reproducible and quickly obtained. For these reasons the technique appears suitable for routine use in both clinical and field work.

While gathering the data, it was evident that although measurements were made repeatedly, the technique remained acceptable to the subjects, indicating that the equipment was suitable for routine monitoring.

Results from section B show the importance of correct electrode placement, and reveal that subjects can enjoy a light meal and a drink before being tested without adversely affecting impedance readings.
Figure 5.4
Linear regression of fat-free weight (FFW) from densitometry on height²/resistance (H²/R).

\[ y = 6.15 + 0.75x \]

\[ r = 0.821; \quad P < 0.0001 \]

S.E.E. = 0.105
Figure 5.5

Linear regression of total body water (TBW) on height$^2$/resistance ($H^2/R$).
It is suggested, however, that subjects empty their bladders before measurements are made.

Results from section C confirm the validity of bioelectric impedance measurements for predicting total body water and fat-free weight. Strong correlations were found between height^2/resistance and measurements of total body water (r = 0.839) and fat-free weight derived from densitometry (r = 0.821). Moderate correlations (r = 0.6 to 0.7) were also found when height^2/resistance was related to fat-free weight derived from anthropometric measurements.

The coefficient of variation of the impedance measurements taken over a period three weeks was 2%. As this variation comprised biological variation as well as measurement error, it indicates that the BIA gives readings of acceptable reproducibility.

In evaluating the accuracy of impedance measurements, it must be recognized that the estimates of both total body water and fat-free weight are indirect. It is assumed that the D_2O dilution volume is representative of the total body water pool and that the density of the fat-free body compartment is constant.

The bioelectric impedance method for measuring water volume or fat-free weight of the body should be viewed in the light of other available methods. Laboratory methods require a high level of subject co-operation and operator skill, involve the use of expensive equipment and do not produce smaller errors in body composition estimates. The most common field techniques involve anthropometric measurements which rely on prediction equations and/or assumptions about the constancy of body types.
In addition to using bioelectric impedance measurements for body composition determinations in nutritional surveys, epidemiological studies, or health, fitness and weight reduction programmes, impedance measurements could constitute an important bed-side method for monitoring small fluid volume changes during procedures such as haemodialysis and peritoneal dialysis, and in the treatment of heart failure or severe burns. Current methods for obtaining fluid balance estimates usually rely on physical examination in conjunction with data on body weight, blood pressure and electrolyte concentrations, the monitoring of fluid intake and output, or the use of bed scales for detecting small weight changes.

Problems which have not yet been addressed include the effects caused by perspiration and body temperature changes (Solomons 1986) and whether the method is valid in abnormal subjects, such as wasted cancer patients and renal patients who are dehydrated and possess an altered osmolality (Cohn 1985 and 1986; Nash 1985).

There is still a need for additional research to determine the relationship between bioelectric impedance measurements and direct chemical analyses of fat-free body components in animals so that the effects of altering the composition of the fat-free body compartment are known.
A. INTRODUCTION

Webster et al. (1984) reported a high correlation ($r = 0.955$) between body weight and body fat, both corrected for stature ($\text{kg/m}^2$), based on the mean estimate of body fat derived from measurements of body density, total body water and total body potassium in a group of women whose fat content ranged from 6 to 60% of body weight. However, use of body weight, or body weight corrected for stature, as a measure of body fatness has been criticized on the basis that it takes no account of differences in body composition between individuals (Brozek and Keys 1951; Clark et al. 1977; Edmonds et al. 1975; Lesser et al. 1971; Morgan and Ferro-Luzzi 1982; Pollack et al. 1980; Seltzer and Mayer 1965; Welham and Behnke 1942; Wright and Wilmore 1974). Other, apparently more specific, anthropometric measurements of body fat, such as single or multiple skinfold measurements, are therefore frequently used in community studies to assess body fat (Behnke and Wilmore 1974; Durnin and Womersley 1974; Forsyth and Sinning 1973; Jackson and Pollock 1978; Jackson et al. 1980; Katch and McArdle 1973; Lohman 1981; Parizkova 1961; Pollock et al. 1976; Pollock et al. 1975; Sinning 1978; Sloan 1967; Sloan et al. 1962; Wilmore and Behnke 1970).

Differences in body composition might be expected to occur, particularly between elite athletes and the general population, if an increased proportion of fat-free weight in the former is a consequence
of their high level of physical activity and performance. In this study, comparisons have been made of the relationship between estimates of body fat (kg/m²) based on body mass index, or weight/height² (kg/m²), (Webster et al. 1984) and estimates based on one or more skinfolds (Durnin and Womersley 1974) in a group of females representing the general population (non-athletes) and in a group of Australian Olympic athletes. If important differences in body composition existed between the two groups, it would be expected that the relationship between the two estimates of body fat would differ significantly.

Estimates of body fat (kg/m²) predicted from body mass index (Webster et al. 1984), skinfold thickness (Durnin and Womersley 1974) and bioelectric impedance have also been compared for the group of non-athletes.

B. METHODS

The 50 female volunteers studied were mainly University staff and students, and members of a local slimming group. This group is referred to as non-athletes. The athlete group consisted of the 62 female members of the 1984 Australian Olympic Team for whom complete anthropometric data were available from the Australian Olympic Federation. This group included competitors in a wide variety of sports including track and field, basketball, hockey, swimming and gymnastics. Table 6.1 lists the ages and anthropometric data for the two groups of women.
Table 6.1
Mean, standard deviation and range for age and anthropometric data of the female non-athletes and athletes studied.

<table>
<thead>
<tr>
<th></th>
<th>Non-athletes</th>
<th>Athletes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n = 50)</td>
<td>(n = 62)</td>
</tr>
<tr>
<td>Mean ± s.d.</td>
<td>Range</td>
<td>Mean ± s.d.</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>27.5 ± 10.7</td>
<td>19-66</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.639 ± 0.074</td>
<td>1.488-1.797</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>59.7 ± 9.14</td>
<td>44.5-81.4</td>
</tr>
<tr>
<td>W/H² (kg/m²)</td>
<td>22.2 ± 3.18</td>
<td>16.7-31.0</td>
</tr>
</tbody>
</table>

Body fat (%) derived from:

- body mass index* 22.4 ± 7.20 5.6-39.1 22.7 ± 7.18 4.3-47.0
- triceps skinfold# 29.9 ± 6.01 16.4-45.1 23.9 ± 5.75 13.7-40.8
- sum 4 skinfolds# 28.5 ± 5.53 14.9-41.4 23.0 ± 5.67 12.3-41.9
- bioelectric impedance 26.4 ± 5.41 14.0-39.4

* Webster et al. (1984)
# Durnin and Womersley (1974)
Height, weight and four skinfold thicknesses (at the triceps, biceps, subscapular and supra-iliac sites) were measured according to the techniques described in chapter 5, section B.

The resistive component (R) of bioelectric impedance between the right wrist and ankle was measured to the nearest ohm with the bioelectric impedance analyzer (BIA) described in chapter 5. Body fat was taken as the mean of the estimates from the following prediction equations:

\[
\begin{align*}
(1) \quad \text{body density} &= 1.1262 - 0.0680 (W \times R/H^2) \\
(2) \quad \text{total body water} &= 0.3859 H^2/R + 0.1458 W + 4.7951
\end{align*}
\]

where \( W \) = body weight (kg)
\( H \) = height (cm)
\( R \) = resistance (ohm).

Those equations were derived by regression analysis of total body impedance and body density data from over 500 males and females (RJL Systems, personal communication) in studies such as that described by Nyboer (1981). The weight of body fat was estimated from body density in equation (1) with the Siri equation, and from total body water in equation (2) by assuming that the fat-free weight of the body contains 73.2% water (Pace and Rathbun 1945).

C. RESULTS

Figure 6.1 shows the regression lines and equations for estimates of body fat (kg/m\(^2\)) based on body mass index (Webster et al. 1984) with estimates based on the triceps skinfold for athletes and non-athletes.
Figure 6.1
Regression lines and equations for body fat (kg/m²) estimated from body mass index and the triceps skinfolds for athletes and non-athletes. The 95% confidence intervals of the mean are shaded for the athletes.
Figure 6.2 shows similar data for body fat predicted from the sum of four skinfolds.

There was no significant difference (P > 0.05) between the slopes of the regression lines for the two groups of women when fat was estimated either from a single or from four skinfolds, nor did the slopes differ significantly from 1.0. However, the intercepts for the regression lines differed significantly between the athletes and non-athletes both for estimates based on a single skinfold (P < 0.05) and on four skinfolds (P < 0.01).

Over the range of body mass index observed in this study, estimates of body fat from body mass index and from skinfolds differed by less than 0.5 kg/m² in the athletes. In contrast, in the non-athletes the estimates from skinfolds were consistently at least 1 kg/m² greater than from body mass index.

Table 6.2 compares mean estimates of body fat (kg/m²) based on body mass index, triceps skinfold, the sum of four skinfolds and bioelectric impedance at body mass index values of 20, 25 and 30 in the group of non-athletes. Over this range, estimates based on the triceps skinfold gave the highest value and those based on body mass index the lowest. Estimates of body fat from skinfold measurements were all highly significantly different and higher than those based on body mass index (P < 0.002). Although estimates of fat from impedance measurements differed significantly from those based on body mass index at body mass index values of 20 (P < 0.001) and 25 (P < 0.05), there was no significant difference (P > 0.05) between these estimates at a body mass index of 30.
Figure 6.2

Regression lines and equations for body fat (kg/m²) estimated from body mass index and the sum of four skinfold thicknesses for athletes and non-athletes. The 95% confidence intervals of the mean are shaded for the athletes.
Table 6.2

Mean and 95% confidence interval for estimates of body fat corrected for stature (kg/m²) from anthropometric and bioelectric impedance measurements for body mass index values 20, 25 and 30 in the non-athletes.

<table>
<thead>
<tr>
<th>Body mass index (kg/m²)</th>
<th>Body fat (kg/m²) estimated from:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Body mass index</td>
</tr>
<tr>
<td></td>
<td>Triceps skinfold</td>
</tr>
<tr>
<td></td>
<td>Sum of 4 skinfolds</td>
</tr>
<tr>
<td></td>
<td>Bioelectric impedance</td>
</tr>
<tr>
<td>20</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>5.1 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>4.9 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>4.4 ± 0.3</td>
</tr>
<tr>
<td>25</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>9.0 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>8.5 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>7.9 ± 0.3</td>
</tr>
<tr>
<td>30</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>12.9 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>12.1 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>11.4 ± 0.6</td>
</tr>
</tbody>
</table>
D. DISCUSSION

The consistent significant difference of approximately 1 kg fat/m$^2$ observed between the estimates of body fat from skinfold measurements in athletes and non-athletes, with the same body mass index, indicates a difference in body composition in terms of the proportion of subcutaneous body fat between the two groups. This illustrates the problem of applying prediction equations for body fat based on body size or subcutaneous fat to groups of people other than those from whom they were derived. Prediction equations based on body size (weight, height and circumferences) do not allow for differences in the ratio of fat to fat-free tissue between individuals, while those based on subcutaneous fat do not allow for differences between individuals in the proportion of subcutaneous to internal body fat.

Comparison of the four different estimates of body fat obtained for the group of non-athletes shows that in this group, estimates based on subcutaneous fat alone (skinfold measurements) are higher than those based on body mass index, while those based on impedance measurements are intermediate, but closer to the estimates based on body mass index. In the absence of laboratory estimates of total body fat in this study, it is not possible to say which of these estimates is the most accurate. However, since impedance measurements provide the possibility of distinguishing between differences in the proportion of fat to fat-free tissue in individuals of the same body size, this field method of estimating body fat should provide more accurate estimates in individuals with a body-fat distribution, or proportion of fat to fat-free tissue, which differs from the average.
CHAPTER 7

DEVELOPMENT OF A TEST CAPACITOR SUITABLE FOR DETERMINING BODY COMPOSITION

A. INTRODUCTION

This chapter describes the development of a test capacitor, large enough to accommodate a human subject and suitable for use in determining the amounts of fat and fat-free tissue in the body. The method is based on the different electrical properties of fat and fat-free tissues. A weak electromagnetic field is established in the test capacitor and measurement of the change in field characteristics upon introduction of a subject into the capacitor can be related to the proportions of fat and fat-free tissues in the body.

The different stages of development involved the testing of three models which differed in plate design and spatial arrangement. In each model the capacitor was connected in series with an inductor, the circuit was tuned and the effect caused by the presence of a subject or phantom on the electromagnetic field involved measurement of resonant frequency and quality factor of the system.

1. Electrical Theory

(a) Resonance in a series-connected inductance-capacitance (LC) circuit
An inductance offers little resistance to low frequencies but opposes higher frequencies. This apparent resistance is called inductive reactance and is represented by:

\[ X_L = 2\pi fL \]

where \( X_L \) = inductive reactance (ohm)
\( L \) = inductance (H)
\( f \) = frequency (Hz).

The apparent resistance of a capacitor in an AC circuit decreases as the applied frequency increases. This apparent AC resistance is called capacitive reactance and is represented by:

\[ X_C = \frac{1}{2\pi fC} \]

where \( X_C \) = capacitive reactance (ohm)
\( f \) = frequency (Hz)
\( C \) = capacitance (F).

In practice, inductors and capacitors have DC resistance as well as inductive or capacitive reactance. With an increase in frequency of an applied field, there is an increase in inductive reactance and a decrease in capacitive reactance. Therefore, for every combination of inductor and capacitor, there is a specific frequency, called resonant frequency, at which the inductive and capacitive reactances are equal.

In a series-connected LC circuit the inductive and capacitive reactances are \( 180^\circ \) out of phase, so the total effective reactance, \( X_T \), is:
\[ X_T = X_L - X_C \]

where \( X_T \) = total effective reactance  
\( X_L \) = inductive reactance  
\( X_C \) = capacitive reactance.

As \( Z \) is the circuit impedance,

then \[ Z = \sqrt{R^2 + X_T^2} \]

and so \[ Z = \sqrt{R^2 + (X_L - X_C)^2}. \]

If \( X_L = X_C \)

then \[ Z = R. \]

Therefore, in a series-connected LC circuit, the impedance is at a minimum at resonant frequency and is determined solely by the DC resistance.

(b) Quality factor

The quality factor of a circuit is proportional to the ratio of energy stored to energy lost per cycle (Marconi Instruments 1960). Quality factor, \( Q \), is numerically equal to the ratio of reactance to resistance at the operating frequency, and is expressed as:

\[ Q = \frac{X}{R} = \frac{2\pi f L}{R} = \frac{1}{2\pi f C R} \]
where \( X \) = reactance (ohm)  
\( R \) = resistance (ohm)  
\( f \) = frequency (Hz)  
\( L \) = inductance (H)  
\( C \) = capacitance (F).

\( Q \) is measured with a Q-motor.

B. DEVELOPMENT OF CAPACITOR DESIGN

The three models of test capacitor developed for body composition measurement were:

Model 1: Parallel-plate capacitor  
Model 2: Vertical rod or end-panel and parallel plates  
Model 3: Horizontal rod or end-panel and cylinder.

The basic circuitry for these models is shown in Figure 7.1 where \( R \) is the total internal resistance, \( L \) the inductor coil, \( C_1 \) the variable or adjustable capacitor and \( C_2 \) the test capacitor, which is large enough to accommodate the subject.

The capacitors were driven by a 40 kHz - 50 MHz generator (model TF 1246, Marconi Instruments Ltd., Hartfordshire, England) connected to a circuit magnification meter (Q-motor) (model TF1245, Marconi Instruments Ltd., Hartfordshire, England). Frequency was detected with a 5 Hz - 30 MHz electronic counter (model SM-4100, Heath-Schlumberger, U.S.A.). A variety of coils with inductance (L) ranging
$R = \text{total internal resistance}$

$L = \text{inductor coil}$

$C_1 = \text{variable capacitor}$

$C_2 = \text{test capacitor}$

**Figure 7.1**

Basic circuitry of electrical equipment for measuring body composition, in a system in which the subject occupies the space between the plates of a test capacitor.
from 0.2 nH to 25 mH was available and the range of the variable capacitor \( C_1 \) was 20 to 500 pF.

1. **Model 1: Parallel-Plate Capacitor**

A large parallel-plate capacitor was constructed so that a subject could stand freely on a wooden platform between the plates without touching them. Plate 7.1 shows a view of model 1. The plates were made of sheet aluminium which was secured to an external pine frame (Pinus radiata) by means of 1 cm screws so that the aluminium plates were supported and did not bow when placed in the vertical position.

The plates measured 120 x 240 cm, and the earthed plate consisted of a central panel, 60 x 180 cm, surrounded by a 30 cm wide guard ring (Faraday ring) with a gap of 1 mm between the central panel and the outer ring. The guard ring and the central panel were maintained at the same potential with connecting strips of conductive tape (Scotch 3M Electrical Tape, St. Paul, U.S.A.). The purpose of the guard ring was to remove end-effects so the field between the plates, where the subject stood, was uniform (Zahn 1979).

The instruments were connected to the plates by a pair of aluminium terminal plates which were tapered so there was a gradual change in characteristic impedance which led to better matching than would be achieved by having wires directly connected to the plates of the capacitor.

The plates of the test capacitor could be set at various distances apart; plate separation \( d \) being fixed by pine spacer beams. To
Plate 7.1

The parallel-plate test capacitor, model 1.
occupy the capacitor, the subject stood on a pine platform facing one of the parallel plates. The field between the plates was uniform, but a field also existed in the region outside the plates.

2. Model 2: Vertical Rod or End-Panel and Parallel Plates

This model was a modification of model 1. The parallel plates had the same dimensions, but they were electrically connected by a copper bar mounted overhead. A conductor, which was either a hollow copper rod or an elongated aluminium panel, was supported vertically on a pine stand in front of the parallel plates and could be placed between the plates or moved outwards beyond the end of the plates. The rod measured 200 cm in length and the external diameter was 7 mm. A variety of end-panels was made, with heights of 170, 205 and 240 cm, and widths of 5, 15, 22 and 30 cm. Plate 7.2 shows the equipment with one of the end-panels in place.

The parallel plates were connected to the earth terminal and the rod or end-panel to the active terminal of the generator. To occupy the test capacitor, the subject stood on a pine platform between the parallel plates, facing, and as close as possible to the vertical rod or end-panel. The field radiated out from the rod or end-panel towards the parallel plates and was most concentrated near the rod or end-panel.
Plate 7.2

Photograph of model 2: An end-panel is mounted on a vertical pine stand in front of the parallel plates.
3. Model: Horizontal Rod or Panel and Cylinder

Model 3 consisted of a large, open-ended aluminium cylinder with a rod or panel, as before, running longitudinally through the centre. The cylinder, which had a length of 220 cm and a diameter of 70 cm, was large enough to accommodate an adult subject in a supine position.

The cylinder consisted of two halves as shown in Plate 7.3, and was hinged along one side to allow easy access when the top half was opened. The two halves were electrically connected through four brass hinges on one side and aluminium strips at four sites which were clamped together on the other side when the top half was closed onto the bottom half. The closed cylinder is shown in Plate 7.4.

The cylinder and rod or panel were held on a pine platform which ran the length of the cylinder and 30 cm beyond, providing support for the cylinder. When the cylinder was opened, the subject lay on the wooden platform and was centred above the rod or panel. The top half was then closed leaving the subject to lie motionless and in comfort inside the cylinder, without making electrical contact with the cylinder or central rod or panel.

An electromagnetic field was maintained between the plates by the generator described for models 1 and 2. Short leads connected the cylinder to the earth terminal and the rod or panel to the active terminal of the generator. The leads were as short as possible in order to minimize the capacitance between them, and were held in a fixed position to keep that interaction constant.
Plate 1.3

View of model 3: The large cylinder of the test capacitor is open, showing the pine platform, which supports a central conducting rod extending the length of the cylinder.
Plate 7.4

The closed cylinder of the test capacitor of model 3.
Inside the cylinder, the electric field radiated from the rod or panel to the cylinder walls and, with the exception of end-effects at the open ends, the field was contained within the cylinder.

C. MEASUREMENT OF ΔQ CAUSED BY THE INTRODUCTION OF A TEST SUBJECT INTO THE TEST CAPACITORS

1. Methods

For any particular combination of coil inductance (L) and variable capacitance (C₁), the circuit containing the test capacitor (C₂) empty was tuned by altering the signal frequency until a peak value was reached on the Q-meter; this was the resonant frequency for the circuit. At this frequency, impedance in the circuit was at a minimum and Q at a maximum. For models 1, 2 and 3, operating frequencies ranged from 0.1 to 5 MHz. Resonant frequency and Q were recorded for the empty capacitor. When a subject was introduced into the test capacitor, the circuit was de-tuned, causing a shift away from resonance and a corresponding reduction in the value registered on the Q-meter. This change in Q is designated ΔQ.

With each model, tests were carried out to determine conditions which produced the largest ΔQ, i.e. the change in Q from the resonance point when empty to the value observed when occupied. ΔQ was taken to be proportional to sensitivity.

The subject chosen for initial tests was a female, aged 20 yr, who was 162 cm tall, with a body weight of 56 kg and a body fat content of
30.7%, based on measurements of body density. Throughout this section, she occupied the test capacitor each time \( \Delta Q \) was measured.

The following series of experiments was carried out in which \( L \) (coil inductance) and \( C_1 \) (variable capacitance) were varied, and \( \Delta Q \) (the change in the value of \( Q \) when the subject entered the test capacitor) was measured:

(a) **Model 1**
   (i) Effect on \( \Delta Q \) of altering \( L \), \( C_1 \) and plate separation.
   (ii) Reproducibility of \( \Delta Q \).

(b) **Model 2**
   (i) Effect on \( \Delta Q \) of altering \( L \) and \( C_1 \).
   (ii) Effect on \( \Delta Q \) of changing rod or end-panel position in relation to the parallel plates.
   (iii) Effect of end-panel dimension on \( \Delta Q \).
   (iv) Reproducibility of \( \Delta Q \).

(c) **Model 3**
   (i) Effect on \( \Delta Q \) of altering \( L \) and \( C_1 \).
   (ii) Effect of panel dimension on \( \Delta Q \).
   (iii) Reproducibility of \( \Delta Q \).

2. Results

(a) **Model 1. Parallel-plate capacitor**
   (i) Effect on \( \Delta Q \) of altering \( L \), \( C_1 \) and plate separation:
For plate separations of 40 and 60 cm, ΔQ values were obtained for coils with inductances ranging from 10 to 2500 μH, each with C₁ set at 20, 100, 200, 300, 400 and 500 pF. Table 7.1 shows maximum ΔQ found for each coil, together with corresponding C₁ settings and resonant frequencies. For both plate separations, the highest maximum ΔQ was obtained with L = 500 μH and C₁ = 300 pF. When the plate separation was increased from 40 to 60 cm, there was a decrease in ΔQ values.

To investigate further the effect of plate separation, ΔQ values were obtained with C₁ = 300 pF for coils with L = 100, 250, 500 and 1000 μH, at plate separations of 40, 50 and 60 cm. The results are shown in Figure 7.2. Maximum ΔQ was obtained for L = 400 to 500 μH. As there was a marked increase in ΔQ with a decrease in plate separation, it was desirable to have the plates as close together as possible. The practical minimum plate separation which allowed a subject to stand between, and facing the plates, was 40 cm.

Of the combinations of L and C₁ tested, the following produced the largest ΔQ for the particular subject used: L = 500 μH and C₁ = 300 pF at a plate separation of 40 cm.

(ii) Reproducibility of ΔQ:
Values of ΔQ were determined 10 times for the subject on the same day, resulting in a coefficient of variation of 2.1%.

(b) Model 2. Vertical rod or end-panel and parallel plates
Plate separation was set to 50 cm, the minimum distance which would
Table 7.1

Maximum $\Delta Q$ value for coils with inductance ($L$) as listed, together with corresponding variable capacitance ($C_1$) setting and resonant frequency ($f_R$). Measurements were made in model 1.

<table>
<thead>
<tr>
<th></th>
<th>L (mH)</th>
<th>$C_1$ (pF)</th>
<th>$f_R$ (MHz)</th>
<th>Maximum $\Delta Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate separation 40 cm.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>2.375</td>
<td>-5</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>400</td>
<td>0.878</td>
<td>-33</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>500</td>
<td>0.580</td>
<td>-48</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>400</td>
<td>0.398</td>
<td>-60</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>300</td>
<td>0.308</td>
<td>-61</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>300</td>
<td>0.221</td>
<td>-52</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>100</td>
<td>0.180</td>
<td>-31</td>
<td></td>
</tr>
<tr>
<td>Plate separation 60 cm.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>2.472</td>
<td>-2</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>400</td>
<td>0.897</td>
<td>-11</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>500</td>
<td>0.591</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>300</td>
<td>0.408</td>
<td>-21</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>300</td>
<td>0.317</td>
<td>-24</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>100</td>
<td>0.295</td>
<td>-17</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>100</td>
<td>0.187</td>
<td>-16</td>
<td></td>
</tr>
</tbody>
</table>
Figure 7.2

Relationship between change in Q value ($\Delta Q$) and coil inductance (L) with variable capacitance ($C_1$) = 300 pF, for plate separations (d) = 40, 50 and 60 cm. Measurements were made in model 1.
accommodate a subject who faced the vertical rod or end-panel and was therefore sideways to the parallel plates. Figure 7.3 shows the positions of the rod or end-panel relative to the parallel plates, where adjacent positions are separated by 10 cm and position 0 is level with the ends of the parallel plates.

(i) Effect on ΔQ of altering L and C₁:
The rod was placed in the position -30 cm in Figure 7.3 and ΔQ was determined for coils with L = 10, 25, 50, 100, 200, 250 and 1000 μH, each with C₁ set at 20, 100, 200, 300, 400 and 500 pF. Table 7.2 shows the maximum ΔQ found for each coil, together with corresponding C₁ settings and resonant frequencies. The highest maximum ΔQ value was recorded for L = 25 μH and C₁ = 200 pF.

With a plate separation of 50 cm, ΔQ was determined for three end-panels with dimensions 30 x 240 cm, 30 x 170 cm and 15 x 170 cm, placed in the position -20 cm in Figure 7.3. Coils with L = 10, 25, 50, 100, 250, 500 and 1000 μH were each tested with C₁ = 20, 100, 200, 300, 400 and 500 pF. Table 7.3 shows the maximum ΔQ values, together with C₁ settings and resonant frequencies, for the end-panels with dimensions 30 x 240 cm and 30 x 170 cm.

The highest maximum ΔQ value for the 30 x 240 cm end-panel was obtained with L = 250 μH and C₁ = 400 pF, and for the 30 x 170 cm panel, L = 25 μH and C₁ = 300 pF. On repeating the measurements with an end-panel measuring 15 x 170 cm, a maximum ΔQ was again obtained with L = 25 μH and C₁ = 300 pF.
Figure 7.3

Positions of the rod or end-panel relative to the parallel plates of model 2. Position 0 is level with the ends of the parallel plates, and adjacent positions are separated by 10 cm.
Table 7.2

Maximum $\Delta Q$ value for coils with inductance ($L$) as listed, together with corresponding variable capacitance ($C_1$) setting and resonant frequency ($f_R$). Measurements were made in model 2 with the rod as the central conductor.

<table>
<thead>
<tr>
<th>$L$ (uH)</th>
<th>$C_1$ (pF)</th>
<th>$f_R$ (MHz)</th>
<th>Maximum $\Delta Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>100</td>
<td>3.539</td>
<td>-114</td>
</tr>
<tr>
<td>25</td>
<td>200</td>
<td>1.896</td>
<td>-171</td>
</tr>
<tr>
<td>50</td>
<td>200</td>
<td>1.357</td>
<td>-165</td>
</tr>
<tr>
<td>100</td>
<td>200</td>
<td>0.953</td>
<td>-160</td>
</tr>
<tr>
<td>200</td>
<td>200</td>
<td>0.684</td>
<td>-157</td>
</tr>
<tr>
<td>250</td>
<td>200</td>
<td>0.611</td>
<td>-150</td>
</tr>
<tr>
<td>1000</td>
<td>100</td>
<td>0.412</td>
<td>-108</td>
</tr>
</tbody>
</table>
Table 7.3

Maximum $\Delta Q$ value for coils with inductance ($L$) as listed, together with corresponding variable capacitance ($C_1$) setting and resonant frequency ($f_R$). Measurements were made in model 2 with end-panels of dimensions 30 x 240 cm and 30 x 170 cm.

<table>
<thead>
<tr>
<th>$L$ (mH)</th>
<th>$C_1$ (pF)</th>
<th>$f_R$ (MHz)</th>
<th>max. $\Delta Q$</th>
<th>$C_1$ (pF)</th>
<th>$f_R$ (MHz)</th>
<th>max. $\Delta Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>300</td>
<td>2.086</td>
<td>-56</td>
<td>200</td>
<td>2.436</td>
<td>-124</td>
</tr>
<tr>
<td>25</td>
<td>500</td>
<td>1.194</td>
<td>-102</td>
<td>300</td>
<td>1.495</td>
<td>-196</td>
</tr>
<tr>
<td>50</td>
<td>500</td>
<td>0.850</td>
<td>-96</td>
<td>200</td>
<td>1.251</td>
<td>-180</td>
</tr>
<tr>
<td>100</td>
<td>500</td>
<td>0.607</td>
<td>-102</td>
<td>300</td>
<td>0.805</td>
<td>-172</td>
</tr>
<tr>
<td>250</td>
<td>400</td>
<td>0.413</td>
<td>-108</td>
<td>300</td>
<td>0.510</td>
<td>-176</td>
</tr>
<tr>
<td>500</td>
<td>300</td>
<td>0.328</td>
<td>-102</td>
<td>200</td>
<td>0.414</td>
<td>-157</td>
</tr>
<tr>
<td>1000</td>
<td>300</td>
<td>0.232</td>
<td>-82</td>
<td>200</td>
<td>0.287</td>
<td>-128</td>
</tr>
</tbody>
</table>
(ii) Effect on $\Delta Q$ of changing rod or end-panel position in relation to the parallel plates:

Values of $\Delta Q$ were determined for the positions shown in Figure 7.3. When the central conductor was the rod, measurements were made using $L = 25 \text{ } \mu\text{H}$ and $C_1 = 200 \text{ } \mu\text{F}$. When the central conductor was an end-panel which measured $30 \times 240 \text{ cm}$, $L = 250 \text{ } \mu\text{H}$ and $C_1 = 400 \text{ } \mu\text{F}$.

Figure 7.4 shows how $\Delta Q$ was affected by the position of the rod or end-panel in relation to the parallel plates. With both the rod and end-panel, the smallest $\Delta Q$ value, representing the smallest shift away from resonance, was obtained for the position $+40 \text{ cm}$. As the rod or end-panel was moved closer to the parallel plates, $\Delta Q$ values increased until the rod or end-panel reached the position $+10 \text{ cm}$, beyond which there was little change in $\Delta Q$ indicating that moving the rod or end-panel further in between the parallel plates had little apparent effect on sensitivity. It was observed that when the rod or end-panel occupied the positions $0$ to $+40 \text{ cm}$ there was interference caused by the presence of the operator who had to be positioned near the rod or end-panel to read the instruments. Therefore it appeared that the rod or end-panel should be moved in between the parallel plates, at least as far as the position $-10 \text{ cm}$ for best results.

(iii) Effect of end-panel dimension on $\Delta Q$:

Values of $\Delta Q$ were obtained using the test subject and end-panels with the following dimensions of width (cm) x height (cm):

- $5 \times 170$, $5 \times 205$, $5 \times 240$
- $15 \times 170$, $15 \times 205$, $15 \times 240$
- $22 \times 170$, $22 \times 205$, $22 \times 240$
- $30 \times 170$, $30 \times 205$, $30 \times 240$
Figure 7.4

Effect on change in Q value ($\Delta Q$) of changing the rod or end-panel position in relation to the parallel plates of model 2. Positions are illustrated in Figure 7.3. Measurements of $\Delta Q$ were made with coil inductance ($L_r$) = 25 $\mu$H and variable capacitance ($C_1$) = 200 pF for the rod, and coil inductance ($L_r$) = 250 $\mu$H and variable capacitance ($C_1$) = 400 pF for the end-panel, which had dimensions 30 x 240 cm.
The end-panels were placed in the position -20 cm in Figure 7.3. The coil with $L = 25 \ \mu H$ was used and $C_1$ was set at 300 pF. The effects of end-panel dimension on $\Delta Q$ are listed in Table 7.4. The result using the rod (height 200 cm) is included for comparison.

For each end-panel, $\Delta Q$ decreased with the increase in panel height, suggesting that as end-panel height was increased the subject interfered with a smaller proportion of the electromagnetic field. From the end-panels used, maximum $\Delta Q$ was recorded for the 15 x 170 cm end-panel.

(iv) Reproducibility of $\Delta Q$:
Values of $\Delta Q$ were determined for the subject 10 times on the same day with the rod and with three end-panels measuring 205 cm high and 5, 15 and 30 cm wide. The coefficients of variation were 2.8%, 2.9%, 1.5% and 1.5% respectively. This trend may indicate that as the width of the end-panel increased, making the field less concentrated at the surface of the end-plate, the positioning of the subject relative to the end-plate had less effect on $\Delta Q$ readings, thereby decreasing the coefficient of variation for repeated readings.

(c) Model 3. Horizontal rod or panel and cylinder
(i) Effect on $\Delta Q$ of altering $L$ and $C_1$:
Values of $\Delta Q$ were measured for the test subject using a hollow copper rod mounted in the centre of the cylinder, and then a second time with the rod replaced by an aluminium panel measuring 30 x 170 cm. Coils with $L = 10, 25, 50, 100, 250, 500$ and $1000 \ \mu H$ were each tested with $C_1$ settings ranging from 100 to 500 pF. Maximum $\Delta Q$ values for the coils, together with corresponding $C_1$ settings, are shown in Table
Table 7.4

Change in Q value ($\Delta Q$) for end-panels with dimensions as tabulated, for coil inductance ($L$) = 25 $\mu$H and variable capacitance ($C_1$) = 300 pF. Measurements were made in model 2 and the result using the rod is included for comparison.

<table>
<thead>
<tr>
<th>End-panel height (cm)</th>
<th>End-panel width (cm)</th>
<th>5</th>
<th>15</th>
<th>22</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>170</td>
<td></td>
<td>-166</td>
<td>-201</td>
<td>-170</td>
<td>-196</td>
</tr>
<tr>
<td>205</td>
<td></td>
<td>-158</td>
<td>-188</td>
<td>-164</td>
<td>-165</td>
</tr>
<tr>
<td>240</td>
<td></td>
<td>-94</td>
<td>-78</td>
<td>-79</td>
<td>-54</td>
</tr>
<tr>
<td>Rod height (cm)</td>
<td></td>
<td>200</td>
<td></td>
<td></td>
<td>-170</td>
</tr>
</tbody>
</table>
7.5. Operating frequencies were in the range 1 - 2 MHz. For both the rod and the panel, greatest maximum δQ was obtained for L = 25 μH, with C₁ values of 400 and 500 pF respectively.

(ii) Effect of panel dimension on δQ:

Values of δQ were obtained using the test subject and panels with the following dimensions of width (cm) x height (cm):

\[
\begin{align*}
5 \times 170, & \quad 5 \times 180, & \quad 5 \times 190, & \quad 5 \times 200 \\
10 \times 170, & \quad 10 \times 180, & \quad 10 \times 190, & \quad 10 \times 200 \\
22 \times 170, & \quad 22 \times 180, & \quad 22 \times 190, & \quad 22 \times 200 \\
30 \times 170, & \quad 30 \times 180, & \quad 30 \times 190, & \quad 30 \times 200
\end{align*}
\]

Measurements of δQ were made using the coil with L = 25 μH, and C₁ settings were 400 and 500 pF. Operating frequencies ranged from 1 - 2 MHz. Values of δQ are shown in Table 7.6, which includes results obtained with the rod (length 200 cm) for comparison.

For each panel width, δQ decreased with an increase in panel length indicating that the shortest panel tested produced the largest δQ value. With the exception of panel width 22 cm, there were little differences in δQ values for panels of the same length but different widths. The panel measuring 22 cm wide produced consistently larger δQ values than the other panels, suggesting that this width was the best. When δQ values for the panels with the same length as the rod are compared, the rod produced the largest δQ with C₁ = 400 pF, but with C₁ = 500 pF, the δQ value for the 22 cm wide panel was the largest.
Table 7.5

Maximum change in $Q$ value ($\Delta Q$) for coils with inductance ($L$) as listed, together with corresponding variable capacitance ($C_1$) settings for readings taken with the rod and a panel measuring 30 x 170 cm alternately occupying the central position in the cylinder of model 3.

<table>
<thead>
<tr>
<th>$L$ ((\mu)H)</th>
<th>$C_1$ (pF)</th>
<th>max. $\Delta Q$</th>
<th>$C_1$ (pF)</th>
<th>max. $\Delta Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>300</td>
<td>-129</td>
<td>400,500</td>
<td>-125</td>
</tr>
<tr>
<td>25</td>
<td>400</td>
<td>-195</td>
<td>500</td>
<td>-191</td>
</tr>
<tr>
<td>50</td>
<td>300</td>
<td>-176</td>
<td>400,500</td>
<td>-171</td>
</tr>
<tr>
<td>100</td>
<td>300</td>
<td>-171</td>
<td>500</td>
<td>-169</td>
</tr>
<tr>
<td>250</td>
<td>300</td>
<td>-175</td>
<td>400,500</td>
<td>-169</td>
</tr>
<tr>
<td>500</td>
<td>300</td>
<td>-155</td>
<td>500</td>
<td>-150</td>
</tr>
<tr>
<td>1000</td>
<td>300</td>
<td>-122</td>
<td>400</td>
<td>-124</td>
</tr>
</tbody>
</table>
Table 7.6
Change in Q value (△Q) value for panels with dimensions as tabulated for coil inductance (L) = 25 μH and variable capacitance \( C_1 \) = 400 and 500 pF. Measurements were made in model 3 and the results using the rod are included for comparison.

<table>
<thead>
<tr>
<th>Panel length (cm)</th>
<th>5</th>
<th>10</th>
<th>22</th>
<th>30</th>
<th>5</th>
<th>10</th>
<th>22</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_1 = 400 ) pF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Panel width (cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>-185</td>
<td>-184</td>
<td>-199</td>
<td>-186</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>-182</td>
<td>-181</td>
<td>-196</td>
<td>-187</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>-180</td>
<td>-179</td>
<td>-188</td>
<td>-181</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>-178</td>
<td>-176</td>
<td>-190</td>
<td>-177</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rod length (cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>-195</td>
<td></td>
<td></td>
<td>-185</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Panel length (cm)</th>
<th>5</th>
<th>10</th>
<th>22</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_1 = 500 ) pF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panel width (cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>-190</td>
<td>-190</td>
<td>-203</td>
<td>-190</td>
</tr>
<tr>
<td>180</td>
<td>-187</td>
<td>-186</td>
<td>-196</td>
<td>-188</td>
</tr>
<tr>
<td>190</td>
<td>-187</td>
<td>-184</td>
<td>-193</td>
<td>-184</td>
</tr>
<tr>
<td>200</td>
<td>-184</td>
<td>-182</td>
<td>-192</td>
<td>-180</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rod length (cm)</th>
<th>200</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-185</td>
</tr>
</tbody>
</table>
(iii) Reproducibility of $\Delta Q$:
Values of $\Delta Q$ were determined 10 times for the subject using the rod mounted in the cylinder, resulting in a coefficient of variation of 0.27%.

D. MEASUREMENT WITH GRADED AMOUNTS OF ABSORBING MATERIALS

1. Methods

Measurements presented in this section were obtained using model 3. It became evident that in order to gauge equipment sensitivity, it was necessary to measure the effects of introducing materials such as water, saline, meat and fat, separately and in combination, into the test capacitor, rather than using the whole body of a test subject. For ease of handling, measured quantities of water, saline, fat and ground lean meat were separately packaged in plastic containers.

Distilled water was used, and the saline comprised 0.9% (w/v) NaCl solution. The fat was beef dripping which was packaged in 500 g containers. After melting approximately 100 g fat, there was no visible water layer and so it was assumed that the fat was essentially anhydrous. Lean mutton, which had been trimmed of visible fat, was ground and packaged in 500 g lots. Following the methods of the A.O.A.C. (Horwitz 1975), duplicate samples of the meat were analysed for moisture (method number 24.003a) and ether-extractable fat (method number 24.005a, using petroleum ether, B.P. 35-60°C). On the basis of wet weight, the ground meat contained 78.9% moisture (duplicate results were 78.6% and 79.2%), and 3.9% ether-extractable fat (duplicate results were 3.9% and 3.9%).
The following series of experiments was performed using the test capacitor of model 3:

(a) Electromagnetic field effect measurements involving changes in Q value (ΔQ)
   (i) Effect on Q of increasing the volume of saline or water in the test capacitor with different combinations of L and C₁.
   (ii) Optimum C₁ for maximizing ΔQ for range of volumes of saline normally present in the adult human body.

(b) Electromagnetic field effect measurements involving changes in resonant frequency (Δfᵢᵣ)
   (i) Relationship between Q and frequency for different volumes of water.
   (ii) Method for measuring Δfᵢᵣ.
   (iii) Effect on Δfᵢᵣ per litre of water for different combinations of L and C₁.
   (iv) Reproducibility of Δfᵢᵣ.
   (v) Effect of panel width on Δfᵢᵣ.
   (vi) Effect on Δfᵢᵣ of changing the quantities and combinations of meat and fat in the test capacitor.

2. Results

(a) Electromagnetic field effect measurements involving changes in Q value (ΔQ)
   (i) Effect on Q of increasing the volume of saline or water in the test capacitor with different combinations of L and C₁.
Using the rod as the central conductor in the cylinder, 2 L volumes of 0.9% saline or distilled water were placed in plastic containers with lids, and positioned in pairs, one either side and above the rod, in a line running the length of the cylinder. Initial tests showed that Q was not affected by the position of the material along the length of the cylinder.

With the test capacitor empty, the system was tuned to resonance by varying frequency. After each 2 L increment of saline or water, the value on the Q-meter was recorded. Readings were obtained with L = 10, 25, 50, 100 and 500 μH, each with C₁ = 100, 200, 300, 400 and 500 pF. Graphs showing the change in Q with increasing volumes of saline are shown in Figures 7.5 and 7.6 where C₁ = 400 pF and L = 25 μH respectively.

In Figure 7.5, a constant value of 400 pF was used for C₁ with each coil so that the effect of changing L could be seen. The Q values with the test capacitor empty differed for each coil, and adding saline caused the reading on the Q-meter to decrease by different amounts for the first 20 L. For volumes greater than 20 L, however, Q values were similar for all the coils tested. These results explain that the greatest maximum ∆Q for the test subject was found with L = 25 μH (Table 7.5) because with this coil, Q for the empty capacitor was greatest. It was then clear that greatest sensitivity was related not to maximum ∆Q between the empty capacitor and when it was occupied by the test subject, but to the greatest change in Q value caused by volumes of saline corresponding to those found in the body. Most adult body types contain between 30 and 50 L saline, and Figure 7.5 shows that the slopes of the graphs are similar over this range for each coil tested.
Figure 7.5

The change in Q with increasing volumes of saline using a constant variable capacitance setting \((C_1) = 400\ \text{pF}\) and coils with inductance \((L) = 10, 25, 50, 100\) and \(500\ \mu\text{H}\). Measurements were made in model 3 with the rod as the central conductor.
Figure 7.6

The change in $Q$ with increasing volumes of saline using a constant coil inductance ($L = 25 \ \mu H$), and variable capacitance settings ($C_1$) = 100, 200, 300, 400 and 500 pF. Measurements were made in model 3 with the rod as the central conductor.
In Figure 7.6, the effects of changing \( C_1 \) can be seen when \( L = 25 \mu\text{H} \). Between volumes 30 and 50 L, the slopes of the graphs increase as \( C_1 \) increases, indicating that greatest sensitivity is related to higher values of \( C_1 \).

Results obtained for the change in \( Q \) with increasing volumes of water followed similar patterns, and the \( Q \) values obtained with water were generally about 14% greater than corresponding \( Q \) values obtained with saline.

(ii) Optimum \( C_1 \) for maximizing \( \Delta Q \) for range of volumes of saline normally present in the adult human body:

From Figure 7.6 it appears that greater sensitivity was associated with larger \( C_1 \) settings. In order to increase \( C_1 \) beyond 500 pF, it was necessary to add capacitors in parallel to the variable capacitor built into the equipment. Values of \( \Delta Q \) were measured for 30 and 50 L saline, the range of volumes representing normal adult human bodies, with \( L = 25 \mu\text{H} \) and \( C_1 \) settings ranging from 100 to 2000 pF. Figure 7.7 shows that the greatest \( \Delta Q \) value per litre of saline, obtained between 30 and 50 L saline, was recorded for \( C_1 = 1000 \) pF.

(b) Electromagnetic field effect measurements involving changes in resonant frequency \( (\Delta f_R) \):

(i) Relationship between \( Q \) and frequency for different volumes of water:

Three 20L-capacity rectangular plastic bins were placed end-to-end and centred above the rod in the test capacitor. Using \( L = 25 \mu\text{H} \) and \( C_1 = 120 \) pF, the system was tuned by varying frequency, and \( Q \) and \( f_R \) were recorded. Frequency \( (f) \) was then altered to frequencies either side
Figure 7.7

Relationship of change in Q value (ΔQ) per litre of saline (measured between 30 and 50 L saline) with variable capacitance (C₁). Readings were obtained in model 3 with the rod as the central conductor, and coil impedance (L) = 25 mH.
of the peak frequency and the corresponding Q values recorded. This was repeated when the bins contained 30 and 60 L water. Figure 7.8 shows the variation of Q with frequency for each volume of water. The peak frequency in each case was the resonant frequency, associated with maximum Q. As the volume of water was increased the curve was displaced to the left, the extent of displacement of the peak or resonant frequency being related to the volume of water.

(ii) Method for measuring $\Delta f_R$: A new method evolved for measuring the electromagnetic field effect caused by the presence of an absorbing material in the test capacitor. The measured parameter was the change in resonant frequency ($\Delta f_R$).

With the test capacitor empty, the system was tuned, by varying frequency, until a maximum Q value was reached, and resonant frequency was recorded. Introduction of an absorbing material into the test capacitor caused de-tuning of the system which could then be re-tuned by varying the frequency again until a maximum Q value was obtained. The resonant frequency of the occupied test capacitor was recorded, and $\Delta f_R$ calculated as the difference in resonant frequencies between the empty and occupied test capacitor.

When it was necessary to place the absorbing material in plastic containers, the resonant frequency for the 'empty' capacitor was measured with the plastic containers (empty) inside the cylinder. Therefore $\Delta f_R$ values which were subsequently measured related only to the absorbing materials and were not affected by the presence of the containers.
Figure 7.8

Variation of $Q$ with frequency ($f$) when 0, 30 and 60 L water occupied the test capacitor of model 3 with the rod as the central conductor. Readings were made with coil inductance ($L$) = 15 $\mu$H and variable capacitance ($C_1$) = 120 pF.
(iii) Effect on $\Delta f_R$ per litre of water for different combinations of $L$ and $C_1$.

To determine the effect on $\Delta f_R$ of altering $L$ and $C_1$, $\Delta f_R$ was measured for 30 and 60 L water, where $\Delta f_R$ was the difference in resonant frequencies between the empty and occupied test capacitor. The volumes 30 and 60 L were chosen because they approximated the range of volumes which represented most adult body types. Coils with $L = 10$, 25 and 250 $\mu$H were tested in combination with $C_1 = 20$, 30, 120 and 500 pF. Figure 7.9 shows that for each coil, $\Delta f_R$ per litre of water increased with decreasing values of $C_1$. Therefore, the $C_1$ value associated with maximum $\Delta f_R$, indicating greatest sensitivity, was the lowest setting (20 pF).

From Figure 7.9 it was evident that decreasing $L$ also increased sensitivity, so this was investigated further by determining $\Delta f_R$ per litre of water for $L = 1$, 5, 10, 25 and 100 $\mu$H, with $C_1 = 20$ pF. Results are plotted in Figure 7.10 which shows that greater $\Delta f_R$ values per litre of water were obtained for coils with smaller inductances. A problem arose, however, when coils with low inductances were used.

To find resonant frequency, frequency was varied until $Q$ was a maximum. Figure 7.11 shows how $Q$ changes with frequency for two coils, $L = 1$ and 25 $\mu$H. In each case the test capacitor contained 60 L water in plastic containers. For $L = 25 \mu$H, the peak was broad and in practice this meant it was more difficult to accurately tune the system to resonance, as maximum $Q$ was difficult to locate. One method to overcome this problem was to determine the frequencies for a $Q$ value which was approximately 80% of the maximum $Q$ on both sides of the peak, and calculate the resonant frequency ($f_R$) as the mean. This is illustrated below:
Figure 7.9

Relationship of the change in resonant frequency ($\Delta f_R$) per litre of water (measured between 30 and 60 L water) with variable capacitance ($C_1$) for coils with inductance ($L$) = 10, 25 and 250 $\mu$H. Measurements were made in model 3 with the rod as the central conductor.
Figure 7.10
Curve showing an increase in change in resonant frequency ($\Delta f_R$) per litre of water with decreasing coil inductance (L) values. Readings were made in model 3 with the rod as the central conductor, and a variable capacitance ($C_1$) = 20 pF.
Figure 7.11
Curves showing how $Q$ varies with frequency for coils with inductance $L = 1$ and $25 \mu H$. In both cases the test capacitor of model 3 contained 60 L water, and the rod was used as the central conductor.
(iv) Reproducibility of $\Delta f_R$:
Using the rod as the central conductor, and three coils, each with $C_1 = 20$ pF, $\Delta f_R$ was determined 10 times on the same day for a test subject. The coefficients of variation were 0.44%, 0.17% and 0.17% for $L = 1, 10, \text{ and } 25 \text{ mH}$ respectively. When $f_R$ was calculated as $(f_1 + f_2)/2$ for $L = 1 \text{ mH}$, the coefficient of variation decreased to 0.24%, indicating that by using this method, $f_R$ was determined with greater precision.

(v) Effect of panel width on $\Delta f_R$:
The effect of panel width on sensitivity and the importance of panel width in minimizing radial positioning of absorbing material within the test capacitor were tested in this section. The rod and three panels, of widths 22, 30 and 45 cm, were tested and compared; the panels and the rod were all the same length (200 cm). The absorbing material was lean meat which was stacked into the test capacitor in 500 g lots.

To test sensitivity effects, 7 and 14 kg meat were separately placed in the test capacitor with the containers of meat placed in pairs, one each side and above the central conductor. Greatest sensitivity was related to the greatest $\Delta f_R$ per kilogram of meat. Results, which were
determined for \( L = 1 \) and 25 gH, are listed in Table 7.7. The trend shown in these results is that sensitivity decreases as plate width increases.

To test the importance of panel width in minimizing radial positioning effects, 14 kg meat in 500 g lots, was stacked (a) in pairs in a single layer along the length of the central conductor, and then (b) four rows across, extending only halfway along the length of the central conductor. This meant that half of the meat in (b) was moved radially away from the central conductor and towards the walls of the cylinder. The panel which minimized radial positioning effects would be the one which had the smallest difference between \( \Delta f_R \) values for positions (a) and (b). The results for \( L = 1 \) gH are presented in Figure 7.12. Of the rod and panels tested, the plate of width 22 cm produced the smallest difference in \( \Delta f_R \) values for the two arrangements of meat. Measurements using \( L = 25 \) gH produced a similar pattern of results.

As the width of the central conductor increased, \( \Delta f_R \) became less dependent on the radial positioning of the meat because the surface area of the central conductor increased, creating a field which was less concentrated along the centre of the cylinder. As panel width increased beyond 30 cm and approached the diameter of the cylinder, it was likely that the field became concentrated between the panel and the walls of the cylinder instead of passing through the meat. This would explain the decrease in the difference between \( \Delta f_R \) values, for plate widths greater than 30 cm, with the two arrangements of meat.

To obtain optimal plate width, so that \( \Delta f_R \) was least affected by the radial positioning of the absorbing material, a balance had to be reached between the two opposing trends which occurred as plate width
Table 7.7
Change in resonant frequency per kilogram of meat (measured between 7 and 14 kg meat) for coils with inductance \( L = 1 \) and 25 \( \mu \)H, using model 3 with the rod and panels of widths 22, 30 and 45 cm. Rod and panel lengths were 200 cm.

<table>
<thead>
<tr>
<th>Change in resonant frequency (kHz/kg)</th>
<th>( L = 1 ) ( \mu )H</th>
<th>( L = 25 ) ( \mu )H</th>
</tr>
</thead>
<tbody>
<tr>
<td>rod</td>
<td>-69.57</td>
<td>-9.57</td>
</tr>
<tr>
<td>panels of width:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22 cm</td>
<td>-54.29</td>
<td>-10.43</td>
</tr>
<tr>
<td>30 cm</td>
<td>-37.00</td>
<td>-6.71</td>
</tr>
<tr>
<td>45 cm</td>
<td>-18.86</td>
<td>-3.14</td>
</tr>
</tbody>
</table>
Figure 7.12

The difference between change in resonant frequency ($\Delta f_R$) values obtained for 14 kg meat placed in 500 g lots in two arrangements, (a) and (b), which differed in radial positioning (refer to text). Results are presented for the rod (○) and three panels (●) of different widths. Measurements were made in model 3, using a coil with inductance ($L$) = 1 $\mu$H.
increased. Of the plates tested, the 22 cm width appeared to be the best for the quantities and arrangements of meat used.

(vi) Effect on $\Delta f_R$ of changing the quantities and combinations of meat and fat in the test capacitor:

Containers holding 500 g of meat or fat were used in this investigation. Resonant frequency for the 'empty' test capacitor was measured when the capacitor held 112 empty containers, stacked in 14 rows and 4 columns, 2 deep. The columns ran the length of the cylinder, parallel to the central conductor, and the rows extended across the cylinder. Each row therefore contained 8 containers which held a total of 4 kg meat or fat. Meat or fat was then added to the capacitor in 4 kg lots (8 containers) by replacing a row of empty containers. A panel of width 22 cm was chosen as the central conductor because it minimized the effects of radial positioning of the material inside the test capacitor.

To determine the effect of adding only meat or fat, $\Delta f_R$ was measured for 4 kg increments up to 44 kg meat and 20 kg fat using $L = 0.2, 1$ and $25 \mu H$, with $C_1 = 20 \mu F$. Figure 7.13 shows the results for $L = 1 \mu H$. Similar patterns were obtained for $L = 0.2$ and $25 \mu H$. The $\Delta f_R$ value per kilogram of meat was greater than the $\Delta f_R$ value per kilogram of fat. Ratios of ($\Delta f_R$ meat/$\Delta f_R$ fat) were calculated for 4, 8, 12, 16 and 20 kg and these are listed in Table 7.8.

To determine the effect of changing the combinations of meat and fat, 32, 36, 40 and 44 kg meat were each placed in the test capacitor with 0, 4, 8 and 12 kg fat, and $\Delta f_R$ was determined for $L = 0.2, 1$ and $25 \mu H$, with $C_1 = 20 \mu F$. The combinations resulted in the compositions
Figure 7.13

The change in resonant frequency ($\Delta f_R$) caused by increasing the amounts of meat or fat in the test capacitor of model 3. A panel of width 22 cm was used, and measurements were made using a coil with inductance ($L$) = 1 mH and variable capacitance ($C_1$) = 20 pF.
Table 7.8

Ratios ($\Delta f_R$ _meat/$\Delta f_R$ _fat) where $\Delta f_R$ is the change in resonant frequency (MHz). Measurements were made for 4 - 20 kg lots of meat and fat in model 3, using coils with inductance ($L$) = 0.2, 1 and 25 $\mu$H, and variable capacitance ($C_1$) = 20 pF. A panel of width 22 cm was used as the central conductor.

<table>
<thead>
<tr>
<th>kg</th>
<th>L = 0.2 $\mu$H</th>
<th>L = 1 $\mu$H</th>
<th>L = 25 $\mu$H</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.198</td>
<td>4.474</td>
<td>4.636</td>
</tr>
<tr>
<td>8</td>
<td>4.585</td>
<td>4.477</td>
<td>4.500</td>
</tr>
<tr>
<td>12</td>
<td>4.353</td>
<td>4.075</td>
<td>3.944</td>
</tr>
<tr>
<td>16</td>
<td>4.171</td>
<td>4.054</td>
<td>3.936</td>
</tr>
<tr>
<td>20</td>
<td>3.937</td>
<td>3.953</td>
<td>3.828</td>
</tr>
</tbody>
</table>

mean 4.249 4.207 4.169

± s.d. 0.240 0.250 0.370
shown in Table 7.9, where total weight = weight of meat + weight of fat. The $\Delta f_R$ values are plotted against weight of meat for $L = 1 \mu H$ in Figure 7.14. A family of lines was produced, a separate line for each total weight. The slopes are due to the increasing electromagnetic field effect with increments of meat, while vertical distances between lines represent the electromagnetic field effect due to differences in the quantity of fat. These trends were also found for $L = 0.2$ and 25 $\mu H$.

Using these results as a model, measurements of $\Delta f_R$ and total body weight are the requirements for determining the fat-free weight (FFW) of the body.

E. MEASUREMENT OF HUMAN SUBJECTS IN THE TEST CAPACITOR

1. Methods

This part of the study was aimed at measuring a group of subjects in the test capacitor and developing regression equations for predicting body composition from $\Delta f_R$ values. A group of subjects was measured in the test capacitor with:

(a) a panel of width 22 cm, using $L = 0.2$, 1 and 10 $\mu H$; and

(b) a rod, using $L = 1$, 2.5, 10 and 25 $\mu H$.

Both central conductors were 200 cm in length, and measurements of $\Delta f_R$ were made with $C_1 = 20 \mu F$. Values of $\Delta f_R$ were measured in triplicate and the calculated mean was used in subsequent analyses. As shown in Figure 7.11, sensitivity (measured as the change in $\Delta f_R$ per litre of water) increased with a decrease in $L$, but as shown in Figure 7.12,
Table 7.9
The composition of various combinations of meat and fat placed in the test capacitor of model 3. Total weight = weight of meat + weight of fat.

<table>
<thead>
<tr>
<th>weight of meat (kg)</th>
<th>weight of fat (kg)</th>
<th>total weight (kg)</th>
<th>% fat</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>0</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>32</td>
<td>4</td>
<td>36</td>
<td>11</td>
</tr>
<tr>
<td>32</td>
<td>8</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>32</td>
<td>12</td>
<td>44</td>
<td>27</td>
</tr>
<tr>
<td>36</td>
<td>0</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>36</td>
<td>4</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>36</td>
<td>8</td>
<td>44</td>
<td>18</td>
</tr>
<tr>
<td>36</td>
<td>12</td>
<td>48</td>
<td>25</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>4</td>
<td>44</td>
<td>9</td>
</tr>
<tr>
<td>40</td>
<td>8</td>
<td>48</td>
<td>17</td>
</tr>
<tr>
<td>40</td>
<td>12</td>
<td>52</td>
<td>23</td>
</tr>
<tr>
<td>44</td>
<td>0</td>
<td>44</td>
<td>0</td>
</tr>
<tr>
<td>44</td>
<td>4</td>
<td>48</td>
<td>8</td>
</tr>
<tr>
<td>44</td>
<td>8</td>
<td>52</td>
<td>15</td>
</tr>
<tr>
<td>44</td>
<td>12</td>
<td>56</td>
<td>21</td>
</tr>
</tbody>
</table>
Figure 7.14

The change in resonant frequency ($\Delta f_R$) for different combinations of meat and fat placed in the test capacitor of model 3. A panel of width 22 cm was used, and measurements were made using a coil with inductance ($L$) = 1 mH and variable capacitance ($C_1$) = 20 pF.
when I was decreased resonant frequency was more difficult to locate accurately. Therefore, when measuring subjects, a range of coil inductances was tested to find the one best suited for use in practice.

Table 7.10 lists the ages and physical characteristics of the 17 female University students who volunteered to participate in this part of the study. Body composition estimates were based on densitometric and anthropometric data, and bioelectric impedance measurements were also made. Body density was determined by the technique described in chapter 2, with lung volumes estimated by the hydrogen dilution method at the time of underwater weighing. Height, weight, skinfold thickness and bioelectric impedance were measured as described in chapter 5, section B. When subjects were measured in the test capacitor, they were asked to empty their pockets of metallic objects, such as loose change and keys, and to remove continuous bands of metal, such as rings, bangles and watches.

Multiple regression analyses (Minitab, Inc. 1985. Version 5.1 for TOPS-20) were performed to derive equations for predicting body composition from the measured $A_R$ values and additional variables such as height (H) and weight (W). The dependent variable was FFW based on body density measurements. The contribution of each variable into the prediction equation was determined using stepwise regression, and then separate equations were tested in order to maximize the coefficient of determination ($R^2$) and minimize the standard error of estimate (S.E.E.).
Table 7.10
Mean, standard deviation and range for age and physical
characteristics of 17 female subjects in the study of the effect of
human bodies on the electromagnetic field in model 3.

<table>
<thead>
<tr>
<th></th>
<th>Mean ± s.d.</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>21.7 ± 3.3</td>
<td>20 – 34</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.630 ± 0.082</td>
<td>1.489 – 1.799</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>56.8 ± 6.87</td>
<td>43.4 – 69.4</td>
</tr>
<tr>
<td>W/H² (kg/m²)#</td>
<td>21.3 ± 1.95</td>
<td>18.0 – 25.8</td>
</tr>
<tr>
<td>% fat calculated from:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>densitometry</td>
<td>26.1 ± 4.66</td>
<td>16.0 – 32.1</td>
</tr>
<tr>
<td>sum four skinfolds*</td>
<td>26.4 ± 3.79</td>
<td>16.8 – 31.8</td>
</tr>
<tr>
<td>W/H²**</td>
<td>23.9 ± 3.00</td>
<td>18.9 – 30.3</td>
</tr>
</tbody>
</table>

# W/H² = weight/height²
* Durnin and Womersley (1974)
** Womersley and Durnin (1977)
2. Results

(a) Measurements using a panel of width 22 cm as the central conductor of the test capacitor

Changes in resonant frequency were measured with coils of inductance 0.2, 1 and 10 \( \mu \)H; these values are designated as \( \Delta f_{R1} \), \( \Delta f_{R2} \) and \( \Delta f_{R3} \), respectively. A correlation matrix relating selected variables is shown in Table 7.11. The \( \Delta f_R \) values were strongly correlated with one another (\( r = 0.974 \) to 0.995) and with total body weight (\( r = -0.919 \) to -0.938). The results indicate that, although the correlation of \( \Delta f_R \) with FFW or FW is significant (\( P < 0.001 \)), \( \Delta f_R \) is a better predictor of total body weight than of FFW (\( r = -0.724 \) to -0.787) or FW (\( r = -0.770 \) to -0.835). As \( \Delta f_R \) values are the result of the combined effects of the fat and fat-free body tissues, it is not surprising that, when taken alone, they are not as strongly related to \( \Delta f_R \) as is total body weight which is also a combination of the fat and fat-free tissues.

Table 7.12 shows the results of a stepwise regression of FFW on five predictors (\( \Delta f_{R1} \), \( \Delta f_{R2} \), \( \Delta f_{R3} \), H, W). The regression equation incorporated W and H only, as significant variables (\( P < 0.05 \)); the addition of \( \Delta f_R \) values as separate independent variables did not cause a significant (\( P > 0.10 \); t-ratios for \( \Delta f_{R1} = 0.59 \), \( \Delta f_{R2} = 1.38 \) and \( \Delta f_{R3} = 1.69 \)) improvement in the fraction of explained variance. Table 7.13 shows the equations obtained using W, H and \( \Delta f_R \) values as predictor variables.

(b) Measurements using a rod as the central conductor of the test capacitor
Table 7.11

Correlation matrix of variables related to measurements of electromagnetic field effect and estimates of body composition, height and weight for 17 female subjects. Measurements of the effect of subjects on the electromagnetic field relate to the test capacitor of model 3 with a panel of width 22 cm as the central conductor.

<table>
<thead>
<tr>
<th></th>
<th>FWW</th>
<th>FW</th>
<th>Δf_{R1}</th>
<th>Δf_{R2}</th>
<th>Δf_{R3}</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW</td>
<td>0.413</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δf_{R1}</td>
<td>-0.787*</td>
<td>-0.770*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δf_{R2}</td>
<td>-0.762*</td>
<td>-0.824#</td>
<td>0.988#</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δf_{R3}</td>
<td>-0.724*</td>
<td>-0.835#</td>
<td>0.974#</td>
<td>0.995#</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>0.790*</td>
<td>0.332</td>
<td>-0.656</td>
<td>-0.636</td>
<td>-0.612</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>0.872#</td>
<td>0.806#</td>
<td>-0.925#</td>
<td>-0.938#</td>
<td>-0.919#</td>
<td>0.692</td>
</tr>
</tbody>
</table>

* P < 0.001
# P < 0.0001

H = height (m); W = weight (kg); FW and FW = fat-free weight (kg) and fat weight (kg) respectively, based on densitometry; Δf_{R1}, Δf_{R2} and Δf_{R3} = change in resonant frequency (MHz) using coils with inductance (L) = 0.2, 1 and 10 mH respectively.
Table 7.12

Stepwise regression of fat-free weight (FFW) on five predictor variables ($\Delta f_{R1}$, $\Delta f_{R2}$, $\Delta f_{R3}$, H, W) for 17 subjects measured in the test capacitor of model 3 with a panel of width 22 cm as the central conductor. $\Delta f_{R1}$, $\Delta f_{R2}$ and $\Delta f_{R3}$ = change in resonant frequency for coils with inductance (L) = 0.2, 1 and 10 $\mu$H respectively; H = height (m); W = weight (kg).

<table>
<thead>
<tr>
<th>Term</th>
<th>Step 1</th>
<th>Step 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant: coefficient</td>
<td>9.646</td>
<td>-12.874</td>
</tr>
<tr>
<td>W : coefficient</td>
<td>0.566</td>
<td>0.405</td>
</tr>
<tr>
<td>t-ratio</td>
<td>6.89</td>
<td>4.05</td>
</tr>
<tr>
<td>H : coefficient</td>
<td>19.4</td>
<td></td>
</tr>
<tr>
<td>t-ratio</td>
<td></td>
<td>2.33</td>
</tr>
<tr>
<td>R</td>
<td>0.887</td>
<td>0.909</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.786</td>
<td>0.827</td>
</tr>
<tr>
<td>S.E.E.</td>
<td>2.26</td>
<td>1.98</td>
</tr>
</tbody>
</table>
Table 7.13

Regression equations for predicting fat-free weight (FFW) from change in resonant frequency using coils with inductance (L) = 0.2 \( \times H \) (\( \Delta f_{R1} \)), 1 \( \times H \) (\( \Delta f_{R2} \)) and 10 \( \times H \) (\( \Delta f_{R3} \)), height (H) and weight (W). These results were obtained using a panel of width 22 cm as the central conductor in the test capacitor of model 3.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Equation</th>
<th>R</th>
<th>( R^2 )</th>
<th>S.E.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td>W and H</td>
<td>FFW = -12.9 + 0.405 W + 19.4 H</td>
<td>0.909</td>
<td>0.827</td>
<td>1.98</td>
</tr>
<tr>
<td>W and H with:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta f_{R1} )</td>
<td>FFW = -10.6 + 0.509 W + 19.7 H + 2.39 ( \Delta f_{R1} )</td>
<td>0.912</td>
<td>0.832</td>
<td>2.03</td>
</tr>
<tr>
<td>( \Delta f_{R2} )</td>
<td>FFW = - 7.6 + 0.672 W + 18.8 H + 3.20 ( \Delta f_{R2} )</td>
<td>0.921</td>
<td>0.849</td>
<td>1.92</td>
</tr>
<tr>
<td>( \Delta f_{R3} )</td>
<td>FFW = - 6.7 + 0.583 W + 18.3 H + 25.0 ( \Delta f_{R3} )</td>
<td>0.926</td>
<td>0.858</td>
<td>1.87</td>
</tr>
</tbody>
</table>
Changes in resonant frequency were measured with coils of inductance 1, 2.5, 10 and 25 \( \mu \)H; these values are designated as \( \Delta f_{R4} \), \( \Delta f_{R5} \), \( \Delta f_{R6} \) and \( \Delta f_{R7} \), respectively. A correlation matrix relating selected variables is shown in Table 7.14. The \( \Delta f_{R} \) values were strongly correlated with one another (\( r = 0.971 \) to 0.996), and more strongly correlated with total body weight (\( r = -0.846 \) to -0.887) than with FFW (\( r = -0.613 \) to -0.677) or FW (\( r = -0.831 \) to -0.848). This pattern of results is similar to that obtained when a panel, instead of a rod, was used as the central conductor in the capacitor (Table 7.11).

Table 7.15 shows the results of a stepwise regression of FFW on six predictors (\( \Delta f_{R4} \), \( \Delta f_{R5} \), \( \Delta f_{R6} \), \( \Delta f_{R7} \), H, W). The regression equation incorporated W, H and \( \Delta f_{R6} \) as significant variables (\( P < 0.05 \)). Replacement of \( \Delta f_{R6} \) with \( \Delta f_{R4} \), \( \Delta f_{R5} \) or \( \Delta f_{R7} \) caused only a slight reduction in \( R^2 \), as shown in Table 7.16.

The regression equation with the highest \( R^2 \) value (0.891) and lowest S.E.E. (1.63) involved W, H and \( \Delta f_{R6} \) as variables. The equation is:

\[
\text{FFW} = -4.39 + 0.690 \text{W} + 19.9 \text{H} + 37.6 \Delta f_{R6}
\]

where FFW = fat-free weight (kg)

\( \text{W} \) = body weight (kg)

\( \text{H} \) = height (m)

\( \Delta f_{R} \) = change in resonant frequency (MHz), using \( L = 10 \mu \)H and

\( C_1 = 20 \text{ pF} \).

Using the mean values of W, H and \( \Delta f_{R6} \) from the group of subjects tested, the 95\% confidence intervals were calculated for the predicted FFW obtained from the regression equation above. Similarly, values
Table 7.14
Correlation matrix of variables related to measurements of electromagnetic field effect and estimates of body composition, height and weight for 17 female subjects. Measurements of the effect of subjects on the electromagnetic field relate to the test capacitor of model 3 with a rod as the central conductor.

<table>
<thead>
<tr>
<th></th>
<th>FW</th>
<th>Δf_{R4}</th>
<th>Δf_{R5}</th>
<th>Δf_{R6}</th>
<th>Δf_{R7}</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW</td>
<td>0.413</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δf_{R4}</td>
<td>-0.677</td>
<td>-0.831#</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δf_{R5}</td>
<td>-0.639</td>
<td>-0.843#</td>
<td>0.994#</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δf_{R6}</td>
<td>-0.636</td>
<td>-0.848#</td>
<td>0.983#</td>
<td>0.995#</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δf_{R7}</td>
<td>-0.613</td>
<td>-0.832#</td>
<td>-0.971#</td>
<td>0.987#</td>
<td>0.996#</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>0.790*</td>
<td>0.332</td>
<td>-0.641</td>
<td>-0.607</td>
<td>-0.610</td>
<td>-0.610</td>
</tr>
<tr>
<td>W</td>
<td>0.872#</td>
<td>0.806#</td>
<td>-0.887#</td>
<td>-0.868#</td>
<td>-0.869#</td>
<td>-0.846#</td>
</tr>
</tbody>
</table>

* P < 0.001
# P < 0.0001

H = height (m); W = weight (kg); FFW and FW = fat-free weight (kg) and FW (kg) respectively, based on densitometry; Δf_{R4}, Δf_{R5}, Δf_{R6} and Δf_{R7} = change in resonant frequency (MHz) using coils with inductance (L) = 1, 2.5, 10 and 25 μH, respectively.
Table 7.15

Stepwise regression of fat-free weight (FFW) on six predictor variables (\( \Delta f_{R4} \), \( \Delta f_{R5} \), \( \Delta f_{R6} \), \( \Delta f_{R7} \), H, W) for 17 subjects measured in the test capacitor of model 3 with a rod as the central conductor.

\( \Delta f_{R4} \), \( \Delta f_{R5} \), \( \Delta f_{R6} \) and \( \Delta f_{R7} \) = change in resonant frequency for coils with inductance (L) = 1, 2.5, 10 and 25 \( \mu \)H, respectively; H = height (m); W = weight (kg).

<table>
<thead>
<tr>
<th>Term</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant: coefficient</td>
<td>9.646</td>
<td>-12.874</td>
<td>-4.387</td>
</tr>
<tr>
<td>W: coefficient</td>
<td>0.566</td>
<td>0.405</td>
<td>0.690</td>
</tr>
<tr>
<td>t-ratio</td>
<td>6.89</td>
<td>4.05</td>
<td>5.24</td>
</tr>
<tr>
<td>H: coefficient</td>
<td></td>
<td>19.4</td>
<td>19.9</td>
</tr>
<tr>
<td>t-ratio</td>
<td></td>
<td>2.33</td>
<td>2.90</td>
</tr>
<tr>
<td>( \Delta f_{R6} ): coefficient</td>
<td></td>
<td></td>
<td>38.0</td>
</tr>
<tr>
<td>t-ratio</td>
<td></td>
<td></td>
<td>2.77</td>
</tr>
<tr>
<td>R</td>
<td>0.872</td>
<td>0.909</td>
<td>0.944</td>
</tr>
<tr>
<td>R²</td>
<td>0.760</td>
<td>0.827</td>
<td>0.891</td>
</tr>
<tr>
<td>S.E.E.</td>
<td>2.26</td>
<td>1.98</td>
<td>1.63</td>
</tr>
</tbody>
</table>
Table 7.16

Regression equations for predicting fat-free weight (FFW) from change in resonant frequency ($\Delta f_R$) using coils with inductance ($L$) = 1 $\mu$H ($\Delta f_{R4}$), 2.5 $\mu$H ($\Delta f_{R5}$), 10 $\mu$H ($\Delta f_{R6}$) and 25 $\mu$H ($\Delta f_{R7}$), height ($H$) and weight ($W$). These results were obtained using a rod as the central conductor in the test capacitor of model 3.

<table>
<thead>
<tr>
<th>Predictor variables</th>
<th>Equation</th>
<th>$R$</th>
<th>$R^2$</th>
<th>S.E.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$, $H$, $\Delta f_{R6}$</td>
<td>FFW = -4.39 + 0.690 $W$ + 19.9 $H$ + 37.6 $\Delta f_{R6}$</td>
<td>0.944</td>
<td>0.891</td>
<td>1.63</td>
</tr>
<tr>
<td>$W$, $H$, $\Delta f_{R4}$</td>
<td>FFW = -11.2 + 0.580 $W$ + 20.8 $H$ + 12.2 $\Delta f_{R4}$</td>
<td>0.938</td>
<td>0.880</td>
<td>1.72</td>
</tr>
<tr>
<td>$W$, $H$, $\Delta f_{R5}$</td>
<td>FFW = -5.45 + 0.678 $W$ + 19.8 $H$ + 17.3 $\Delta f_{R5}$</td>
<td>0.941</td>
<td>0.886</td>
<td>1.67</td>
</tr>
<tr>
<td>$W$, $H$, $\Delta f_{R7}$</td>
<td>FFW = -5.29 + 0.653 $W$ + 20.6 $H$ + 55.0 $\Delta f_{R7}$</td>
<td>0.943</td>
<td>0.890</td>
<td>1.65</td>
</tr>
</tbody>
</table>
for the 95% confidence intervals were calculated using $W$, $H$ and $\Delta R$ values corresponding to $+1$ and $+2$ standard deviations (s.d.) from the mean for each variable. These results are presented in Table 7.17 to illustrate the range in which this regression equation predicts FFW values.

Relationships between FFW values predicted from electromagnetic field effects (using the prediction equation above), body density, skinfold thickness and $W/H^2$ (weight/height$^2$), together with $H^2/R$ (height$^2$/resistance) using measurements from the bioelectric impedance analyser, are listed in Table 7.18. The correlation ($r = 0.944$) between FFW values based on body density and electromagnetic field effects (using the prediction equation derived from body density measurements) has already been reported in Table 7.16. There is a significant ($P < 0.0001$) correlation between FFW based on body density, the reference method, and FFW predicted from skinfold thickness ($r = 0.918$) and $W/H^2$ ($r = 0.912$). FFW predicted from electromagnetic field effect was strongly correlated with estimates based on skinfold thickness ($r = 0.937$) and $W/H^2$ ($r = 0.967$) and less strongly, but still significantly ($P < 0.001$) correlated ($r = 0.735$) with $H^2/R$ which is related to FFW (Hoffer et al. 1969; Lukasik et al. 1985; Segal et al. 1985).

F. DISCUSSION

The first part of this chapter dealt with the testing of three test capacitor models, to find the best shape, size and positioning of plates, and the combinations of $C_1$ and $L$ which produced the largest
Table 7.17

Predicted fat-free weights (FFW) together with 95% confidence intervals for the mean and the individual. Results are calculated from weight (W), height (H) and change in resonant frequency ($\Delta f_R$) using coil inductance ($L$) = 10 $\mu$H ($\Delta f_{R6}$), corresponding to mean values for the group of subjects tested, and to H, W and $\Delta f_{R6}$ values which are +1 s.d. and +2 s.d. from the mean for each of the variables.

Prediction equation:

$$\text{FFW} = -4.39 + 0.690 \, W + 19.9 \, H + 37.6 \, \Delta f_{R6}$$

$\text{FFW (kg)}$, $W$ (kg), $H$ (m), $\Delta f_{R6}$ (MHz).

| H, W and $\Delta f_{R6}$ values | Predicted FFW (kg) | 95% confidence intervals |  |
|-------------------------------|-------------------|--------------------------|
|                               | mean              | mean (kg) | individual (kg) |  |
|                               | 41.8              | ±0.9      | ±3.3           |  |
| +1 s.d. from mean             | 45.8              | ±1.3      | ±3.8           |  |
| +2 s.d. from mean             | 50.1              | ±2.2      | ±4.1           |  |
Table 7.18

Correlation matrix for calculated fat-free weights based on prediction equation from electromagnetic field effect, densitometry and anthropometry. Values for height$^2$/resistance are also included for comparison. Results relate to 17 female subjects, and electromagnetic field effect was measured as change in resonant frequency ($\Delta f_R$) in the test capacitor of model 3 with a rod as the central conductor, and coil inductance ($L$) = 10 $\mu$H.

<table>
<thead>
<tr>
<th></th>
<th>FFW(EFE)</th>
<th>FFW(D)</th>
<th>FFW(Skf)</th>
<th>FFW(W/H$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFW(D)</td>
<td>0.944#</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFW(Skf)</td>
<td>0.937#</td>
<td>0.918#</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFW(W/H$^2$)</td>
<td>0.967#</td>
<td>0.912#</td>
<td>0.973#</td>
<td></td>
</tr>
<tr>
<td>$H^2/R$</td>
<td>0.735*</td>
<td>0.826#</td>
<td>0.717</td>
<td>0.658</td>
</tr>
</tbody>
</table>

* $P < 0.001$
# $P < 0.0001$

FFW(EFE), FFW(D), FFW(Skf) and FFW(W/H$^2$) = fat-free weight (kg)
predicted from electromagnetic field effect (using regression equation 
FFW = $-4.39 + 0.690 W + 19.9 H + 37.6 \Delta f_R$), densitometry, skinfold thickness (Durnin and Womersley (1974) and weight/height$^2$ (Womersley and Durnin 1977), respectively; $H^2/R =$ height$^2$/resistance (cm$^2$/ohm)
where resistance is measured with a bioelectric impedance analyser.
maximum δQ values for a test subject. The results are summarized in Table 7.19.

The first design was chosen for its simplicity and because it contained an essentially uniform field between the plates. Any irregularities in the field would have been caused by small distortions in the plates, and fringing effects which had been minimized by the presence of the guard ring. This meant that the effect on the electromagnetic field caused by the presence of a subject was not influenced by the positioning of the subject, provided the central region of the capacitor was occupied where the field was uniform. A disadvantage of this model was that the field extended into the region outside the plates making the equipment sensitive to extraneous interference, caused by people or equipment situated near the plates. One solution to this problem may have been to shield the equipment, but the relatively low δQ values obtained with model 1 suggested that a change in design was indicated.

There was a marked increase in δQ values (Table 7.19) when model 2 was tested. As the parallel plates were earthed, there was less interference caused by movement near the equipment, but new problems were created. As the field radiated out from the rod or end-panel towards the parallel plates, it was most concentrated close to the rod or end-panel. To achieve large δQ values, it was necessary for the subject to stand as close as possible to the rod or end-panel. Any slight movement or swaying by the subject caused fluctuations in the δQ value, so the equipment was extremely sensitive to subject positioning. The coefficient of variation for repeated readings was reduced (from 2.8% to 1.5%) when the rod was replaced with end-panels which were wider, but this did not solve the problem sufficiently.
Table 7.19

Summary of conditions resulting in the largest maximum values of change in $Q$ ($\Delta Q$) for a test subject in each model. $L$ = coil inductance; $C_1$ = variable capacitance.

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Max. $\Delta Q$</th>
<th>$L$ (H)</th>
<th>$C_1$ (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>parallel plates</td>
<td>-61</td>
<td>500</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>($d = 40$ cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>rod</td>
<td>-171</td>
<td>25</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>panel (15 x 170 cm)</td>
<td>-201</td>
<td>25</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>rod</td>
<td>-195</td>
<td>25</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>panel (22 x 170 cm)</td>
<td>-203</td>
<td>25</td>
<td>500</td>
</tr>
</tbody>
</table>
Interference was also caused by movement of the operator who worked near the rod or end-panel, but this was minimized by moving the rod or end-panel in between the parallel plates.

When model 3 was tested, there was a slight increase in \( \Delta Q \) (Table 7.17) and a marked improvement in the problems caused by subject positioning. This was reflected in the smaller coefficient of variation (approximately 0.3\%) for repeated readings using this model. Less variation existed because the subject was supine and able to lie motionless, in a fixed position, while measurements were made. Another advantage of this model was that, except near the open ends, the field was contained within the cylinder; movement near the cylinder exterior had no effect on \( Q \). For these reasons, model 3 appeared to be the best of the three models tested.

When it was realized that introduction of measured quantities of absorbing materials into the test capacitor caused characteristic changes in the resonant frequency of the system (Figure 7.8), the possibility of measuring \( \Delta f_R \), instead of \( \Delta Q \), to quantitate the effect on the electromagnetic field, was explored. The coefficient of variation for repeated readings was reduced (to approximately 0.2\%) and readings could be easily and accurately (± 0.001 MHz) obtained from a digital frequency meter. Further investigation of this model involved testing with measured quantities of materials, such as meat and fat, which showed that meat caused a larger change in resonant frequency than fat (Figure 7.13). As meat is a tissue with a high water content, and fat is a low water content tissue, meat has a larger dielectric constant and a greater conductivity (Johnson and Guy 1972; Pethig 1979). Therefore, compared with fat, meat would have a
greater effect on the electromagnetic field, causing a larger $\Delta f_R$ value per kilogram.

From measurements of human subjects in the test capacitor of model 3, it appeared that $\Delta f_R$ values were more strongly related to total body weight ($r = -0.85$ to $-0.94$) than to measures of FPW ($r = -0.61$ to $-0.79$) and FW ($r = -0.77$ to $-0.85$) based on body density (Tables 7.11 and 7.14). An explanation for these findings is that changes in the electromagnetic field are differentially related to the amounts of fat and fat-free tissue in the body; neither fat nor fat-free tissue is solely responsible for the $\Delta f_R$ value.

Using measurements of subjects in the test capacitor of model 3 with a panel as the central conductor, multiple regression analysis revealed that the best equation ($R^2 = 0.827$, S.E.E. = 1.98) for predicting FPW based on densitometry, involved the variables weight and height, and that addition of $\Delta f_R$ values as separate independent variables did not achieve statistical significance (Table 7.13). When a rod was used as the central conductor, however, the best equation ($R^2 = 0.891$, S.E.E. = 1.63) for predicting FPW incorporated weight, height and $\Delta f_R$ where a coil of inductance 10 $\mu$H was used. The regression equation is:

$$FPW = -4.39 + 0.690W + 19.9H + 37.6 \Delta f_R$$

where $FPW =$ fat-free weight (kg)

$W =$ body weight (kg)

$H =$ height (m)

$\Delta f_R =$ change in resonant frequency (MHz) using $L = 10$ $\mu$H and $C_1 = 20$ pF.
As shown in Table 7.16, use of coils with inductances of 1, 2.5 and 25 \*H, instead of 10 \*H, caused only small decreases in $R^2$ and small increases in S.E.E. values. FFW is calculated as the difference between total body weight and FFW.

The advantages of this method over laboratory methods such as densitometry, total body water and total body potassium, for estimating body composition, is that it is rapid, safe and noninvasive, and causes little inconvenience to the subject. In calibrating the equipment, it was necessary to use body composition estimates based on body density as the reference. Apart from errors in measuring body density and lung volume, the accuracy of the estimated value for FFW is limited by the assumptions concerning the constancy of the density of the fat-free body compartment (Bakker and Struijenkamp 1977; Siri 1956; Wedgwood 1963).

As shown in Figure 7.12, there is a problem related to the radial positioning of the absorbing material within the test capacitor of model 3, especially if a rod is used as the central conductor. This arises because the field within the cylinder is not uniform; it is most concentrated near the central rod. The extent to which this effect is important when measuring subjects is questionable. Although there are interindividual differences in body shape and in the distribution of fat and fat-free tissues, the body causes distortion of the electromagnetic field in the test capacitor. Therefore effects resulting from extreme re-arrangements of containers of meat may be an exaggeration of the effects caused by different body shapes. Further work with phantoms or with a number of subjects who have similar body compositions but different shapes, may clarify these problems.
As the test capacitor was resonated with an inductance connected in series, and was not itself a resonance structure, there was inefficient use of available energy. In model 3, the spacing between the inner and outer conductors was large (35 cm) which meant that the test capacitor could not be easily matched with leads from the generator. This mismatching caused loss of efficiency. Another problem with this design was that, in contrast to the generator which provided balanced output terminals, the test capacitor was unbalanced because the outer cylinder was earthed. The use of a converter would improve this situation by converting from the balanced mode of transmission of the generator to the unbalanced mode of transmission of the test capacitor. This would result, however, in a loss of efficiency and leakage to the outside.
CHAPTER 8

DEVELOPMENT OF A RESONATING CHAMBER SUITABLE FOR
DETERMINING BODY COMPOSITION

A. INTRODUCTION

Following the development of three types of test capacitor suitable
for determining human body composition, there evolved a fourth model,
based on different principles to the previous three.

The new design, called a resonating chamber, consisted of an enclosed
aluminium cylinder with a conducting copper rod running longitudinally
through the centre of the chamber. It was operated at frequencies in
the very high frequency (VHF) band and was tuned to various
characteristic modes of resonance. As a background to this model, the
principles of antenna function, transmission lines, standing wave
patterns and amplitude modulation are described.

1. Antenna Function

A transmitted wave, consisting of a combination of magnetic (H) and
electric (E) fields, is established about an antenna as a result of an
electric current flowing in the antenna. During the rapid transfer of
energy from one field to another, fields become detached from the
transmitting antenna and are radiated into space. When the field
encounters another antenna, some of the energy in the field induces a current in the receiving antenna.

2. Transmission Lines

A transmission line is an arrangement of two conductors that can be used to transmit electromagnetic energy. In an ideal, lossless transmission line, an inductance arises from the net magnetic flux in the space between the two conductors, and a capacitance is developed from the electrostatic capacitance between the conductors (Blum and Roller 1982; Zahn 1979).

When a voltage is applied to one end of a transmission line, it propagates down the line. Propagating with it is the current wave which creates a magnetic field perpendicular to the current and to the electric field between the conductors. Therefore, an electromagnetic disturbance propagates down the space around and between the conductors (Blum and Roller 1982).

These transmission-line waves are called transverse electromagnetic (TEM) waves because they have no component in the direction of propagation. Mathematically they can be considered as a travelling waveform, and physically they can be viewed as a set of field lines of varying density and polarity propagating at the speed of light (Blum and Roller 1982).
3. Standing Wave Patterns

When electrical impulses of appropriate frequencies are fed into the enclosed chamber of model 4 (Figure 8.1), a succession of pulses or waves at equal intervals travels the length of the chamber. The arrangement of electromagnetic waves is similar to that in a coaxial transmission line which is terminated with a plate at each end. When reflected from a terminated end, or end-plate, the reflected waves meet the oncoming waves of the same wavelength. At some points the waves which meet reinforce each other to produce a region where the electric field is a maximum, and at other points, called nodes, the waves cancel each other. The pattern thus established is called a stationary or standing wave because it does not propagate along the conductor. Energy trapped within a 'lossless' system such as this is held in one or more of the allowable modes of the chamber, which is said to be resonating.

Theoretically, with a chamber measuring 2 m in length, a single standing wave is produced at a frequency of 150 MHz. At 75 MHz and 300 MHz respectively, different modes are excited, resulting in the formation of a half-standing wave and two standing waves in the chamber. These modes are illustrated in Figure 8.1.

4. Amplitude Modulation

The process called modulation describes the control of certain aspects of one alternating current (AC) signal by another. Amplitude modulation (AM) occurs when a modulating signal is superimposed onto a
H = magnetic field; E = electric field; f = frequency.

Figure 8.1
(a) Diagram of the enclosed resonating chamber of model 4.
(b) Standing wave patterns produced in the resonating chamber at 75, 150 and 300 MHz.
controlled signal called the carrier; the modulating signal then controls the amplitude of the carrier.

When the form of the modulating signal is a sine wave, the amplitude of the amplitude-modulated carrier varies sinusoidally about its unmodulated value. An expression (Erickson and Bryant 1959) for the amplitude-modulated carrier is:

\[ a = E (1 + A \sin 2\pi f_a t) \sin 2\pi f_c t \]

where:
- \( e \) = amplitude-modulated carrier signal
- \( E \) = amplitude of carrier signal
- \( f_c \) = frequency of carrier signal
- \( A \) = amplitude of modulating signal
- \( f_a \) = frequency of modulating signal
- \( t \) = time

When \( A = 1 \), the modulated carrier has an amplitude which ranges from zero to twice its unmodulated value, producing a modulation described as 100%.

B. EQUIPMENT

A view of model 4 is shown in Plate 8.1. Sheet aluminium was formed into two large cylinder halves measuring 2 m in length and 69 cm in diameter. The cylinder halves were pop-rivetted to rigid L-shape aluminium beams running the length of, and external to, the cylinder. The beams were secured with flat edges together using wing-nuts to
Plate 8.1
Photograph of model 4: The large cylindrical chamber can be seen with circular end-plates in position, enclosing the chamber.
ensure continuous electrical contact between the halves along the cylinder length.

To enclose the chamber, circular end-plates were fashioned to match the cylinder ends, and a spring-loaded fitting action was effected by flanges around the end-plate which gripped the cylinder wall when the end-plate was mounted.

Running longitudinally through the centre of the chamber was a hollow copper rod which made contact with the end-plates by sliding through an aluminium boss mounted on the inside of each end-plate. At each end the rod projected through the end-plate and was secured by a screw which fitted into a thread in the end of the rod.

Inside the chamber, the rod was mounted on a wooden trolley constructed of pine and glue. The trolley rolled into the chamber on six plastic wheels running on hard-wood rails mounted on a pine supporting frame inside the chamber. In Plate 8.2 the rails and supporting frame can be seen inside the chamber. Plate 8.3 shows the trolley which rolled onto an external platform when wheeled out of the chamber.

Figure 8.2 shows a block diagram of the equipment. The system was driven by a VHF signal generator (model 365A, Airmec Instruments Ltd., Buckinghamshire, England); the carrier signal was amplitude-modulated by being superimposed onto a 1 kHz wave, and signal frequency was measured with an electronic counter (model 5243L fitted with a converter, model 5253B, Hewlett-Packard Co., California, U.S.A.).
Plate 8.2

Model 4: View of the chamber interior. Hard-wood rails are mounted on a pine supporting frame.
Plate 8.3

Model 4: With the end-plate removed, the trolley could be rolled out of the chamber and onto an external platform.
Figure 8.2

Block diagram of the equipment used in model 4, the resonating chamber.
A variety of antennae for transmitting and receiving signals was tested until suitable shapes, sizes and positions were found permitting detection of signals when the chamber was empty and when it was occupied by a subject. Two antennae designs which were found to be suitable are illustrated below:

The rectangular antennae were mounted on the end-plates of the chamber, 16 cm below the central rod (end-antennae), and the oblong antennae were fixed to the lower side of the chamber, 49 cm in from the end-plates (side-antennae).

The received signal was passed through a crystal detector (model 8470B, Hewlett-Packard, California, U.S.A.) which filtered out the high frequencies thereby demodulating the signal, and was finally received by a voltage indicator (Standing Wave Indicator, model 415B, Hewlett-Packard, California, U.S.A.).

As signal frequency was scanned, resonance was detected as a maximum in the strength of the received signal as indicated on the voltage indicator. For each measurement, the amplitude of the modulated carrier was set to 50%, because this produced suitable deflections on the voltage indicator at the operating frequencies.
C. METHODS

Using the end-antennae, resonance was detected in the empty chamber at 73 MHz, and with the side-antennae, the resonant frequency was too high to be detected with the available equipment, but was calculated to be approximately 300 MHz. It was therefore decided to measure the frequency and strength of a signal in the chamber under resonance conditions with a fixed (reference) quantity of water in the chamber in plastic containers. This allowed a reference measurement to be made at the high resonant frequency prior to admitting a subject into the chamber. Since, in the measurement of body composition, the effects on the electromagnetic field are produced mainly by water molecules, it was decided to use water as the reference, and because this water is present effectively as a saline solution, 20 L of 0.9% saline was used as the reference signal-absorbing 'body' in the chamber. The saline was contained in four 5L-plastic containers which were placed in marked positions on the trolley, and the resonant frequency and signal strength were measured in the chamber at the beginning of each experimental session. The $\Delta f_R$ and $\Delta A$ values for samples of substances or for subjects were then calculated using the reference values for baselines as follows:

i. The empty capacitor was tuned to resonant frequency using the end-antennae, and the voltage indicator was set to 30 dB.

ii. Saline (20 L) was placed in the chamber which was then tuned to resonance using either the end- or side-antennae. Resonant frequencies and decibel levels on the voltage indicator (signal strength at resonance) were determined three times and the mean
values were used as the baseline reference frequencies \( (f_b) \) and the baseline reference decibel levels \( (dB_b) \).

iii. The saline was removed from the chamber which was then occupied by a sample or subject, and the chamber was again brought to resonance using first the end- and then the side-antennae. Resonant frequencies and decibel levels were determined three times and the mean values were used to represent \( f_s \) and \( dB_s \) where the subscript, \( s \), represents sample or subject.

iv. For each antennae set:

\[
\Delta f_R = f_s - f_b
\]

\[
\Delta A = \text{antilog} \left( \frac{dB_b - dB_s}{20} \right)
\]

Subjects were asked to empty their pockets of metallic objects, such as loose change and keys, and to remove continuous bands of metal, such as rings, bangles and watches.

The following experiments were performed:

1. Effect on the electromagnetic field of changing the quantities and combinations of meat and fat in the chamber.

2. Effect of subjects with different body composition on the electromagnetic field in the chamber: Preliminary study.

3. Measurement of power density in the chamber.
4. Effect of subjects with measured body composition on the electromagnetic field in the chamber.

5. Reproducibility of electromagnetic field effect measurements.

D. RESULTS

1. Effect on the Electromagnetic Field of Changing the Quantities and Combinations of Meat and Fat in the Chamber

This investigation involved the use of 500 g lots of meat and fat in containers as described in chapter 7, section D. To determine the effect of changing the combinations of meat and fat, 32, 38 and 44 kg meat were each placed in the chamber with 0, 6 and 12 kg fat, and $\Delta f_R$ and $\Delta A$ were determined using the end- and side-antennae. These combinations of quantities gave the mixtures shown in Table 8.1, where total weight = weight of meat + weight of fat.

Initial tests showed that measured changes in the electromagnetic field were caused by the position of absorbing materials inside the chamber. Therefore, in order to study the effects of increasing the quantities of meat or fat in the chamber, the experiments were designed so that materials were added in symmetrical patterns.

A total of 112 containers was placed in the chamber in 4 columns of 14 containers, parallel to the central conducting rod and stacked two containers high. Increments of meat and fat were added to an initial quantity of 32 kg meat. Meat or fat was added in 6 kg lots (12 containers) placed evenly throughout the length and width of the
### Table 8.1

The composition of various combinations of meat and fat placed in the chamber of model 4. Total weight = weight of meat + weight of fat.

<table>
<thead>
<tr>
<th>weight of meat (kg)</th>
<th>weight of fat (kg)</th>
<th>total weight (kg)</th>
<th>% fat</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>0</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>32</td>
<td>6</td>
<td>38</td>
<td>16</td>
</tr>
<tr>
<td>32</td>
<td>12</td>
<td>44</td>
<td>27</td>
</tr>
<tr>
<td>38</td>
<td>0</td>
<td>38</td>
<td>0</td>
</tr>
<tr>
<td>38</td>
<td>6</td>
<td>44</td>
<td>14</td>
</tr>
<tr>
<td>38</td>
<td>12</td>
<td>50</td>
<td>24</td>
</tr>
<tr>
<td>44</td>
<td>0</td>
<td>44</td>
<td>0</td>
</tr>
<tr>
<td>44</td>
<td>6</td>
<td>50</td>
<td>12</td>
</tr>
<tr>
<td>44</td>
<td>12</td>
<td>56</td>
<td>21</td>
</tr>
</tbody>
</table>
chamber. In this way, meat or fat was added to the chamber in a longitudinally and radially symmetrical pattern. Figures 8.3 and 8.4 show the effects on $\Delta f_R$ and $\Delta A$ of increasing the amounts of meat or fat in the chamber, with measurements made using the side-antennae. Similar graphs were obtained using the end-antennae. With both antennae sets, the electromagnetic field effects were greater with meat than with fat.

Figures 8.5 and 8.6 show the families of lines produced with the side-antennae when $\Delta f_R$ and $\Delta A$ are plotted against the weight of meat for different combinations of meat and fat. In both figures, a separate line represents a particular total weight. The slopes are due to the increasing electromagnetic field effect with increments of meat, while vertical distances between lines represent the electromagnetic field effect due to differences in the quantity of fat.

Using these results as a model, it appeared that measurements of $\Delta f_R$ or $\Delta A$, together with total body weight, allowed determination of the fat-free weight (FFW) of the body. The containers of meat and fat, however, were placed in a symmetrical pattern of constant total length, which does not satisfactorily represent the variation in human body shape. Therefore this model may need to be modified when applied to normal human subjects where the distribution of fat and fat-free tissue will vary with body shape and composition.
Figure 8.3

The effect on the change in resonant frequency ($\Delta f_R$) with increasing quantities of meat or fat in the chamber of model 4. Increments of meat and fat were made from a base level of 32 kg meat. Measurements were made using side-antennas.
Figure 8.4

The effect on the change in attenuation ($\Delta A$) with increasing quantities of meat or fat in the chamber of model 4. Increments of meat and fat were made from a base level of 32 kg meat. Measurements were made using side-antennae.
Figure 8.5

Relationship between the change in resonant frequency ($\Delta f_R$) and weight of meat for different combinations of meat and fat. Measurements were made in model 4 using side-antennae.
Figure 8.6
Relationship between the change in attenuation (ΔA) and weight of meat for different combinations of meat and fat. Measurements were made in model 4 using side-antennae.
2. Effect of Subjects with Different Body Composition on the

Electromagnetic Field in the Chamber: Preliminary Study

In this section a pilot study with a small group of subjects (15) was
carried out to determine the effect of human bodies of varying
composition on the electromagnetic field in the chamber.
Anthropometric data were used to estimate the body composition of the
subjects. Table 8.2 lists the ages and anthropometric data of the 15
healthy female University staff and students who participated in the
study.

Height and weight were measured to the nearest 0.1 cm and 100 g
respectively. Percent fat, calculated from weight/height$^2$ (W/H$^2$)
(kg/m$^2$) according to Womersley and Durnin (1977), was converted to
kilograms of fat-free weight (FFW) and fat weight (FW). Values for
$\Delta f_R$ and $\Delta A$ were measured in the resonating chamber with the end- and
side-antennae.

Table 8.3 shows the correlation coefficients relating selected
variables. The $\Delta f_R$ and $\Delta A$ values were inversely related to FFW and FW
calculated from measurements of height and weight. The strongest
correlation between measured electromagnetic field effects and FFW of
the subjects was displayed by $\Delta A$ values measured with the side-
antennae ($r = -0.952$); the correlation of $\Delta A$ measured with the end-
antennae and FFW did not achieve statistical significance ($P > 0.05$).
Of the two $\Delta f_R$ values, measurements made with the side-antennae were
more strongly correlated with FFW ($r = -0.717$) than were measurements
made with the end-antennae ($r = -0.616$). The $\Delta A$ values measured with
the side-antennae were also strongly correlated with FW ($r = -0.910$)
and with total body weight ($r = -0.952$).
Table 8.2

Mean, standard deviation and range for age and anthropometric data of 15 females in a preliminary study of the effect of human bodies on the electromagnetic field in model 4.

<table>
<thead>
<tr>
<th></th>
<th>Mean ± s.d.</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>27.3 ± 9.4</td>
<td>19 - 49</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.656 ± 0.063</td>
<td>1.562 - 1.787</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>60.0 ± 11.65</td>
<td>44.8 - 86.2</td>
</tr>
<tr>
<td>W/H² (kg/m²)</td>
<td>21.8 ± 3.61</td>
<td>17.3 - 29.7</td>
</tr>
<tr>
<td>% fat from W/H²**</td>
<td>25.5 ± 6.11</td>
<td>17.7 - 38.5</td>
</tr>
</tbody>
</table>

* W/H² = weight/height²

** Womersley and Durrin (1977)
Table 8.3

Correlation matrix for variables related to measurements of electromagnetic field effects in model 4 and anthropometry for 15 female subjects.

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>W</th>
<th>% fat</th>
<th>FFW</th>
<th>FW</th>
<th>Δf_R(e)</th>
<th>Δf_R(s)</th>
<th>ΔA(e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>0.542</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% fat</td>
<td>0.349</td>
<td>0.952#</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFW</td>
<td>0.668</td>
<td>0.963#</td>
<td>0.848*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FW</td>
<td>0.428</td>
<td>0.982#</td>
<td>0.983#</td>
<td>0.893#</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δf_R(e)</td>
<td>-0.231</td>
<td>-0.651</td>
<td>-0.585</td>
<td>-0.616</td>
<td>-0.646</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δf_R(s)</td>
<td>-0.610</td>
<td>-0.640</td>
<td>-0.598</td>
<td>-0.717</td>
<td>-0.557</td>
<td>0.184</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔA(e)</td>
<td>-0.007</td>
<td>-0.471</td>
<td>-0.439</td>
<td>-0.451</td>
<td>-0.464</td>
<td>0.831*</td>
<td>0.104</td>
<td></td>
</tr>
<tr>
<td>ΔA(s)</td>
<td>-0.612</td>
<td>-0.952#</td>
<td>-0.881#</td>
<td>-0.952#</td>
<td>-0.910#</td>
<td>0.571</td>
<td>0.674</td>
<td>0.366</td>
</tr>
</tbody>
</table>

* P < 0.001
# P < 0.0001

H = height (m); W = weight (kg); % fat calculated from W/H² (Womersley and Durmin 1977); FFW and FW = fat-free weight (kg) and FW (kg) calculated from % fat derived from W/H² (Womersley and Durmin 1977); Δf_R(e) and Δf_R(s) = change in resonant frequency (MHz) using end- and side-antennae, respectively; ΔA(e) and ΔA(s) = change in attenuation using end- and side-antennae, respectively.
There were poor correlations between the two sets of $\Delta f_R$ measurements obtained using the end- and side-antennae ($r = 0.184$), and between the two sets of $\Delta A$ measurements ($r = 0.366$). As the standing wave patterns established in the chamber differ for the frequencies used with the two types of antennae (Figure 8.1), it is possible that the relationships between the two sets of measurements of electromagnetic field effects were confused by a geometry problem resulting from differential effects of the variety of body shapes and sizes on the non-uniform field. It appeared that a combination of $\Delta f_R$ and $\Delta A$ might relate more strongly to body composition of subjects in the chamber.

3. Measurement of Power Density in the Chamber

Power density in the resonating chamber was determined by measuring the generator's power output with a power meter (model 435A, Hewlett-Packard, California, U.S.A.) and the surface area of the cylindrical portion of the chamber.

Using the end- and side-antennae, mean resonant frequencies ($f_R$) for the group of subjects in the preliminary study reported above, were 50 and 271 MHz for an occupied chamber. At these frequencies, the power output ($P$) of the generator was 0.45 and 0.30 mW respectively.

The surface area ($A$) of the cylindrical portion of the chamber was:

$$A = \pi \times d \times l$$

where $d =$ diameter of the chamber

$l =$ length of the chamber.
Therefore \( A = \pi \times 69 \times 200 \text{ cm}^2 \).

If \( P_d = \text{power density} \) and \( A = \text{surface area} \), then

\[
P_d = \frac{P}{A}
\]

At \( f = 50 \text{ MHz} \), \( P_d = 1.04 \times 10^{-5} \text{ mW/cm}^2 \) and at \( f = 271 \text{ MHz} \), \( P_d = 6.92 \times 10^{-6} \text{ mW/cm}^2 \).

The permissible exposure level for humans for frequencies in the range 30 - 300 MHz is 1.0 mW/cm² for 8 hr (Appendix B). This indicates that the exposure to radiation inside the resonating chamber was several orders of magnitude below the recommended safety level.

4. Effect of Subjects with Measured Body Composition on the Electromagnetic Field in the Chamber

In this part of the study, female subjects were measured in the resonating chamber using the end- and side-antennae, and results were compared with body composition estimates based on anthropometry, and measurements of body density and total body water. The group of 27 subjects was heterogeneous with respect to body composition and age, and, because this study was coincident with the validation study for biologic impedance measurements (chapter 5, section C), the protocol for this study is as outlined in that section. The ages and physical characteristics of the subjects are shown in Table 5.7.

Table 8.4 shows a correlation matrix relating electromagnetic field effects measured in the resonating chamber, body composition estimates
Table 8.4
Correlation matrix for variables related to measurements using model 4 and body composition estimates based on measurements of body density and total body water for 27 female subjects.

<table>
<thead>
<tr>
<th></th>
<th>FFW(D)</th>
<th>FW(D)</th>
<th>TSW</th>
<th>FFW(D+H)</th>
<th>FW(D+H)</th>
<th>Δf_R(e)</th>
<th>Δf_R(s)</th>
<th>ΔA(e)</th>
<th>ΔA(s)</th>
<th>H</th>
</tr>
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<tbody>
<tr>
<td>FW(D)</td>
<td>0.433</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>TSW</td>
<td>0.945#</td>
<td>0.602*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFW(D+H)</td>
<td>0.986#</td>
<td>0.524</td>
<td>0.986#</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FW(D+H)</td>
<td>0.462</td>
<td>0.997#</td>
<td>0.609*</td>
<td>0.542</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δf_R(e)</td>
<td>-0.590</td>
<td>-0.796#</td>
<td>-0.640*</td>
<td>-0.624*</td>
<td>-0.815#</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δf_R(s)</td>
<td>-0.394</td>
<td>0.034</td>
<td>-0.387</td>
<td>-0.396</td>
<td>0.040</td>
<td>0.131</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔA(e)</td>
<td>-0.350</td>
<td>-0.446</td>
<td>-0.337</td>
<td>-0.348</td>
<td>-0.467</td>
<td>0.811#</td>
<td>0.257</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔA(s)</td>
<td>-0.746#</td>
<td>-0.896#</td>
<td>-0.851#</td>
<td>-0.809#</td>
<td>-0.903#</td>
<td>0.836#</td>
<td>0.230</td>
<td>0.494</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>0.646*</td>
<td>0.154</td>
<td>0.605#</td>
<td>0.635*</td>
<td>0.167</td>
<td>-0.355</td>
<td>-0.384</td>
<td>-0.369</td>
<td>-0.438</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>0.730#</td>
<td>0.932#</td>
<td>0.835#</td>
<td>0.793#</td>
<td>0.942#</td>
<td>-0.840#</td>
<td>-0.130</td>
<td>-0.478</td>
<td>-0.979#</td>
<td>0.375</td>
</tr>
</tbody>
</table>

* P < 0.001, # P < 0.0001

H = height (m); W = weight (kg); FFW(D) and FW(D) = fat-free weight (kg) and fat weight (kg) respectively, based on densitometry; TSW = total body water (L) estimated from D_{2}O dilution; FFW(D+H) and FW(D+H) = fat-free weight (kg) and fat weight (kg) respectively, calculated as the mean of estimates based on body density and total body water; Δf_R(e) and Δf_R(s) = change in resonant frequency (MHz) using end- and side-antennae, respectively; ΔA(e) and ΔA(s) = change in attenuation using end- and side-antennae, respectively.
determined from measurements of body density and total body water, and height and weight. As in the preliminary study (Table 8.3), changes measured in the resonating chamber were inversely related to body weight, FFW and FW. FFW and FW were calculated from measurements of body density, FFW(D) and FW(D), or as the mean of estimates based on measurements of body density and total body water, FFW(D+W) and FW(D+W). The strongest correlations with FFW(D) and FFW(D+W) occurred with ΔA measured with the side-antennae (r = -0.745 and -0.809, respectively). A strong correlation (r = -0.851) was also found between total body water and ΔA measured with the side-antennae. Values of ΔA measured with the side-antennae were also strongly correlated with FW(D) (r = -0.896), FW(D+W) (r = -0.903) and total body weight (r = -0.979). The other parameter measured in the resonating chamber which displayed significant correlations (P < 0.001) with estimates of body composition, was ΔfR measured with the end-antennae, the strongest correlations being with FW(D) (r = -0.796) and FW(D+W) (r = -0.815).

The mean values, FFW(D+W) and FW(D+W), were used as dependent variables in developing regression equations for predicting FFW and FW from measurements of electromagnetic field effects in the resonating chamber. Stepwise regression analyses (Minitab, Inc. 1985. Version 5.1 for TOPS-20) were performed with an aim to maximizing the coefficient of determination (R²) and minimizing the standard error of estimate (S.E.E.). The following abbreviations are used for the independent variables: ΔfR(e) and ΔfR(s) = change in resonant frequency (MHz) measured with end- and side-antennae, respectively; ΔA(e) and ΔA(s) = change in attenuation measured with the end- and side-antennae, respectively; ΔdB(e) and ΔdB(s) = change in decibel level using end- and side-antennae, respectively; H = height (m) and
$W$ = weight (kg).

Table 8.5(a) shows results of a stepwise regression of FFW on eight predictor variables ($A_f_R(e)$, $A_f_R(s)$, $A_A(e)$, $A_A(s)$, $A_B(e)$, $A_B(s)$, $H$, $W$). The regression equation incorporated $A_A(s)$ and $H$ as significant ($P < 0.05$) variables ($R^2 = 0.752$, S.E.E. = 2.52). However, earlier experiments (chapter 8, section D) had shown that $A_A$ values resulted from the combined effects of FFW and FW. Therefore, if FFW is the dependent variable, total body weight should appear as an independent variable to account for the presence of fat in the chamber. If FW is the dependent variable (Table 8.5(b)), there is an increase in $R^2$ ($R^2 = 0.927$) and a decrease in S.E.E. (S.E.E. = 2.47), but only the variables $W$ and $H$ are included. If $A_f_R$, $A_A$ or $A_B$ values are included as separate independent variables, they do not achieve statistical significance ($P > 0.05$). As there is a strong correlation between $A_A(s)$ and $W$ ($r = -0.979$), $A_A(s)$ will not be added after $W$ into the regression equation with stepwise analysis because there will be no further significant decrease in the unexplained variance. To overcome this problem, several combinations of $A_A(s)$ with $W$ were tested, each combination as a separate independent variable.

Results of a stepwise regression of FW on eight predictor variables, which were the same as before except that $W$ was replaced with $W/A_A(s)$, are shown in Table 8.6. The best regression equation ($R^2 = 0.951$, S.E.E. = 2.12) was obtained when the following variables were included: $A_B(s)$, $H$, $A_f_R(e)$ and $W/A_A(s)$. Considering the number of subjects tested ($n = 27$), this equation contained too many predictor variables. The findings were improved when a stepwise regression analysis of FW was performed using the same predictors as before, except that $W/A_A(s)$ was replaced with $W/\sqrt{A_A(s)}$. Those results are
Table 8.5
Stepwise regression of (a) fat-free weight (FFW) and (b) fat weight (FW) on eight predictor variables ($\Delta f_R(e), \Delta f_R(s), \Delta A(e), \Delta A(s), \Delta dB(e), \Delta dB(s), H, W$) for 27 subjects measured in model 4. $\Delta f_R(e)$ and $\Delta f_R(s)$ = change in resonant frequency (MHz) measured with end- and side-antennae, respectively; $\Delta A(e)$ and $\Delta A(s)$ = change in attenuation measured with end- and side-antennae, respectively; $\Delta dB(e)$ and $\Delta dB(s)$ = change in decibel level with end- and side-antennae, respectively; H = height (m); W = weight (kg).

<table>
<thead>
<tr>
<th>Terms</th>
<th>Step 1</th>
<th>Step 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) FFW as dependent variable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant: coefficient</td>
<td>59.032</td>
<td>-2.33</td>
</tr>
<tr>
<td>$\Delta A(s)$: coefficient</td>
<td>-17.5</td>
<td>-14.2</td>
</tr>
<tr>
<td>t-ratio</td>
<td>-6.88</td>
<td>-5.81</td>
</tr>
<tr>
<td>H: coefficient</td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>t-ratio</td>
<td></td>
<td>3.06</td>
</tr>
<tr>
<td>$R$</td>
<td>0.809</td>
<td>0.867</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.655</td>
<td>0.752</td>
</tr>
<tr>
<td>S.E.E.</td>
<td>2.91</td>
<td>2.52</td>
</tr>
<tr>
<td>(b) FW as dependent variable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant: coefficient</td>
<td>-22.77</td>
<td>39.58</td>
</tr>
<tr>
<td>W: coefficient</td>
<td>0.683</td>
<td>0.742</td>
</tr>
<tr>
<td>t-ratio</td>
<td>14.02</td>
<td>17.24</td>
</tr>
<tr>
<td>H: coefficient</td>
<td></td>
<td>-41</td>
</tr>
<tr>
<td>t-ratio</td>
<td></td>
<td>-3.65</td>
</tr>
<tr>
<td>$R$</td>
<td>0.942</td>
<td>0.963</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.887</td>
<td>0.927</td>
</tr>
<tr>
<td>S.E.E.</td>
<td>3.02</td>
<td>2.47</td>
</tr>
</tbody>
</table>
Table 8.6
Stepwise regression of fat weight (FW) on eight predictor variables ($\Delta f_{R}(e)$, $\Delta f_{R}(s)$, $\Delta A(e)$, $\Delta A(s)$, $\Delta dB(e)$, $\Delta dB(s)$, $W/\Delta A(s)$, $H$) for 27 subjects measured in model 4 with end- and side-antennae. $\Delta f_{R}(e)$ and $\Delta f_{R}(s)$ = change in resonant frequency (MHz) measured with end- and side-antennae, respectively; $\Delta A(e)$ and $\Delta A(s)$ = change in attenuation measured with end- and side-antennae, respectively; $\Delta dB(e)$ and $\Delta dB(s)$ = change in decibel level measured with end- and side-antennae, respectively; $H$ = height (m); $W$ = weight (kg).

<table>
<thead>
<tr>
<th>Terms</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
<th>Step 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant : coefficient</td>
<td>17.32</td>
<td>105.82</td>
<td>100.75</td>
<td>90.94</td>
<td>81.00</td>
</tr>
<tr>
<td>$\Delta dB(s)$ : coefficient</td>
<td>-3.25</td>
<td>-3.69</td>
<td>-3.13</td>
<td>-1.38</td>
<td></td>
</tr>
<tr>
<td>t-ratio</td>
<td>-12.33</td>
<td>-17.26</td>
<td>-10.04</td>
<td>-1.58</td>
<td></td>
</tr>
<tr>
<td>$H$ : coefficient</td>
<td></td>
<td>-54.5</td>
<td>-55.1</td>
<td>-53.2</td>
<td>-50.5</td>
</tr>
<tr>
<td>t-ratio</td>
<td></td>
<td>-4.77</td>
<td>-5.24</td>
<td>-5.41</td>
<td>-5.05</td>
</tr>
<tr>
<td>$\Delta f_{R}(e)$ : coefficient</td>
<td></td>
<td></td>
<td>-0.49</td>
<td>-0.62</td>
<td>-0.79</td>
</tr>
<tr>
<td>t-ratio</td>
<td></td>
<td></td>
<td>-2.31</td>
<td>-2.98</td>
<td>-4.29</td>
</tr>
<tr>
<td>$W/\Delta A(s)$ : coefficient</td>
<td></td>
<td></td>
<td></td>
<td>0.085</td>
<td>0.145</td>
</tr>
<tr>
<td>t-ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.12</td>
</tr>
</tbody>
</table>

| R | 0.927 | 0.963 | 0.970 | 0.975 | 0.972 |
| $R^2$ | 0.859 | 0.928 | 0.941 | 0.951 | 0.946 |
| S.E.E. | 3.38  | 2.47  | 2.27  | 2.12  | 2.19  |
shown in Table 8.7. The best regression equation, i.e. with the highest \( R^2 \) value (0.956) and the lowest S.E.E. (1.97) was:

\[
FW = 73.48 + 0.291 \left( \frac{W}{\sqrt{\Delta A(s)}} \right) - 49.2 H - 0.53 \Delta f_R(e)
\]

where \( FW = \) fat weight (kg)

\( \Delta A(s) = \) change in attenuation measured with side-antennae

\( \Delta f_R(e) = \) change in resonant frequency (MHz) measured with end-antennae

\( W = \) body weight (kg)

\( H = \) height (m)

Despite the inclusion of \( \Delta f_R(e) \) as a variable which achieved statistical significance \( (P < 0.05) \), it can be omitted from the above regression equation with only a small change in \( R^2 \) and S.E.E. \( (R^2 \) decreases from 0.956 to 0.939; S.E.E. increases from 1.97 to 2.27).

Using the above regression equation and mean values of \( \Delta A(s), \Delta f_R(e), \)
\( W \) and \( H \) for the group of subjects tested, the 95\% confidence intervals were calculated for predicted \( FW \) values. Similarly, values for the 95\% confidence intervals were calculated using \( \Delta A(s), \Delta f_R(e), W \) and \( H \) values corresponding to +1 and +2 standard deviations (s.d.) from the mean for each variable. These results are shown in Table 8.8 to illustrate the range in which the regression equation predicts \( FW \) values.

\( FW \) can be calculated from electromagnetic field effects (EFE) as the difference between total body weight and fat weight predicted from the regression equation. In Table 8.9, values of \( FW \) predicted in this way have been compared with \( FW \) values estimated from a variety of
Table 8.7

Stepwise regression of fat weight (FW) on eight predictor variables ($\Delta f_R(e)$, $\Delta f_R(s)$, $\Delta A(e)$, $\Delta A(s)$, $\Delta dB(e)$, $\Delta dB(s)$, $W/\sqrt{A(s)}$, $H$) for 27 subjects measured in model 4 with end- and side-antennae. $\Delta f_R(e)$ and $\Delta f_R(s)$ = change in resonant frequency (MHz) measured with end- and side-antennae, respectively; $\Delta A(e)$ and $\Delta A(s)$ = change in attenuation measured with end- and side-antennae, respectively; $\Delta dB(e)$ and $\Delta dB(s)$ = change in decibel level measured with end- and side-antennae, respectively; $H$ = height (m); $W$ = weight (kg).

<table>
<thead>
<tr>
<th>Terms</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant : coefficient</td>
<td>-1.249</td>
<td>73.179</td>
<td>73.480</td>
</tr>
<tr>
<td>$W/\sqrt{A(s)}$ : coefficient</td>
<td>0.312</td>
<td>0.345</td>
<td>0.291</td>
</tr>
<tr>
<td>t-ratio</td>
<td>13.94</td>
<td>18.93</td>
<td>11.90</td>
</tr>
<tr>
<td>$H$ : coefficient</td>
<td></td>
<td>-47.1</td>
<td>-49.2</td>
</tr>
<tr>
<td>t-ratio</td>
<td></td>
<td>-4.57</td>
<td>-5.47</td>
</tr>
<tr>
<td>$\Delta f_R(e)$ : coefficient</td>
<td></td>
<td></td>
<td>-0.53</td>
</tr>
<tr>
<td>t-ratio</td>
<td></td>
<td></td>
<td>-2.93</td>
</tr>
<tr>
<td>$R$</td>
<td>0.941</td>
<td>0.969</td>
<td>0.978</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.886</td>
<td>0.939</td>
<td>0.956</td>
</tr>
<tr>
<td>S.E.E.</td>
<td>3.04</td>
<td>2.27</td>
<td>1.97</td>
</tr>
</tbody>
</table>
Table 8.8

Predicted fat weight (FW) values together with 95% confidence intervals for the mean and the individual. Results are calculated from the following values: change in attenuation measured with side-antennae (ΔA(s)), change in resonant frequency measured with end-antennae (Δf_R(e)), weight (W) and height (H) which correspond to the mean value for each variable for the group of subjects tested, and to ΔA(s), Δf_R(e), W and H values which are +1 and +2 standard deviations (s.d.) from the mean for each of the variables.

Prediction equation:

FW = 73.48 + 0.291 (W/√ΔA(s)) - 49.2 H - 0.53 Δf_R(e)

FW (kg), W (kg), H (m), Δf_R(e) (MHz).

| ΔA(s), Δf_R(e), H, W values | Predicted FW (kg) | 95% confidence intervals
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>20.4</td>
<td>±0.8</td>
</tr>
<tr>
<td>+1 s.d. from mean</td>
<td>27.7</td>
<td>±1.3</td>
</tr>
<tr>
<td>+2 s.d. from mean</td>
<td>35.0</td>
<td>±2.1</td>
</tr>
</tbody>
</table>
Table 8.9
Correlation matrix relating various estimates of fat-free weight and total body water in 27 female subjects.

<table>
<thead>
<tr>
<th></th>
<th>FFW(EFE)</th>
<th>FFW(D)</th>
<th>TSW</th>
<th>FFW(D+W)</th>
<th>FFW(Skf)</th>
<th>FFW(W/H^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFW(D)</td>
<td>0.884#</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSW</td>
<td>0.939#</td>
<td>0.945#</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFW(D+W)</td>
<td>0.924#</td>
<td>0.985#</td>
<td>0.985#</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFW(Skf)</td>
<td>0.882#</td>
<td>0.877#</td>
<td>0.914#</td>
<td>0.903#</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFW(W/H^2)</td>
<td>0.920#</td>
<td>0.866#</td>
<td>0.913#</td>
<td>0.902#</td>
<td>0.950#</td>
<td></td>
</tr>
<tr>
<td>H^2/R</td>
<td>0.775#</td>
<td>0.821#</td>
<td>0.839#</td>
<td>0.842#</td>
<td>0.695*</td>
<td>0.642*</td>
</tr>
</tbody>
</table>

* P < 0.001, # P < 0.0001

FFW(EFE) = fat-free weight (kg) based on measurements of electromagnetic field effects in model 4;
FFW(D) = fat-free weight (kg) based on densitometry; TSW = total body water (L) estimated from D_2O dilution; FFW(D+W) = mean of fat-free weights (kg) based on body density and total body water;
FFW(Skf) = fat-free weight (kg) derived from sum of four skinfold thicknesses (Durnin and Womersley 1974); FFW(W/H^2) = fat-free weight (kg) derived from weight/height^2 (kg/m^2) (Womersley and Durnin 1977); H^2/R = height^2/resistance (cm^2/ohm) where resistance was measured with a bioelectric impedance analyser.
methods. The strong correlation ($r = 0.924$) between FFW predicted from EFE and the mean of estimates based on measurements of body density and total body water is expected, as the latter was the reference method for the prediction equation.

FFW predicted from EFE is most strongly correlated with total body water ($r = 0.939$), although the correlation with FFW based on body density is also strong ($r = 0.884$). Comparisons between FFW estimated from EFE and anthropometry reveal strong correlations with estimates based on $W/H^2$ (weight/height$^2$) ($r = 0.920$) and skinfold thickness ($r = 0.882$). FFW based on EFE measurements were also compared with $H^2/R$ (height$^2$/resistance) values, where resistance was measured with a bioelectric impedance analyser, because $H^2/R$ has been shown to be related to FFW (Hoffer et al. 1969; Lukaski et al. 1985; Segal et al. 1985). Correlation between FFW from EFE measurements and $H^2/R$ values was moderate ($r = 0.775$).

5. Reproducibility Of Electromagnetic Field Effect Measurements

The following two approaches were used to assess the reproducibility of measurements of electromagnetic field effects in the chamber:

(a) $\Delta f_R$ and $\Delta A$ measurements were repeated immediately on 11 subjects. Measurements were made with both end- and side-antennae.

(b) eight $\Delta f_R$ and $\Delta A$ measurements were made for a fixed volume (20 L) of saline at daily intervals over eight consecutive working days. The containers of saline were placed in marked positions on the trolley and measurements were made with both end- and side-antennae.
Table 8.10 lists the mean paired differences for repeated $\Delta f_R$ and $\Delta A$ readings. There was no significant difference ($P > 0.05$) between repeated readings of $\Delta f_R$ and $\Delta A$. This applied to measurements made with both sets of antennae.

Table 8.11 lists the $\Delta f_R$ and $\Delta A$ values, measured with end- and side-antennae, for 20 L saline which was measured daily. A fixed volume of saline was used instead of human subjects to avoid biological variation which could occur over the measurement period. The coefficients of variation were 1.75 and 8.14% for $\Delta f_R$ values measured with end- and side-antennae, respectively. The standard deviation for each set of $\Delta f_R$ values was similar, but the coefficient of variation was larger for the side-antennae because $\Delta f_R$ values were smaller. The coefficients of variation for $\Delta A_R$ values were 1.54 and 1.39% using end- and side-antennae, respectively.

E. DISCUSSION

As a body composition analyzer, the resonating chamber is considered superior to the earlier models which were capacitors (chapter 7). Unlike the test capacitors, the resonating chamber is a resonance structure, which means that the available energy is used more efficiently. There is no energy lost through radiation from open ends and the problem of mismatching with loads from the generator is avoided.

Electromagnetic field effects in the chamber were detected as changes in resonant frequency ($\Delta f_R$) and attenuation ($\Delta A$). Measurement of these parameters showed that $\Delta f_R$ and $\Delta A$ values were inversely related.
Table 8.10

Mean paired differences ± s.d. for repeated $\Delta f_R(e)$, $\Delta f_R(s)$, $\Delta A(e)$ and $\Delta A(s)$ measurements of 11 subjects in model 4. $\Delta f_R(e)$ and $\Delta f_R(s)$ = change in resonant frequency (MHz) using end- and side-antennae, respectively; $\Delta A(e)$ and $\Delta A(s)$ = change in attenuation using end- and side-antennae, respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean paired differences</th>
<th>± s.d.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta f_R(e)$</td>
<td>-0.103</td>
<td>0.418</td>
</tr>
<tr>
<td>$\Delta f_R(s)$</td>
<td>0.018</td>
<td>0.446</td>
</tr>
<tr>
<td>$\Delta A(e)$</td>
<td>0.0029</td>
<td>0.0068</td>
</tr>
<tr>
<td>$\Delta A(s)$</td>
<td>0.0126</td>
<td>0.0203</td>
</tr>
</tbody>
</table>
Reproducibility of measurements of electromagnetic field effects for 20 L saline measured daily for eight days in model 4. $\Delta f_R(e)$ and $\Delta f_R(s)$ = change in resonant frequency (MHz) using end- and side-antennae, respectively; $\Delta A(e)$ and $\Delta A(s)$ = change in attenuation using end- and side-antennae, respectively.

<table>
<thead>
<tr>
<th>Day</th>
<th>$\Delta f_R(e)$</th>
<th>$\Delta f_R(s)$</th>
<th>$\Delta A(e)$</th>
<th>$\Delta A(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-4.294</td>
<td>-0.789</td>
<td>0.6116</td>
<td>0.7145</td>
</tr>
<tr>
<td>2</td>
<td>-4.140</td>
<td>-0.787</td>
<td>0.6109</td>
<td>0.7413</td>
</tr>
<tr>
<td>3</td>
<td>-4.126</td>
<td>-0.752</td>
<td>0.5977</td>
<td>0.7253</td>
</tr>
<tr>
<td>4</td>
<td>-4.130</td>
<td>-0.756</td>
<td>0.5957</td>
<td>0.7244</td>
</tr>
<tr>
<td>5</td>
<td>-4.158</td>
<td>-0.756</td>
<td>0.5929</td>
<td>0.7178</td>
</tr>
<tr>
<td>6</td>
<td>-4.121</td>
<td>-0.915</td>
<td>0.6180</td>
<td>0.7261</td>
</tr>
<tr>
<td>7</td>
<td>-4.266</td>
<td>-0.898</td>
<td>0.5998</td>
<td>0.7088</td>
</tr>
<tr>
<td>8</td>
<td>-4.094</td>
<td>-0.773</td>
<td>0.6116</td>
<td>0.7145</td>
</tr>
</tbody>
</table>

Mean  

<table>
<thead>
<tr>
<th></th>
<th>$\Delta f_R(e)$</th>
<th>$\Delta f_R(s)$</th>
<th>$\Delta A(e)$</th>
<th>$\Delta A(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-4.166</td>
<td>-0.803</td>
<td>0.6048</td>
<td>0.7216</td>
</tr>
<tr>
<td>± s.d.</td>
<td>0.073</td>
<td>0.065</td>
<td>0.0093</td>
<td>0.0101</td>
</tr>
<tr>
<td>C.V.*</td>
<td>1.75</td>
<td>8.14</td>
<td>1.54</td>
<td>1.39</td>
</tr>
</tbody>
</table>

* C.V. = (s.d./mean) 100%
to the quantities of meat and fat placed in the chamber. Meat caused larger changes in $\Delta f_R$ and $\Delta A$ values than fat (Figures 8.3 and 8.4). This effect can be explained by considering the relatively large dielectric constant and electrical conductivity of meat associated with its high water content (Johnson and Guy 1972; Pethig 1979).

Measurements of subjects in the resonating chamber showed significant correlations between $\Delta A$ values measured with the side-antennae, and estimates of FFW and FW based on measurements of body density and total body water ($P < 0.0001$). Weaker, but still significant, correlations were also found for $\Delta f_R$ values measured with end-antennae, and FFW and FW estimates ($P < 0.05$). Using multiple regression analysis, the following equation was derived for predicting FW from measurements of electromagnetic field effects:

$$FW = 73.48 + 0.291 \left( W/\sqrt{\Delta A} \right) - 49.2 H - 0.53 \Delta f_R$$

where FW = fat weight (kg)

$\Delta A$ = change in attenuation measured with side-antennae

$\Delta f_R$ = change in resonant frequency measured (MHz) with end-antennae

W = body weight (kg)

H = height (m)

Of the variety of equations tested, this one had the largest $R^2$ value (0.956) and the smallest S.E.E. (1.97). FFW is calculated as the difference between total body weight and FW.

In deriving this equation, a mean estimate of FW based on measurements of body density and total body water was used as the dependent
variable. Therefore, a combination of body density and total body water was used as the reference method, but both methods are affected by the inconstancy among individuals in the composition of fat-free body compartment (Bakker and Struikenkamp 1977; Siri 1956; Wedgwood 1963). Values of FW estimated from measurements of total body water were significantly different from, and less than, estimates based on measurements of body density (P < 0.001). Some degree of inaccuracy in predicting body composition can be attributed to inaccuracies in the reference methods. It was judged that by taking the mean of two laboratory methods for estimating the reference values, that the errors would be minimized. Both reference methods are indirect and true body analysis is, of course, not available.

A minor problem with the equipment arose with a small percentage (approximately 5%) of the subjects who suffered claustrophobia when enclosed in the chamber. To overcome this problem, it may be necessary to set a wire-mesh panel in the chamber wall, above the subject’s face, to allow communication and visual contact with people outside the chamber.

A major problem concerned the sensitivity of measurements to the positioning of absorbing materials in the chamber. The implication of this finding is that subjects with similar body composition but different body shapes and distributions of fat and fat-free tissue within the body, would have different effects on the electromagnetic field in the chamber. Another problem is that the electromagnetic field patterns in the chamber may vary from the theoretical pattern shown in Figure 8.1.
In developing this model further, structural changes could be made to the chamber to overcome some of these problems. An advantage of this design is that the modes of resonance can be controlled by changing the operating frequency. This ability to control the modes of resonance could be enhanced if the chamber was constructed so that the ends could be moved, thus altering the length of the chamber. The field pattern within the chamber could then be modified to suit the particular subject. If the antennae could also be moved, a series of readings could be taken, giving a 'picture' of the interference caused by the body to the electromagnetic field within the chamber.
CHAPTER 9

GENERAL DISCUSSION

A. THE TWO-COMPARTMENT BODY: ERRORS IN REFERENCE METHODS

Despite the potential usefulness of a method for analysing the body into its four main functional constituents (water, fat, protein and minerals), practical limitations restrict the determination of body composition to two arbitrarily divided body compartments (fat and fat-free). In the work reported here, the human body was viewed as comprising two such compartments. Fat-free weight (FFW) and fat weight (FW) were estimated by indirect means involving measurements of body density and total body water.

These laboratory methods, which were used as reference methods, depend on assumptions about the composition of the body. The body density method is based on the assumption that the fat-free compartment has a constant density of $1.10 \times 10^3 \text{ kg/m}^3$, and fat has a density of $0.900 \times 10^3 \text{ kg/m}^3$. The total body water method assumes that the fat-free tissues contain 73.2% water. These assumptions, however, are not entirely true (Bakker and Struikenkamp 1977; Siri 1956; Wedgwood 1963). The composition of an individual’s fat-free compartment is affected by many factors, including nutrition, obesity, growth, physical fitness, ageing and disease (Wedgwood 1963; Womersley et al. 1976). Martin and co-workers recently dissected 12 male cadavers. Analyses revealed that bone density varied from $1.18 \times 10^3$ to $1.33 \times 10^3 \text{ kg/m}^3$, the percentage of muscle in the FFW ranged from 45.6 to 59.7%, and the bone mass ranged from 16.4 to 24.9% (Caldwell 1981).
It is unlikely that significant interindvidual differences exist in the density of body fat, and the water content of fat will always be approximately zero (Womersley et al. 1976). Therefore, the major source of error is that tissues of the fat-free body do not have exactly the characteristics assumed.

The density of the fat-free body declines with ageing and obesity (Womersley et al. 1976). If the body composition of an elderly subject is estimated from measurements of body density, FFW will be underestimated and FW overestimated. This is because of a decrease in the density of the fat-free compartment, caused by demineralization of the skeleton, and this process is associated with ageing (Roberts et al. 1984). Durmin and Womersley (1974) estimated that between the ages 50 and 75 yr, males lose from 8 to 15% of their total body mineral, and between the ages 45 and 75 yr, females lose from 18 to 30% of their body mineral. Similar, but smaller, errors arise when the body composition of an obese subject is determined. If the fat-free 'excess tissue', which differentiates obese from lean subjects, consists of 74% cell residue of density 1.078 x 10\(^3\) kg/m\(^3\) at 37°C (Brozek et al. 1963) and 26% extracellular fluid of density 0.9937 x 10\(^3\) kg/m\(^3\), then the net density of the 'excess tissue' would be about 1.055 x 10\(^3\) kg/m\(^3\) (Womersley et al. 1976). Therefore the density of the fat-free body will be lowered with the addition of more of this 'excess tissue'.

The opposite error arises if the body composition of a subject with increased extracellular fluid is estimated from a measurement of total body water: the FFW will be overestimated and the FW will be underestimated.
As the assumptions involved in the methods of body composition analysis differ when based on measurements of body density and total body water, studies of the reliability of bioelectric impedance measurements (chapter 5) compared impedance readings separately with FFW from measurements of body density and measurements of total body water. The means of estimates from these two methods were used as reference values for FFW and FW when multiple regression analyses were performed to derive prediction equations for estimating FFW and FW from measurements of electromagnetic field effects (chapter 8). In these studies, which involved measurement of 27 subjects, there was a significant difference between body composition estimates based on the two different methods (P < 0.001). The mean of FFW estimates from measurements of body density was 1.3 kg less than the mean of estimates from measurements of total body water; conversely, the mean of FW estimates from measurements of body density was 1.3 kg greater than from measurements of total body water. Therefore, some degree of inaccuracy in predicting body composition from measurements of electromagnetic field effects would inevitably have arisen because of inaccuracies in the reference methods. These inaccuracies were a combination of theoretical errors resulting from incorrect assumptions, plus measurement errors. To eliminate errors associated with the individual variability in the density and composition of the fat-free body, measurements from new methods, such as electrical methods, need to be compared with direct analysis of body constituents. This would require studies with animals.
B. BIOELECTRIC IMPEDANCE ANALYSIS

The strong relationships found between bioelectric impedance measurements, corrected for height, and total body water ($r = 0.839$) and FFW from measurements of body density ($r = 0.821$), suggest that this method may be useful in the assessment of human body composition. The bioelectric impedance analyser (BIA) is portable and safe, the results are obtained rapidly, and demands made on the subject are minimal. The technique therefore offers advantages over many existing methods of determining body composition.

Preliminary studies with 20 subjects revealed that BIA readings were reproducible and the coefficient of variation of measurements taken over three weeks was 2%. The baseline of the instrument, therefore, remained acceptably stable which is an essential attribute for proper calibration.

The hypothesis that impedance can be used as a measure of total body water or FFW is based on the following principle: the impedance of a simple geometrical system is a function of the conductor's length, its cross-sectional area, and the signal frequency (Hoffer et al. 1970). Using a fixed signal frequency and a constant conductor configuration, the impedance measurement is then related to the volume of the conductor. In applying this principle, the human body has been pictured as a model of uniform configuration with a constant cross-sectional area. It may be argued that this model is an oversimplification of the body which is a complex biological system comprising a heterogeneous collection of tissues with differing properties.
The BIA operates at a frequency of 50 kHz. At this frequency the cell membranes behave as insulating boundaries, so the current is transmitted only via the extracellular fluid space (Ackmann and Seitz 1984). The conduction of the applied signal is therefore determined largely by extracellular water and the associated electrolyte content. It is not surprising that a strong correlation was found between impedance readings and measurements of total body water, assuming that the distribution of intracellular and extracellular water is constant. This is probably true in a normal population, but the assumption would be invalid in individuals with abnormal hydration or osmolality.

The electrodes of the BIA are attached to the subject's wrist and ankle, and the distance between them is the length of the transmission pathway. The use of the subject's height as a measure of conductor length is, therefore, questionable. In relating height²/impedance to total body water, it is assumed that there is an even distribution of fluid throughout the body. Such an assumption will not be true for subjects with ascites, hydrothorax or oedema, where there is unusual fluid localization.

It appears that impedance measurements relate primarily to the extracellular fluid volume. If impedance measurements are used to estimate FFW, then an assumption about the level of hydration of the fat-free tissues has to be made. To convert impedance readings to absolute quantities of FFW or FW, or even total body water, prediction equations are needed. Equations provided with the BIA were used to predict body fat in normal women (chapter 6). It was found that fat values based on impedance measurements fell between those calculated from skinfold measurements and body mass index (weight/height²). There have been reports of unsatisfactory results of body fat
estimated from impedance measurements using prediction equations provided with the BIA (Kushner et al. 1984; Segal et al. 1985), especially in obese subjects because of a systematic overestimation of FFW with increasing obesity. Revision of the constants in the prediction equations may improve the accuracy of the BIA. Perhaps impedance measurements will be most useful in short-term assessment of subjects where changes in body composition, rather than absolute values, are measured.

C. MEASUREMENT OF ELECTROMAGNETIC FIELD EFFECTS

Electromagnetic field effects (EFE) were measured in a variety of test capacitors and chambers. Unlike bioelectric impedance analysis, which introduces a current into the body, the EFE method involves measurement of the disturbance, caused by the body, in a weak electromagnetic field established in the test capacitor or chamber. As fat-free tissue and fat differentially affect the field, EFE measurements can be related to the proportions of FFW and FW in the body.

Three designs of test capacitor were tested and the most effective was the third model which consisted of a large open-ended cylindrical outer conductor with a rod or panel set in the centre along the cylinder's longitudinal axis (chapter 7). Initially, electromagnetic field effects were measured as the difference in Q value (ΔQ) between the empty test capacitor and when it contained a sample or subject. The measuring technique was later modified so that changes in resonant frequency (Δf_R) were measured. Studies with phantoms, consisting of containers of meat or fat, showed that an increase in the amount of
these materials placed in a symmetrical pattern yielded a linear
response from the instrument, the effect being approximately four
times greater with meat than with fat.

Measurements on 17 subjects were made in the test capacitor using a
rod as the central conductor. Operating frequencies were in the range
3 - 14 MHz. EPE readings were compared with body composition
estimates based on measurements of body density. Multiple regression
analyses indicated that the following equation was suitable for
predicting FFW:

\[
FFW = -4.39 + 0.690 W + 19.9 H + 37.6 \Delta f_R
\]

where FFW = fat-free weight (kg)

W = body weight (kg)

H = height (m)

\( \Delta f_R \) = change in resonant frequency (MHz) using \( L = 10 \times H \) and
\( C_1 = 20 \, \text{pF} \).

The coefficient of determination \( R^2 \) was 0.891 and the standard error
of estimate (S.E.E.) was 1.63.

Although this result was encouraging, the equipment underwent a change
in design. The new model, which was a resonating chamber, consisted
of a large enclosed cylinder with a rod mounted along the longitudinal
axis as a central conductor (chapter 8). Two sets of antennae were
used to deliver and receive the chamber signals. The two parameters
that were measured were change in signal attenuation (\( \Delta A \)) and change
in resonant frequency (\( \Delta f_R \)). Both \( \Delta A \) and \( \Delta f_R \) values were related to
baseline measurements of a standard (20 L saline). Studies with
containers of meat and fat showed curvilinear relationships between increasing amounts of meat or fat, and $\Delta f_R$ and $\Delta A$ values. Once again, meat had a larger effect on the field than fat.

Measurements on 27 subjects were made in the resonating chamber and results were compared with body composition estimates based on measurements of body density and total body water. Operating frequencies were in the range 40 - 54 MHz for antennae mounted on the end-plates (end-antennae), and 268 - 274 MHz for antennae on the chamber walls (side-antennae). Using multiple regression analyses, and mean estimates of FW from measurements of body density and total body water, the following equation for predicting FW was derived:

$$FW = 73.48 + 0.291 (W/\sqrt{\Delta A}) - 49.2 H - 0.53 \Delta f_R$$

where $FW = \text{fat weight (kg)}$

$\Delta A = \text{change in attenuation measured with side-antennae}$

$\Delta f_R = \text{change in resonant frequency (MHz) measured with end-antennae}$

$W = \text{body weight (kg)}$

$H = \text{height (m)}$

The $R^2$ value was 0.956 and S.E.E. was 1.97

This model of body composition analyser was considered better than previous ones because it was a resonance structure and consequently the available energy was used more efficiently. However, using the results from subjects from whom the prediction equations were derived, the correlations between FW predicted from electromagnetic field effects and FW estimated from skinfold thickness or weight/height$^2$
were higher when measured in the test-capacitor model ($r = 0.937$ and 0.967, respectively) than when measured in the resonating-chamber model ($r = 0.882$ and 0.920, respectively). These measurements, however, were made on different groups of subjects. There was a higher correlation between height$^2$/resistance (BIA measurements) and FFW estimated from the resonating-chamber model ($r = 0.775$) than from the test-capacitor model ($r = 0.735$). As discussed earlier, in interpreting comparative measurements of this type, it must be recognized that there are limitations in using indirect measures of body composition. The limitations arise from errors of measurement and errors resulting from biological variability.

The major problem with the equipment, especially the resonating-chamber model, is that measurements of electromagnetic field effects are influenced by the position of the absorbing tissue within the chamber. Further modifications, such as moveable end-plates and moveable antennae, may overcome this geometry problem.

The amount of electromagnetic radiation received by a subject while lying in the resonating chamber is several orders of magnitude below established limits for continuous exposure to radiofrequency waves. It is important to keep exposure levels low because, at high radiation intensities, there can be harmful effects to man. These include thermal effects such as burns, cataracts, and chemical changes in tissues; and non-thermal effects such as the pearl chain effect (where particles form into chains parallel to the electric lines of force) and dielectric saturation (where polarized side chains of macromolecules line up with the direction of the electric field, resulting in breakage of hydrogen bonds and alteration to hydration zones) (Johnson and Guy 1972). Thermal effects arise because absorbed
energy is transformed into increased kinetic energy of the absorbing molecules, producing heating of the tissue. The absorption is dependent on the electrical properties of the tissues, specifically the dielectric constant and electrical conductivity. Tissue with a low water content, such as fat, is penetrated to a greater extent than muscle with a high water content. This means that the energy penetrates the subcutaneous fat without major energy loss and becomes available for heat transfer in the deep tissues.

When choosing operating frequencies for the resonating chamber, it had to be remembered that the depth of penetration of the energy decreases as frequency increases. Under the assumption that the energy strikes at right angles to the surface of the body, most of the energy reaches the deep tissues if the frequency is below 1000 MHz (Michaelson 1974). The frequencies used with the test-capacitor and resonating-chamber models were well below this frequency.

Changes to the electromagnetic field are attributed mainly to the tissues with high water contents because it is these tissues which have the relatively high dielectric constants and electrical conductivities. Therefore, it must be recognized that, as with the RIA, there will be interference with the measurements in any situation where the fluid and electrolyte balances are disturbed. These problems, and difficulties with instrument calibration arising from errors inherent in the reference methods, can be investigated further by work with phantoms and animals. Disadvantages of working with phantoms arise because of the difference between 'dead' tissue and tissues in the living body. The living body is warm and has a functioning circulatory system. The tissues are combined in a complex system creating boundaries between different tissues in a way that is
difficult to represent with phantoms. Partial reflection of electromagnetic waves occurs at the boundaries of different tissues. The relative amount of the total energy which is reflected is determined by the dielectric constants and specific resistance values of the different tissues (Johnson and Guy 1972). Studies with animals may offer an improved model because of the possibility of measuring the effects on an electromagnetic field with a live animal, followed by direct chemical analysis.

Interest in this electrical equipment has already been displayed by the meat and livestock industry. Estimation of fat and fat-free tissue in carcasses has considerable economic significance in marketing and brooding. Trends are now toward the marketing of leaner meats. Accurate estimation of the fat to fat-free ratio is not easy; current methods generally lack precision and accuracy, and involve high labour costs. If this electrical measuring equipment could be incorporated into a conveyor system and give acceptable measures of fat and fat-free tissue, rapid automated grading of carcasses would be possible, creating significant benefits to the beef, lamb and pig meat industries. It may also be possible to extend the use of the equipment to live animals, thus assisting in selection for breeding.

Whether the application is to humans in gymnasiums and health clubs, in clinics and hospitals, or to animals in the meat industry, it is envisaged that the method should be developed as a fully automated system. After further modifications to the design, towards eliminating geometry and calibration problems, measurements of EFE could be made in quick succession and results processed in an on-line computer system. The method holds clear promise for the future.
APPENDIX A

INFORMATION SHEET FOR SUBJECTS PARTICIPATING IN THE HUMAN BODY COMPOSITION STUDY

The purpose of this study is to estimate the proportions of fat and fat-free tissues in humans using a variety of techniques. These include: underwater weighing, heavy water dilution, skinfold thickness, biological impedance and the new electrical technique being developed at Deakin where the subject is measured in a large resonating chamber. Descriptions of these techniques are outlined below. Your weight, height and two silhouette photographs will also be taken.

Detailed Instruction:

On the morning of the tests, you may have a light breakfast at least two hours before your appointment, consisting of one cup of tea, coffee or juice and one slice of toast with butter and spread. Please come to the Clinical Room (Level A) at 9.30 a.m. Please bring bathers, a towel, thongs and a warm jumper or track suit. The tests will take approximately 2 - 3 hours. The results will be given to you later, if you wish.

Description of Techniques:

Underwater weighing. The density of the human body can be determined by weighing first in air and then in water. To obtain the underwater weight, the subject climbs into a tank of warm water and sits on a chair suspended from scales. The subject then leans forward to become fully submerged while the reading is taken. Lung volume is determined at the time of underwater weighing using a hydrogen dilution method which requires the subject to rebreathe a volume of air containing a trace of hydrogen.

Heavy water dilution. Heavy water (containing deuterium, a non-radioactive isotope of hydrogen) behaves like ordinary water and is non-toxic in low doses. The subject drinks approximately 30 mL of heavy water and two hours later, a saliva sample is collected for analysis. From the heavy water dilution, total body water volume and hence the amount of fat-free tissue is calculated.

Skinfold thickness. The percentage of body fat can be predicted from the sum of four skinfolds which are measured with calipers.

Biological impedance. The impedance to the flow of a low voltage electric current through the fat-free tissues of the body is measured with a bioelectric impedance analyser (BIA). While resting on a bed, strip electrodes are placed on the subject's hands and feet and a weak, harmless current is passed through the body while impedance is measured.

Resonating chamber. Like the method above, this new method is based on the different electrical properties of fat and fat-free tissues. The subject lies on a trolley inside a large, enclosed aluminium cylinder which contains a weak electromagnetic field. By measuring the field disturbance caused by the body, the amounts of fat and fat-free tissues will be calculated. The subject makes no electrical contact with the equipment and readings take only a few minutes. If
you have a tendency to claustrophobia please mention this and try out the chamber before beginning the tests.

These studies have been approved by the University's Ethics Committee.

Thank you for your co-operation.

Julie Pasco
APPENDIX B

RADIOFREQUENCY (0.3 - 300,000 MHz) SAFETY STANDARDS

Table B.1 (Telecom Australia 1983) is a guideline to permissible exposure levels (PEL) for people working in radiofrequency environments for normal occupational durations e.g. 8 hr per day. These standards are intended to prevent a heat load greater than 1°C developing in body tissues.

<table>
<thead>
<tr>
<th>Frequency (f)</th>
<th>Power Density (mW/cm²)</th>
<th>Electric (E) Field (V/m)²</th>
<th>Electric (E) Field (V/m)</th>
<th>Magnetic (H) Field (A/m)²</th>
<th>Magnetic (H) Field (A/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 - 3 MHz</td>
<td>100</td>
<td>3.77 x 10⁵</td>
<td>614</td>
<td>2.65</td>
<td>1.63</td>
</tr>
<tr>
<td>3 - 30 MHz</td>
<td>900/f²</td>
<td>3.39 x 10⁶/f²</td>
<td>1842/f</td>
<td>23.87/f²</td>
<td>4.89/f</td>
</tr>
<tr>
<td>30 - 300 MHz</td>
<td>1.0</td>
<td>3.77 x 10³</td>
<td>61.40</td>
<td>0.0265</td>
<td>0.16</td>
</tr>
<tr>
<td>300 - 1500 MHz</td>
<td>f/300</td>
<td>12.57f</td>
<td>3.54 √f</td>
<td>8.84 x 10⁻⁵f</td>
<td>0.0094 √f</td>
</tr>
<tr>
<td>1500 - 300,000MHz</td>
<td>5</td>
<td>1.88 x 10⁴</td>
<td>137.30</td>
<td>0.13</td>
<td>0.36</td>
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</table>
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