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The relationship of the incidence of medullated fibres to the dimensional properties of mohair over the lifetime of Angora goats

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Abstract

In a range of animals, increasing mean fibre diameter (MFD) of fibre is associated with an increasing incidence of medullated fibres (Med). It would thus be expected that Med in mohair fleeces, from animals in a flock, would be related to the MFD of those fleeces. MFD of mohair is not the only dimensional attribute of fibres. Med in mohair is phenotypically and genetically related to the size of animals. This study examined how Med is related to dimensional properties of mohair over the lifetime of Angora goats and how the relationship varies with other lifetime factors. The relationship found is then examined to determine the extent that the relationship can be explained by variations in animal size of the goats. Measurements were made over 11 shearing periods on a population of Angora goats representing the current range and diversity of genetic origins in Australia, including South African, Texan and interbred admixtures of these and Australian sources. Records of breed, sire, dam, date of birth, dam age, birth weight, birth parity, weaning weight, live weight, fleece growth and fleece attributes were taken for castrated males (wethers). Animals’ fleece-free live weight (FFLwt, kg) were determined for each goat at shearing time by subtracting the greasy fleece weight from the live weight recorded immediately prior to shearing. The average of the FFLwt at the start of the period and the FFLwt at the end of the period was calculated. Two restricted maximum likelihood (REML) models were developed to relate Med to MFD, staple length (SL) and other lifetime factors. One model allowed FFLwt in the model and the other excluded FFLwt. With the exception of the 1.5 years shearing, Med strongly increased with increasing MFD whether or not adjustments were made for FFLwt measurements. In particular Med increased by 2.0% for each 1 µm increase in MFD, with no adjustment for FFLwt measurements, and increased by 1.5% for each 1 µm increase in MFD, with adjustment for FFLwt measurements. Within each shearing interval increasing average FFLwt was associated with increasing incidence of Med in a similar way to that which has been previously reported without including MFD in the model. There was no evidence that SL needed to be included in the models for Med. Mohair grown by the goats of Mixed genetic background grew mohair which had a higher incidence of Med at ages 2 and 2.5 years and the trend was apparent in other shearing periods. We can conclude that there is both a large response of Med to live weight and
a large response to MFD, and that these responses are largely functionally separate. While the
response to MFD is in accord with earlier work, there is an unrelated and unreported physiological
mechanism that favours the production of Med in larger Angora goats. Clearly, larger Angora goats
are biologically different compared with smaller animals from the same flock, in ways that are not
purely related to the allometrics of size.

Keywords: Age effects, Allometric, Fibre length, Genetic effects, Live weight effects, Medulla, Wool
production
1. Introduction

In mohair, medullation of mohair fibres appears to only occur once the fibre exceeds 20 µm in diameter (Lupton et al., 1991). It would thus be expected that the incidence of medullation in mohair fleeces, from animals in a flock, would be related to the mean fibre diameter (MFD) of those fleeces. Such a generalised relationship has been observed in wool (Auber, 1952; Shah et al., 1971; Scobie et al., 1993; Sienra et al., 2011) and in alpaca (McGregor, 2006).

Medullation incidence in mohair is known to be phenotypically and genetically related to the size of animals (Nicoll et al., 1989; Bolormaa et al., 2010; McGregor, 2010a; McGregor et al., 2013c). MFD is also known to be phenotypically and genetically related to the size of the animals (Shelton and Bassett, 1970; Yalçın et al., 1979; Nicoll et al., 1989; Gifford et al., 1991; Snyman and Olivier, 1996; Bolormaa et al., 2010; McGregor, 2010a; McGregor et al., 2012). It would thus be plausible that medullation incidence and MFD might be related purely due to their common relationship with animal size.

MFD of mohair is not the only dimensional attribute of fibres. Fibre length is also important. If medullation incidence is related to MFD, then it is plausible that medullation incidence may be related to fibre length, although Gifford et al. (1991) found no phenotypic relationship between mohair staple length and a subjective medullation score.

This study examined how the incidence of medullated fibres is related to dimensional properties of mohair over the lifetime of Angora goats and how the relationship varies with other lifetime factors. The relationship found is then examined to determine the extent that the relationship can be explained by variations in animal size of the goats.

2. Materials and methods

2.1. General
We used Angora goats involved in a previous report where shearing interval had a major
effect on the incidence of medullated fibres and other fleece attributes (McGregor and Butler, 2008).
However, the present work, was not focussed on the effect of shearing interval. Management details
have been provided by McGregor and Butler (2008) and McGregor et al. (2012, 2013a,b,c). In brief,
Angora goats (n=94) born in September 2002 in a progeny testing evaluation at Horsham, Victoria,
(36°42’50"S, 142°18’30"E, altitude 180 m) with pedigree breeding records from known sires, were
grazed on pasture from birth until 6 years of age. The goats were progeny of various genetic sources
including sires of 100% South African origin (n = 2), 100% Texan origin (n = 4), and other interbred
admixtures that included sires of South African, Texan and Australian origin (n = 4). These sires were
representative of the genotypes available in Australia (Ferguson and McGregor, 2004, 2005). Records
of dam, birth weight, birth parity, live weight, fleece growth and fleece quality were taken for
castrated males (wethers, n = 94). All animals were shorn every 6 months from 6 months of age,
except as described below. One month after shearing in February 2004 the goats were transported to
Attwood, Victoria (37°40’S, 144°53’E, altitude 135 m) and grazed as a flock until November 2008.

2.2. Management

Goats were grazed as 1 flock, at near the recommended stocking rate on improved annual
pasture (McGregor 2010a,b). Goats were moved between paddocks to match feed requirements.
Shelter was available in the form of covered and enclosed building that was always accessible and
could accommodate all goats. Fresh water was provided in all paddocks. During most years in autumn
and winter, pastoral conditions were affected by drought and supplementary feeding was undertaken
following Australian practice (McGregor 2005) from mid May to early September to maintain live
weight (McGregor and Butler 2008). A mineralised stock block was always available (Ridley
AgriProducts Pty. Ltd., Melbourne) with the following content: minimum content Ca 4.9%; P 1%; S 2%;
Cu 600 mg/kg; Co 60 mg/kg; I 60 mg/kg; Zn 1000 mg/kg; Fe2+ 1100 mg/kg; Se 5 mg/kg; based
on NaCl 75 to 85%.
The goats were given a full crutching and wigging 3 months prior to any shearing. Goats were vaccinated against 5 in 1 Clostridia spp. and “drenched” with an effective anthelmintic to control gastro-intestinal parasites no more frequently than once per year.

All goats were weighed to the nearest 0.2 kg one day prior to any shearing except for the third shearing when the nearest live weight prior to shearing was taken 3 months earlier at 15 months of age and following shearing 1 month later. All goats were fasted overnight prior to shearing or crutching. Goats were returned to pasture together following shearing. Fleece-free live weights (FFLwt) were determined for each goat at shearing time by subtracting the greasy fleece weight from the live weight recorded immediately prior to shearing. Average FFLwt between shearings (AvFFLwt) was determined as the average of the FFLwt at the start of the period and the FFLWt at the end of the period. Live weight change (LwtCh) was the change in FFLwt over the period between shearings.

2.3. Design

The goats studied were the castrated male progeny of a sire evaluation project (Ferguson and McGregor, 2004, 2005). Between February 2004 and February 2006 the goats were part of a replicated experiment studying the influence of shearing treatments. There were 4 or 8 individual goat replicates of 21 treatments arranged as a 7 shearing treatments by 3 genetic strains factorial (McGregor and Butler, 2008). The shearing treatments were:

- Three different 6-month shearing intervals, each with different months of shearing: February-August, April-October, June-December;
- Two 12-month shearing intervals with different months of shearing: August-August, September-September;
- One 3-month shearing interval (Often treatment); and
- One 7-month winter shearing interval, February-September.
Genetic strain was based on sire line as follows:

- South African: sires 100% South African bloodline;
- Texan: sires 100% Texan bloodline; and
- Mixed: sires of approximately 50% South African and 50% Texan bloodlines.

Some strains of wethers, whose breeding did not fit within these criteria, were culled.

2.4. Mohair measurement and testing

The practices were exactly as previously described (McGregor and Butler, 2008). At crutching and shearing, fleeces, pieces, bellies, locks and samples were weighed to the nearest 1 g. Mid-side samples were taken at shearing, identified, and stored in a plastic bag. Following laboratory evaluation, the mid-side samples were tested for clean washing yield, then mini-cored. The fibre snippets were tested for MFD and the incidence by number of medullated fibre (Med) using the OFDA100 following international wool testing standard methods (International Wool Textile Organisation, 1996, 2005a,b). For each test 8000 fibre measurements were made. Clean fleece weight was determined as: total greasy fleece weight including weight of crutchings (kg) × clean washing yield (%).

Staple length (SL) was measured as an indicator of fibre length (McGregor et al., 2013b). Three staples from the mid side sample were measured for SL to the nearest 0.5 cm following the removal of adhesions and twists, and then stretched along a ruler to straighten the crimps. The assessed SL was not the longest fibres in the staple tip but was subjectively determined with the aim of measuring to the point where most of the fibres were present before any significant narrowing of the staple near the tip, as per industry selling broker practice.
2.5. Statistical methods

Before statistical analysis, Med was log(y + 1) transformed so that the residuals did not increase as the mean increased. Then, a restricted maximum likelihood (REML) model, that allowed the observations of the same animal at different ages to be correlated in an unstructured manner, was developed to relate log_{10}(Med + 1) to MFD, SL, age of animal and other lifetime factors, but not AvFFLwt and LwtCh. The unstructured correlation allowed the between animal variance to differ between ages and the covariance of two observations from the same animal to differ between each pair of ages. Within this framework, a parsimonious model for fixed effects was developed using Wald F-tests (Payne, 2011). Once a parsimonious fixed effects model had been established, random sire effects and random dam effects were examined for inclusion in the model but the sire effect was rejected based on a chi-squared change in deviance test ($P > 0.1$), and the dam effect was rejected based on the lack of numerical convergence when fitting a model with an extra term for a dam effect. Small random effects commonly lead to over parameterisation and this often leads to numerical convergence difficulties.

To test the extent that the relationship developed could be explained by precursor live weight responses, a similar parsimonious model was developed but also allowing the possibility of including AvFFLwt and LwtCh effects. This parsimonious model was fitted with the same correlation structure as the parsimonious model without AvFFLwt and LwtCh effects. As before, sire and dam effects were examined but rejected.

Confidence intervals of back-transformed means, from both parsimonious models, were constructed using asymptotic normal approximations on the log_{10}(Med + 1) scale and back-transformed to the original Med scale. No outliers were detected from either model.
3. Results

Scatterplots showing the relationship, using raw animal data, between Med and MFD at different shearing ages are shown in Fig. 1 and between Med and SL in Fig. 2. Both Med and MFD, but not SL, are larger at older shearing ages.

AvFFLwt was equal to 38.9 kg, standard deviation was equal to 14.3 kg, the minimum was equal to 10.4 and the maximum was equal to 73.2 kg. Average LwtCh was equal to 4.0 kg; standard deviation was equal to 5.9 kg, varying from a lowest value of -13.8 to a largest value of +22.8 kg.

The fixed effects in the model for Med, that does not contain terms relating to AvFFLwt and LwtCh, can be represented as (Tables 1 and 2):

\[ Med = \text{Shearyears}*\text{Shearregime} + \text{Age}^{*}\text{Mixed} + \text{Age1p5}^{*}\text{MFD}. \]

The fixed effects in the model for Med, that does contain terms relating to AvFFLwt and LwtCh, can be represented as (Tables 1 and 2):

\[ Med = \text{Shearyears}*\text{Shearregime} + \text{Age}^{*}\text{Mixed} + \text{Age1p5}^{*}\text{MFD} + \text{Age}^{*}\text{AvFFLwt}. \]

With the exception of the 1.5 years shearing, Med strongly increased with increasing MFD whether or not adjustments were made for live weight measurements (Fig. 3). In particular Med + 1 increased by 2.0% (95% confidence interval = (1.5%, 2.6%)) for each 1 µm increase in MFD, with no adjustment for live weight measurements, and increased by 1.5% (95% confidence interval = (0.9%, 2.1%)) for each 1 µm increase in MFD, with adjustment for live weight measurements. The opposite trend was detected at age 1.5 years (Fig. 3) with Med decreasing from 1.4% at 22.5 µm to 1.0% at 35 µm, whether or not an adjustment was made for live weight measurements. There was no evidence ($P > 0.05$) that SL needed to be included in the models for Med (Table 2).

The statistical significance (Table 2) and the response of Med to genetic background was almost identical whether or not an adjustment was made for live weight measurements, and thus only the unadjusted results are tabulated (Table 3). Mohair grown by the goats of Mixed genetic background grew mohair which had a higher incidence of Med at ages 2 and 2.5 years and the trend was apparent in other shearing periods (Table 3).
Within each shearing interval increasing AvFFLwt was associated with increasing incidence of Med (Table 2, Fig. 4). In some shearing intervals the increase in Med with increasing AvFFLwt was much greater than in other shearing intervals (ages, Fig. 4).

4. Discussion

The results indicate that one dimensional property of mohair, MFD, had important effects on the incidence of Med, while another dimensional property of mohair, fibre length, was not important (Table 2). The importance of these responses did not alter appreciably if terms related to animal size were included in the model (Table 2).

4.1. The effect of MFD on Med

The results confirm that within a single age cohort of Angora goats, the incidence of Med is positively related to MFD, with the exception of age 1.5 years. This result agrees with the phenotypic correlations between Med and MFD that have been obtained from previous genetic studies with Angora goats aged 1 year and older (0.39, 0.20 and 0.23; Gifford et al., 1991; Allain and Roguet, 2006; Bolormaa et al., 2010). In these studies, the goats were mainly younger and fleeces examined only 2 to 4 times. Our results extend these results to a greater range of genetic sources and over the lifetime of the Angora goats.

At the third shearing (1.5 years old) the relationship between Med and MFD was different to the other ages ($P = 2.6 \times 10^{-10}$; Table 2; Fig. 3a). We suggest that this effect is an artefact of no reliable pre-shearing live weight. For all other shearings a live weight was taken within two days of shearing. For the third shearing, the nearest live weight measurement prior to shearing was three months earlier at 15 months of age, and the nearest measurement following shearing was one month after shearing. During the four month period the goats experience drought and live weight loss averaging 1 kg but live weight change varied from -7 to + 7 kg between goats. This effect may be
similar to that recorded in grazing experiments where Angora goats subject to severe competition had
depressed incidence of both kemp and medullated fibre in mohair compared with better fed goats
(McGregor, 2010a).

4.2. The effect of SL on Med

The lack of a response of Med to variations in fibre length (SL, Table 2) confirms a low
phenotypic correlation between total Med and SL of 0.01 reported by Gifford et al. (1991) and 0.11-
0.16 reported by Kosimov et al. (2013). This implies that larger fibres may or may not be associated
with more Med depending on whether the increase in size is associated with MFD (latitudinal), or
associated with fibre length (longitudinal). A similar phenomenon is found in the relationship between
live weight and fibre dimensions, where larger Angora goats have mohair with greater MFD
(McGregor et al., 2012) but not greater fibre length (McGregor et al., 2013b).

4.3. Influence of live weight

Adjusting for live weight measurements had only a minor, if any, effect on the relationship
between Med and MFD as the slopes on the lines in Figs. 3a and 3b are similar. Thus the suggestion,
in the introduction, that medullation incidence and MFD might be related purely due to their common
relationship with animal size is not correct. Such a relationship might have somewhat reduced the
magnitude of the relationship between Med and MFD because Med + 1 increased by 2.0% for each 1
µm increase in MFD, with no adjustment for live weight measurements, compared with 1.5% for each
1 µm increase in MFD, with adjustment for live weight measurements. However, we cannot be sure
because the 95% confidence limits of each of these two quantities (2.0% and 1.5%) overlap the value
of the other quantity.

There was no response of Med to LwtCh in either model suggesting that Med is not closely
related to nutrition, and thus the relationship of Med to MFD is not affected by nutrition. This
indicates that previously reported findings that Med responds to nutrition (McGregor, 1984; Lupton et al., 1991; McGregor, 2010a) are likely to be mediated via the effect of nutrition on MFD.

4.4. Influence of genetics and other factors

This study found that the Mixed bred goats had greater Med than Texan or South African bred goats. This result was similar to that reported using different analyses of the same experimental study (McGregor et al., 2013c). In the present study, as there was no interaction between MFD and Mixed, we can conclude that the effect does not appreciably affect the relationship between Med and the dimensional properties of fibres (Table 2).

In neither of the models was there any effect of pure bred type or other lifetime effects such as birth weight, weaning weight, parity, age of dam (Table 2). Thus it is unlikely that any of these effects will influence the relationship between Med and the dimensional properties of fibres.

At the time of the shearing experiment (fleeces harvested from 2 year old to 3.5 years old) there were major nuisance effects of shearing regime (Table 2). This relates to the previous results that shearing interval has a major effect on fleece weight, increased MFD and the incidence of medullated fibres and affected other fleece attributes (McGregor and Butler, 2008). Rudall (1935) also reported that shearing increased Med in Romney Marsh lambs.

4.5. Influence of MFD of Med response to live weight

At each age, the magnitude of the Med response to live weight after adjusting for MFD terms (Fig. 4a and b) was similar to that obtained previously without adjustment for MFD (McGregor et al., 2013b). This indicates that the Med response to live weight is not mediated through the associated response to MFD.

4.6. Implications of work
We have found that Med responds positively to both increases in live weight and to MFD, and that these responses are largely unaffected by adjusting for the other response. This implies that we can conclude that there is both a response of Med to live weight and to MFD, and that these responses are largely functionally separate. This indicates that they will affect Med via different physiological mechanisms.

As previous work has shown, there are no or very few medullated fibres below a MFD of 20 µm in mohair, alpaca and wool (Khan, 1974; Lupton et al., 1991; McGregor, 2006). This implies that for the follicle bulb to begin producing medullas a limiting thickness of solid keratin surrounding the medulla is about 10 µm. Over the range in fibre diameters where medullas are formed in mohair (20 to 100 µm), Lupton et al. (1991) estimated a limiting thickness of solid keratin surrounding the medulla of 5 µm and a minimum medulla diameter of about 5 µm. Khan (1974) and Ross (1990) reported similar findings when they examined the relationship between medulla diameter and fibre diameter in sheep kept for carpet wool production. Ross (1990) found that with Drysdale wool fibres from 22 to 52 µm, an increase in fibre diameter of 1 µm was associated with an increase in medulla diameter of < 1 µm. Between 52 and ≈ 80 µm, for each 1 µm increase in fibre diameter, medulla diameter increased at > 1 µm. At the highest fibre diameters the cortex became a constant of 5 µm and 91% of the fibre diameter was occupied by the medulla.

The increase in Med with increases in MFD and with live weight will be associated with an increase in fleece volume at any given fleece mass. This is because the density of medullated fibres is lower than for non-medullated fibres. For example, non-medullated keratin fibres have a density of about 1.307 g/cm³, where as fibres with low medullation (2-10%) have a density of 1.235 g/cm³ and fibres with high medullation (> 10%) a density of 1.076 g/cm³ (Merrick et al., 1998).

The sometimes large Med response to AvFFLwt, even after adjusting for MFD, is very interesting. It implies that, within a flock, larger animals have more Med than smaller animals even when mohair dimensional properties are the same. There is clearly some unreported physiological mechanism that favours the production of medullated fibres in larger Angora goats. We have
previously reported that, within an age group of Angora goats, the largest animals will be the least
efficient in converting improved nutrition to mohair (McGregor et al., 2013a). It is reasonable to
conclude that larger animals are biologically different compared with smaller animals from the same
flock, in ways that are not purely related to the allometrics of size.

Scobie and Woods (1992) proposed a theoretical mechanism for the production of medullated
fibres. In this model, medulla formation is explained as a consequence of competition between fibre
follicles for keratin precursors such that when fibre volume production exceeds available precursors
the follicles produce fibres with medullas. Furthermore, Auber (1952) described the formation of cells
which lead to medullas as being high in fluid content, implying that keratin precursors are in low
supply, somewhat akin to oedema formation in response to low plasma protein concentrations
elsewhere in the body of animals (Radostits et al., 2007). Clearly in a steady state nutritional
environment, an increase in MFD would place extra demands on keratin precursor supply until the
point is reached where there is insufficient supply resulting in the production of medullas. Such a
mechanism may explain why shearing Angora goats or sheep, or even small patches on the sides of
sheep, induce greater medulla formation (Rudall, 1935; McGregor and Butler, 2008). This would be
explained by the increase in energy demand to maintain the thermoneutral state of the animal
following the removal of the insulating fleece (SCA, 1990) and would result in less precursors being
available for keratin formation. Given the greater maintenance energy and protein requirements of
larger animals compared with smaller animals, under a steady state nutritional environment larger
animals are more likely to face restrictions on keratin precursor production and thus are more likely to
produce medullated fibres.

There has been debate and disagreement that the efficiency of fibre production can be
quantified using ratios of fibre length (l) to functions of fibre diameter (d). These ratios include l/d
and l/d² (Black, 1987; Hynd, 1989; Reis, 1992; Hynd, 1994; Masters and Hynd, 2000). Many of these
studies are of short duration and data on live weight are not reported. We have shown that increasing
animal size is associated with proportional increases in MFD and clean fleece weight but not SL and
that both increasing animal size and MFD are associated with increasing incidence of medullated
fibres. This indicates that efforts to identify animals producing longer keratin fibres should seek genes associated with longitudinal growth only rather than latitudinal growth. It is also apparent that the use of various ratios of l and d are not appropriate in assessing the efficiency of fibre production over the lifetime of Angora goats as these different dimensional attributes are controlled by different factors.

The current international standard for measuring medullation is length based (IWTO 2005c).

We have shown that the incidence of Med was not related to fibre length, but is strongly related to MFD. A consequence is that the length of medullated fibre can be a very poor indicator of the volume of medullated fibre. It is agreed that the gold standard for measuring the amount of medullated fibre should be volume based (Auber, 1952; Khan, 1974; Scobie and Woods, 1992). Thus there is good evidence to review the use of the international standard for measuring Med, and to develop alternative standards.

It is important to note that staple crimp can mask variations in the actual length of the straightened fibre (Goldsworthy and Lang, 1954). Goldsworthy and Lang concluded that “staple crimp may be a minority effect and the fibres producing successive elements of the staple crimp may not be the same throughout.” Using machine measured SL as a proxy for fibre length (IWTO, 2007) has problems in this regard as there is currently no corrections for variations in staple crimp frequency. The effects of variation in fibre crimping frequency, fibre crimp form and crimp amplitude on fibre length have been modelled (Balasubramaniam and Whitely, 1964). This work shows that the actual straight length of a fibre depends on its crimp form, with helical fibres being longer than sine fibres given the same initial crimped length. In our study with mohair we removed fibre crimping effects by unravelling the crimping and stretching the staples before measurement.

The findings of this work may explain the observation that increasing the frequency of shearing is associated with an increase in the incidence of medullated fibre in mohair (McGregor and Butler, 2008). In that study increasing the frequency of shearing was also associated with an increase in MFD of mohair.

5. Conclusion
We can conclude that there is both a large response of Med to live weight and a large response to MFD, and that these responses are largely functionally separate. While the response to MFD is in accord with earlier work, there is clearly some unrelated and unreported physiological mechanism that favours the production of medullated fibres in larger Angora goats. Clearly, larger Angora goats are biologically different compared with smaller animals from the same flock, in ways that are not purely related to the allometrics of size.

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Fig. Captions

Fig. 1. Scatterplots showing the raw data relating the incidence of medullated fibres (% by number, y-axis) in mohair to the mean fibre diameter measurements (µm, x-axis) of Angora wether goats at each shearing age. Ages are a) 1 year; b) 1.5 years; c) 2 years; d) 2.5 years; e) 3 years; f) 3.5 years; g) 4 years; h) 4.5 years; i) 5 years; j) 5.5 years; k) 6 years of age.

Fig. 2. Scatterplots showing the raw data relating the incidence of medullated fibres (% by number, y-axis) in mohair to the mean staple length measurements (cm, x-axis) of Angora wether goats at each shearing age. Ages are a) 1 year; b) 1.5 years; c) 2 years; d) 2.5 years; e) 3 years; f) 3.5 years; g) 4 years; h) 4.5 years; i) 5 years; j) 5.5 years; k) 6 years of age.

Fig. 3. Effect of mean fibre diameter on the incidence of medullation (% by number), (a) not adjusted for fleece-free live weight and (b) adjusted for fleece-free live weight. Predicted values are equally weighted for the Purebred versus Mixed genotypes on the transformed scale. In (b), at each age of shearing, values are given for a typical value of goat fleece-free live weight (kg) during the growing period. These typical values are: 1 year, 15 kg; 1.5 years 20 kg; 4 years, 43 kg; 6 years, 56 kg. Results are only presented for 4 years because the responses to mean fibre diameter are the same for all ages other than 1.5 years and to help with graph clarity. The error bars represent the 95% confidence intervals. Symbols for different ages: ■, 1-year-old; □, 1.5-year-old; ×, 4-year-old; ●, 6-year-old.

Fig. 4. Effect of average fleece-free live weight (kg), after adjusting for mean fibre diameter (MFD), on the incidence of medullated fibres (% by number) in mohair (a) after each winter growing period, and (b) after each summer growing period. At each age, values are given in brackets for a typical value of mohair MFD during the growing period. Predicted values are equally weighted for the Purebred versus Mixed genotypes on the transformed scale, and during the shearing experiment years predicted means are equally weighted for shearing regimes occurring at each particular age. The error bars represent the 95% confidence intervals. Symbols: ■, 1-year-old (21 µm); □, 1.5-year-old (29
µm); ●, 2- year-old (27 µm); ◊, 2½-year-old (33 µm); ▲, 3-year-old (32 µm); △, 3½-year-old
(34 µm); ×, 4-year-old (32 µm); *, 4½-year-old (33 µm); †, 5-year-old (31 µm); ○, 5½-year-old (36 µm); ●, 6-year-old (32 µm).
Table 1

Fixed terms used in parsimonious models for $\log_{10}(\text{incidence of medullation by number + 1})$. Abbreviations: clean fleece weight (CFWt); average fleece-free live weight (AvFFLwt).

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Factor/variate</th>
<th>Number of levels</th>
<th>Description</th>
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<td>Shearyears</td>
<td>Factor</td>
<td>5</td>
<td>4 if CFWt measured at 2 - year - old shearing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 if CFWt measured at 2½ - year - old shearing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6 if CFWt measured at 3 - year - old shearing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7 if CFWt measured at 3½ - year - old shearing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NA otherwise</td>
</tr>
<tr>
<td>Shearregime</td>
<td>Factor</td>
<td>8</td>
<td>FebAug if animal was in February and August shearing regime and measured in Shearyears 4 to 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>FebSept if animal was in February and September shearing regime and measured in Shearyears 4 to 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AprOct if animal was in April and October shearing regime and measured in Shearyears 4 to 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JunDec if animal was in June and December shearing regime and measured in Shearyears 4 to 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AugAug if animal was in August and August shearing regime and measured in Shearyears 4 to 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SeptSept if animal was in September and September shearing regime and measured in Shearyears 4 to 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Often if animal was in every 3 months shearing regime and measured in Shearyears 4 to 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NA if measurement taken in other Shearyears</td>
</tr>
<tr>
<td>Age</td>
<td>Factor</td>
<td>11</td>
<td>Age (years) at shearing (1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6)</td>
</tr>
<tr>
<td>Age1p5</td>
<td>Factor</td>
<td>2</td>
<td>1.5 if shearing is at 1.5 years</td>
</tr>
</tbody>
</table>
Other if any other age shearing

<table>
<thead>
<tr>
<th>Mixed</th>
<th>Factor</th>
<th>2</th>
<th>Indicating whether breed is Mixed or Pure bred (South African or Texan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AvFFLwt</td>
<td>Variate</td>
<td>Not applicable</td>
<td>Average of the fleece-free live weight at the start of the period and at the end of the period</td>
</tr>
</tbody>
</table>
Table 2

Tests for including and excluding fixed effects in the models for log$_{10}$(incidence of medullation by number + 1). \(P\)-values in bold are significant at the 5% level. Abbreviations: mean fibre diameter (MFD); average fleece-free live weight (AvFFLwt); live weight change between shearings (LwtCh).

<table>
<thead>
<tr>
<th>Adjustment to model</th>
<th>Model without AvFFLwt and LwtCh terms</th>
<th>Model with AvFFLwt and LwtCh terms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Degrees of freedom</td>
<td>(P)-value</td>
</tr>
<tr>
<td>Terms included</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shearyears (\times) Shearregime interaction</td>
<td>11, 94.1 1.8 (\times) 10(^{-5})</td>
<td>11, 95.6 8.1 (\times) 10(^{-7})</td>
</tr>
<tr>
<td>Interaction of Mixed breed and Age</td>
<td>10, 70.3 0.047</td>
<td>10, 69.2 0.041</td>
</tr>
<tr>
<td>Any effect of Mixed breed (main effect plus interaction with age)</td>
<td>11, 70.4 0.021</td>
<td>11, 69.2 0.018</td>
</tr>
<tr>
<td>MFD effect differs with Age1p5</td>
<td>1, 139.6 2.6 (\times) 10(^{-10})</td>
<td>1, 136.9 4.9 (\times) 10(^{-8})</td>
</tr>
<tr>
<td>AvFFLwt effect differs with Age</td>
<td>Not applicable</td>
<td>10, 108.1 0.019</td>
</tr>
<tr>
<td>Terms excluded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Texan versus South African purebreds</td>
<td>1, 81.3 0.81</td>
<td>1, 80.7 0.62</td>
</tr>
<tr>
<td>MFD(^2)</td>
<td>1, 140.8 0.47</td>
<td>1, 158.8 0.44</td>
</tr>
<tr>
<td>AvFFLwt(^2)</td>
<td>Not applicable</td>
<td>1, 194.8 0.22</td>
</tr>
<tr>
<td>MFD differing between other ages</td>
<td>9, 108.3 0.28</td>
<td>9, 104.2 0.49</td>
</tr>
<tr>
<td>MFD differs with shearregime (shearregime includes separate level for periods outside shearing experiment)</td>
<td>7, 110.1 0.13</td>
<td>7, 107.7 0.26</td>
</tr>
<tr>
<td>Parameter</td>
<td>df</td>
<td>Mean</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>----</td>
<td>------</td>
</tr>
<tr>
<td>Interaction of shearregime and Mixed</td>
<td>6</td>
<td>76.4</td>
</tr>
<tr>
<td>MFD effect differs with Mixed</td>
<td>1</td>
<td>350.5</td>
</tr>
<tr>
<td>AvFFLwt effect differs with shearregime</td>
<td></td>
<td>Not applicable</td>
</tr>
<tr>
<td>AvFFLwt effect differs with Mixed</td>
<td></td>
<td>Not applicable</td>
</tr>
<tr>
<td>Product of MFD and AvFFLwt</td>
<td></td>
<td>Not applicable</td>
</tr>
<tr>
<td>Live weight change</td>
<td></td>
<td>Not applicable</td>
</tr>
<tr>
<td>Staple length</td>
<td>1</td>
<td>446.5</td>
</tr>
<tr>
<td>Single vs Twins</td>
<td>1</td>
<td>84.0</td>
</tr>
<tr>
<td>Dam age</td>
<td>1</td>
<td>87.6</td>
</tr>
<tr>
<td>Weaning weight</td>
<td>1</td>
<td>85.0</td>
</tr>
<tr>
<td>Birth weight</td>
<td>1</td>
<td>92.0</td>
</tr>
<tr>
<td>Date of birth</td>
<td>16</td>
<td>64.4</td>
</tr>
</tbody>
</table>
Table 3

Effect of breed (Purebred versus Mixed) on the incidence of medullation (% by number) at each age of shearing, using an analysis without adjustment for live weight. Predictions are adjusted for other terms in the model on the transformed scale. During the shearing experiment years predicted means are equally weighted for shearing regimes occurring at each particular age. At each age, values are given for typical values of mohair mean fibre diameter (MFD).

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Typical MFD (µm)</th>
<th>Log_{10}(y + 1) transformed</th>
<th>s.e.d.</th>
<th>Back transformed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Purebred</td>
<td>Mixed</td>
<td></td>
<td>Purebred</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>0.18</td>
<td>0.19</td>
<td>0.017</td>
</tr>
<tr>
<td>1.5</td>
<td>29</td>
<td>0.33</td>
<td>0.34</td>
<td>0.011</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>0.22</td>
<td>0.26</td>
<td>0.018</td>
</tr>
<tr>
<td>2.5</td>
<td>33</td>
<td>0.40</td>
<td>0.46</td>
<td>0.021</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>0.37</td>
<td>0.37</td>
<td>0.021</td>
</tr>
<tr>
<td>3.5</td>
<td>34</td>
<td>0.46</td>
<td>0.48</td>
<td>0.022</td>
</tr>
<tr>
<td>4</td>
<td>32</td>
<td>0.30</td>
<td>0.30</td>
<td>0.020</td>
</tr>
<tr>
<td>4.5</td>
<td>33</td>
<td>0.43</td>
<td>0.47</td>
<td>0.023</td>
</tr>
<tr>
<td>5</td>
<td>31</td>
<td>0.37</td>
<td>0.40</td>
<td>0.021</td>
</tr>
<tr>
<td>5.5</td>
<td>36</td>
<td>0.37</td>
<td>0.40</td>
<td>0.024</td>
</tr>
<tr>
<td>6</td>
<td>32</td>
<td>0.35</td>
<td>0.36</td>
<td>0.022</td>
</tr>
</tbody>
</table>