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Estimating global injuries morbidity and mortality: methods and data used in the Global Burden of Disease 2017 study

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ABSTRACT

Background While there is a long history of measuring death and disability from injuries, modern research methods must account for the wide spectrum of disability that can occur in an injury, and must provide estimates with sufficient demographic, geographical and temporal detail to be useful for policy makers. The Global Burden of Disease (GBD) 2017 study used methods to provide highly detailed estimates of global injury burden that meet these criteria.

Methods In this study, we report and discuss the methods used in GBD 2017 for injury morbidity and mortality burden estimation. In summary, these methods included estimating cause-specific mortality for every cause of injury, and then estimating incidence for every cause of injury. Non-fatal disability for each cause is then calculated based on the probabilities of suffering from different types of bodily injury experienced.

Results GBD 2017 produced morbidity and mortality estimates for 38 causes of injury. Estimates were produced in terms of incidence, prevalence, years lived with disability, cause-specific mortality, years of life lost and disability-adjusted life-years for a 28-year period for 22 age groups, 195 countries and both sexes.

Conclusions GBD 2017 demonstrated a complex and sophisticated series of analytical steps using the largest known database of morbidity and mortality data on injuries. GBD 2017 results should be used to help inform injury prevention policy making and resource allocation. We also identify important avenues for improving injury burden estimation in the future.

INTRODUCTION

The Global Burden of Disease (GBD) study is a comprehensive assessment of population health loss. GBD has expanded in scope since its original release in 1994 (GBD 1990) and was most recently updated in autumn 2018 (GBD 2017).[1–7] Each update of the study has provided updated results through the most recent year of data availability as well as increasingly refined detail in terms of locations, age groups and causes. In addition, GBD incorporates new data as well as updated methods for each annual release that represent the expanding complexity of the study. Cumulatively, the increasing volume of data and increasingly sophisticated estimation methods have necessitated near-continual refinements in terms of data processing, statistical modelling, computational storage and processing as well as global collaboration with the over 4000 GBD collaborators in over 140 countries and territories.

Historically, injuries have formed one of the three broad cause groups in the GBD cause hierarchy alongside the other two main groups of health loss (communicable, maternal, neonatal and nutritional diseases; non-communicable diseases). Not surprisingly, there is considerable variation in how morbidity and mortality are estimated across different causes in the GBD hierarchy and study design. The methods for estimating morbidity and mortality from injuries have evolved over time through the most recent release of GBD 2017. Historically, there have been certain challenges in injuries burden estimation, some of which have been addressed and updated over time, and some of which remain as methodological challenges to address as population health measurement develops more sophisticated modelling strategies. For example, methodological challenges that have been identified over the past three decades in population health research have included obtaining data in data-sparse, burden-heavy areas of the world, developing adjustments for ill-defined causes of death, separately estimating *cause* of injury from the bodily harm that results from an injury event and adjusting for known biases in data, such as underestimation in sexual violence data.[3 8 9] Cumulatively, the global injuries research community has developed a wide array of methodological innovations and advancements to overcome many of these challenges, although undoubtedly the science will continue to advance as higher-quality datasets become available, as modelling methods improve and as computational processing power becomes more accessible to population health research groups around the world.

Many studies have been published based on different releases of the GBD study, ranging from studies on intentional injuries in the eastern Mediterranean to detailed assessments of traumatic brain injury and spinal cord injury disability rates on a global scale.[10 11] While this array of published GBD injury studies demonstrates a broad spectrum of expert knowledge on specific injuries or specific geographies or both, it is also critical to recognise that population health is a rapidly evolving, collaborative science that has benefited from near-continual improvements even through the current updates being implemented for GBD 2019. As a result, it should benefit the scientific enterprise to focus on publishing the most updated results with perspective on global, demographic and temporal patterns, and on sharing iterative updates on the current state of the science of GBD injuries burden estimation. The goal of this study is to comprehensively review and report methods used for GBD 2017 and associated publications that have gone through extensive collaborator-review and peer-review processes.

METHODS

GBD 2017 study

GBD is predicated on the principle that every case of death and disability in the population should be systematically identified and accounted for in the formulation of global disease and injury burden. On the side of mortality, every death that occurs in the population should have one underlying cause of death which can be assigned to a cause in a mutually exclusive, collectively exhaustive hierarchy of diseases and injuries that can cause death. These data can be used in a method described below to calculate cause-specific mortality rates and years of life lost. For morbidity, every non-fatal case of disease or injury should have an amount of disability assigned for some period of time. These data can be used in a process described below to estimate the incidence, prevalence and years lived with disability. Summing morbidity and mortality from some cause form the burden from that cause, expressed as disability-adjusted life-years (DALY). For causes with known risk factors, some portion of this burden may be explained by exposure to that risk factor. Across causes within some population, it is also a principle of GBD that the sum of all cause-specific deaths should equal all-cause mortality in the population, and that rates of incidence, prevalence, remission and cause-specific mortality can be reconciled with one another such that all death and disability in a population is internally consistent across causes and geographies. As examples, the sum of different types of road injury cases must sum up to overall road injuries, and the sum of deaths from different injuries in a given country must sum up to the estimate of all-injury deaths. The principle of internal consistency extends to populations used in GBD, where every birth, death and net migration must be accounted for in the population estimates which form the denominators of GBD results. While there is immense complexity in the process summarised above, it is important to begin with these core principles which govern the computation processes at the heart of GBD burden estimation. A summarised overview of key GBD 2017 methods is also provided in online supplementary appendix 1.

GBD study design and hierarchies

GBD study design, including cause-specific methods, is described in a high level of detail in associated publications.[2–7] In addition to the injury-focused methods described in this paper, it is important to define hierarchies used in the GBD study design. In particular, GBD 2017 was built around a location hierarchy where different subnational locations (eg, US states, India states, China provinces) which form a composite of a national location (eg, the USA, India, China). National locations are aggregated to form GBD regions, which are then aggregated to form GBD super regions. These designations affect the modelling structure and utilisation of location random effects, processes which are described in more detail later. The country-level and regional-level GBD location hierarchy used in GBD 2017 is provided in online supplementary appendix table 1. In addition to locations, GBD processes are conducted to produce estimates for every one of 22 age groups, male and female sex and across 28 years from 1990 to 2017 (inclusive). Age-standardised, all-age and combined sex results are also computed for each GBD result. Exceptions exist to the rules above, for example, self-harm is not permitted to occur in the 0–6 days (early neonatal) age group in the GBD age hierarchy. There are no sex restrictions placed on any GBD injury causes, although these restrictions exist for other GBD causes, such as cancers like prostate, cervical and uterine being related to one sex.

GBD injury classification

In the GBD cause hierarchy, injuries are part of the first level of the GBD cause hierarchy, which consists of three broad groups: communicable, maternal, neonatal and nutritional diseases; non-communicable diseases and injuries. Additional levels of the GBD cause hierarchy provide additional detail. The hierarchy of injuries in GBD is provided in table 1. The organisation of the hierarchy has implications both in terms of how results are produced and in terms of analytical and processing steps which are discussed in more detail below. Case definitions including International Classification of Diseases (ICD) codes used to identify injury deaths and cases are provided in table 2.

GBD separates the concept of cause of injury from nature of injury. Cause of injury (eg, road injuries, falls, drowning) have historically been used for assigning cause of death as opposed to the 'nature' of injury, which more directly specifies the pathology that resulted in death. For example, an individual who falls, fractures his or her hip, undergoes surgery and then develops hospital-acquired pneumonia and dies while hospitalised would still have a fall as the underlying cause of death, regardless of whether sepsis or some other disease process leads to death more proximally in the chain of events. In this individual, the 'nature' of injury would have been specified as a hip fracture, since it is the bodily injury that would dictate the disability this person experiences. Since it is evident that a hip fracture is more

Table 1 Global Burden of Disease cause-of-injury hierarchy

Transport injuries	Unintentional injuries	Self-harm and interpersonal violence	Forces of nature, conflict and terrorism and executions and police conflict
Road injuries	Falls	Self-harm	Exposure to forces of nature
Pedestrian road injuries	Drowning	Self-harm by firearm	Conflict and terrorism
Cyclist road injuries	Fire, heat and hot substances	Self-harm by other specified means	Executions and police conflict
Motorcyclist road injuries	Poisonings	Interpersonal violence	
Motor vehicle road injuries	Poisoning by carbon monoxide	Assault by firearm	
Other road injuries	Poisoning by other means	Assault by sharp object	
Other transport injuries	Exposure to mechanical forces	Assault by other means	
	Unintentional firearm injuries		
	Unintentional suffocation		
	Other exposure to mechanical forces		
	Adverse effects of medical treatment		
	Animal contact		
	Venomous animal contact		
	Non-venomous animal contact		
	Foreign body		
	Pulmonary aspiration and foreign body in airway		
	Foreign body in eyes		
	Foreign body in other body part		
	Environmental heat and cold exposure		
	Other unintentional injuries		

disabling than a mild skin abrasion, it is important for measuring non-fatal burden to consider both the cause and the nature in the formulation of complete injury burden. A full list of nature of injury is provided in table 3.

Cause-specific mortality and years of life lost

As described above, cause-specific mortality is measured for every cause of injury in the GBD cause hierarchy with the exception of foreign body in the ear and sexual violence, which undergo only non-fatal burden estimation (described in more detail below). GBD adheres to five general principles for measuring cause-specific mortality, which are described in more detail elsewhere but are summarised as follows.[12] First, GBD 2017 identifies all available data. For injuries, this includes vital registration (VR), vital registration samples, verbal autopsy (VA), police records and mortuary/hospital data. VR is the preferred data source but is not available in every location in the GBD location hierarchy. Prior VA research has demonstrated that VA is more accurate for certain injury causes than it is for certain diseases.[13] Police data undergo additional validity checks to ensure that systematic under-reporting does not occur in comparison to VR data, which is described in more detail in a related publication.[6] The second general principle relevant to injury mortality estimation is maximising comparability and quality of the dataset. For the purposes

Table 2 Case definitions for cause of injury in GBD 2017

Child causes	ICD codes	Case definition (fatal)	Case definition (non-fatal)
Self-harm	**ICD9**: E950-E959 **ICD10**: X60-X64.9, X66-X84.9, Y87.0	Deliberate bodily damage inflicted on oneself resulting in death	Deliberate bodily damage inflicted on oneself with or without intent to kill oneself.
Self-harm by firearm	**ICD9**: E955-E955.9 **ICD10**: X72-X74.9	Deliberate bodily damage inflicted by firearm on oneself resulting in death	Deliberate bodily damage inflicted on oneself by firearm with or without intent to kill oneself.
Self-harm by other specified means	**ICD9**: E950-E954, E956-E958.0, E958.2-E959 **ICD10**: X60-X64.9, X66-X67.9, X69-X71.9, X75-X75.9, X77-X84.9, Y87.0	Deliberate bodily damage inflicted on oneself resulting in death by means of:* ► Self-poisoning ► Medication overdose ► Transport incident ► Falling from height ► Hanging/strangulation *(not exhaustive)	Deliberate bodily damage inflicted on oneself with or without intent to kill oneself by means of:* ► Self-poisoning ► Medication overdose ► Transport incident ► Falling from height ► Hanging/strangulation *(not exhaustive)
Poisoning	**ICD9**: E850.3-E858.99, E862-E869.99, E929.2 **ICD10**: J70.5, X40-X44.9, X47-X49.9, Y10-Y14.9, Y16-Y19.9	Death resulting from accidental exposure to a non-infectious substance which contacts the body or enters into the body via inhalation, ingestion, injection or absorption and causes deranged physiological function of body and/or cellular injury/death.	Unintentional exposure to a non-infectious substance which contacts the body or enters into the body via inhalation, ingestion, injection or absorption and causes deranged physiological function of body and/or cellular injury/death.
Poisoning by carbon monoxide (CO)	**ICD9**: E862-E862.99, E868-E869.99 **ICD10**: J70.5, X47-X47.9	Death from exposure to carbon monoxide (CO) as identified based on carboxyhemoglobin levels (specified based on smoking status and age) or proximity to a confirmed CO poisoning case.	Non-fatal exposure to CO as identified based on carboxyhemoglobin levels (specified based on smoking status and age) or proximity to a confirmed CO poisoning case.
Poisoning by other means	**ICD9**: E850.3-E858.99, E866-E866.99 **ICD10**: X40-X44.9, X49-X49.9, Y10-Y14.9, Y16-Y19.9	Death resulting from accidental exposure to a non-infectious substance (other than CO) which contacts the body or enters into the body via inhalation, ingestion, injection or absorption and causes deranged physiological function of body and/or cellular injury/death.	Accidental exposure to a non-infectious substance (other than CO) which contacts the body or enters into the body via inhalation, ingestion, injection or absorption and causes deranged physiological function of body and/or cellular injury/death.
Animal contact	**ICD9**: E905-E906.99 **ICD10**: W52.0-W62.9, W64-W64.9, X20-X29.9	Death resulting from unintentionally being attacked, struck, impaled, bitten, stung, crushed, exposed to or stepped on by a non-human animal.	Bodily damage resulting from unintentionally being attacked, butted, impaled, bitten, stung, crushed, exposed to or stepped on by a non-human animal.
Venomous animal contact	**ICD9**: E905-E905.99 **ICD10**: W52.3, X20-X29.9	Death resulting from unintentionally being bitten by, stung by, or exposed to a non-human venomous animal.	Bodily damage resulting from unintentionally being bitten by, stung by or exposed to a non-human venomous or poisonous animal.
Non-venomous animal contact	**ICD9**: E905-E906.99 **ICD10**: W52.0-W62.9, W64-W64.9, X20-X29.9	Death resulting from unintentionally being attacked, struck, impaled, crushed, exposed to or stepped on by a non-human animal.	Bodily damage resulting from unintentionally being attacked, struck, impaled, crushed, exposed to or stepped on by a non-human animal.
Falls	**ICD9**: E880-E886.99, E888-E888.9, E929.3 **ICD10**: W00-W19.9	A sudden movement downwards due to slipping, tripping or other accidental movement which results in a person coming to rest inadvertently on the ground, floor or other lower level, resulting in death.	A sudden movement downward due to slipping, tripping or other accidental movement which results in a person coming to rest inadvertently on the ground, floor or other lower level, resulting in tissue damage.
Drowning	**ICD10:** W65-W70.9, W73-W74.9 **ICD9:** E910-E910.99	Death that occurs as a result of immersion in water or another fluid.	Non-fatal immersion or submersion in water or another fluid, regardless of whether tissue damage has occurred. The subject can be resuscitated and has not suffered brain death.
Fire, heat, and hot substances	**ICD9:** E890-E899.09, E924-E924.99, E929.4 **ICD10:** X00-X06.9, X08-X19.9	Death due to unintentional exposure to substances of high temperature sufficient to cause tissue damage on exposure, including bodily contact with hot liquid, solid or gas such as cooking stoves, smoke, steam, drinks, machinery, appliances, tools, radiators and objects radiating heat energy.	Unintentional exposure to substances of high temperature sufficient to cause tissue damage on exposure, including bodily contact with hot liquid, solid or gas such as cooking stoves, smoke, steam, drinks, machinery, appliances, tools, radiators and objects radiating heat energy.
Road injuries	**ICD9:** E800.3, E801.3, E802.3, E803.3, E804.3, E805.3, E806.3, E807.3, E810.0-E810.6, E811.0-E811.7, E812.0-E812.7, E813.0-E813.7, E814.0-E814.7, E815.0-E815.7, E816.0-E816.7, E817.0-E817.7, E818.0-E818.7, E819.0-E819.7, E820.0-E820.6, E821.0-E821.6, E822.0-E822.7, E823.0-E823.7, E824.0-E824.7, E825.0-E825.7, E826.0-E826.1, E826.3-E826.4, E827.0, E827.3-E827.4, E828.0, E828.4, E829.0-E829.4 **ICD10:** V01-V04.99, V06-V80.929, V82-V82.9, V87.2-V87.3	Interaction with an automobile, motorcycle, pedal cycle or other vehicles resulting in death.	Interaction with an automobile, motorcycle, pedal cycle or other vehicles resulting in bodily damage.
Pedestrian road injuries	**ICD9:** E811.7, E812.7, E813.7, E814.7, E815.7, E816.7, E817.7, E818.7, E819.7, E822.7, E823.7, E824.7, E825.7, E826.0, E827.0, E828.0, E829.0 **ICD10:** V01-V04.99, V06-V09.9	Interaction, as a pedestrian on the road, with an automobile, motorcycle, pedal cycle or other vehicles resulting in death.	Interaction, as a pedestrian on the road, with an automobile, motorcycle, pedal cycle or other vehicles resulting in bodily damage.
Cyclist road injuries	**ICD9:** E800.3, E801.3, E802.3, E803.3, E804.3, E805.3, E806.3, E807.3, E810.6, E811.6, E812.6, E813.6, E814.6, E815.6, E816.6, E817.6, E818.6, E819.6, E820.6, E821.6, E822.6, E823.6, E824.6, E825.6, E826.1 **ICD10:** V10-V19.9	Accident, as a cyclist or passenger on a pedal cycle, resulting in death.	Accident, as a cyclist or passenger on a pedal cycle, resulting in bodily damage.
Motorcyclist road injuries	**ICD9:** E810.2-E810.3, E811.2-E811.3, E812.2-E812.3, E813.2-E813.3, E814.2-E814.3, E815.2-E815.3, E816.2-E816.3, E817.2-E817.3, E818.2-E818.3, E819.2-E819.3, E820.2-E820.3, E821.2-E821.3, E822.2-E822.3, E823.2-E823.3, E824.2-E824.3, E825.2-E825.3 **ICD10:** V20-V29.9	Accident, as a rider on a motorcycle, resulting in death.	Accident, as a rider on a motorcycle, resulting in bodily damage.

Continued

Table 2 Continued

Child causes	ICD codes	Case definition (fatal)	Case definition (non-fatal)
Motor vehicle road injuries	**ICD9:** E810.0-E810.1, E811.0-E811.1, E812.0-E812.1, E813.0-E813.1, E814.0-E814.1, E815.0-E815.1, E816.0-E816.1, E817.0-E817.1, E818.0-E818.1, E819.0-E819.1, E820.0-E820.1, E821.0-E821.1, E822.0-E822.1, E823.0-E823.1, E824.0-E824.1, E825.0-E825.1 **ICD10:** V30-V79.9, V87.2-V87.3	Accident, as a driver or passenger in a motor vehicle, resulting in death.	Accident, as a driver or passenger in a motor vehicle, resulting in bodily damage.
Other road injuries	**ICD9:** E810.4-E810.5, E811.4-E811.5, E812.4-E812.5, E813.4-E813.5, E814.4-E814.5, E815.4-E815.5, E816.4-E816.5, E817.4-E817.5, E818.4-E818.5, E819.4-E819.5, E820.4-E820.5, E821.4-E821.5, E822.4-E822.5, E823.4-E823.5, E824.4-E824.5, E825.4-E825.5, E826.3-E826.4, E827.3-E827.4, E828.4, E829.4 **ICD10:** V80-V80.929, V82-V82.9	Death resulting from being a driver or passenger of a vehicle not including automobiles, motorcycles, bicycles (ie, streetcar).	Bodily damage resulting from being a driver or passenger of a vehicle not including automobiles, motorcycles, bicycles (ie, streetcar).
Other transport injuries	**ICD9:** E800-E800.2, E801-E801.2, E802-E802.2, E803-E803.2, E804-E804.2, E805-E805.2, E806-E806.2, E807-E807.2, E810.7, E820.7, E821.7, E826.2, E827.2, E828.2, E830-E838.9, E840-E849.9, E929.1 **ICD10:** V00-V00.898, V05-V05.99, V81-V81.9, V83-V86.99, V88.2-V88.3, V90-V98.8	Interaction with a means of transport other than automobile, motorcycle, pedal cycle or other road vehicles resulting in death.	Interaction with a means of transport other than automobile, motorcycle, pedal cycle or other road vehicles resulting in bodily damage.
Interpersonal violence	**ICD9:** E960-E969 **ICD10:** X85-Y08.9, Y87.1-Y87.2	Death from intentional use of physical force or power, threatened or actual, from another person or group not including military or police forces.	Sustaining bodily harm in terms of tissue damage from intentional use of physical force or power, threatened or actual, from another person or group not including military or police forces.
Physical violence by firearm	**ICD9:** E965-E965.4 **ICD10:** X93-X95.9	Death from intentional use of physical force or power by a firearm from another person or group or community not including military or police forces.	Sustaining bodily harm in terms of tissue damage from intentional use of physical force or power by a firearm from another person or group not including military or police forces.
Physical violence by sharp object	**ICD9:** E966 **ICD10:** X99-X99.9	Death from intentional use of physical force or power by a sharp object from another person or group or community not including military or police forces.	Sustaining bodily harm in terms of tissue damage from intentional use of physical force or power by a sharp object from another person or group not including military or police forces.
Sexual violence	**ICD9:** E960-E960.1 **ICD10:** Y05-Y05.9	NA	Experiencing at least one event of sexual violence in the last year, where sexual violence is defined as any sexual assault, including both penetrative sexual violence (rape) and non-penetrative sexual violence (other forms of unwanted sexual touching).
Physical violence by other means	**ICD9:** E961-E964, E965.5-E965.9, E967-E969 **ICD10:** X85-X92.9, X96-X98.9, Y00-Y04.9, Y06-Y08.9, Y87.1-Y87.2	Death from intentional use of physical force or power by an object other than a firearm or sharp object from another person or group or community not including military or police forces.	Sustaining bodily harm in terms of tissue damage from intentional use of physical force or power by an object other than a firearm or sharp object from another person or group not including military or police forces.
Conflict and terrorism	**ICD9:** E979-E979.9, E990-E999.1 **ICD10:** U00-U03, Y36-Y38.9, Y89.1	Death resulting from the instrumental use of violence by people who identify themselves as members of a group—whether this group is transitory or has a more permanent identity—against another group or set of individuals, in order to achieve political, economic or social objectives.	Bodily harm resulting from the instrumental use of violence by people who identify themselves as members of a group—whether this group is transitory or has a more permanent identity—against another group or set of individuals, in order to achieve political, economic or social objectives.
Executions and police conflict	**ICD9:** E970-E978 **ICD10:** Y35-Y35.93, Y89.0	State-sanctioned executions or police-related altercations leading to death.	State-sanctioned executions or police-related altercations leading to bodily damage.
Exposure to forces of nature	**ICD9:** E907-E909.9 **ICD10:** X33-X38.9	Death resulting from an unforeseen and often sudden natural event such as a hurricane, earthquake, tsunami or tornado.	Bodily damage resulting from an unforeseen and often sudden natural event such as a hurricane, earthquake, tsunami or tornado.
Exposure to mechanical forces	**ICD9:** E913-E913.19, E916-E922.99, E928.1-E928.7 **ICD10:** W20-W38.9, W40-W43.9, W45.0-W45.2, W46-W46.2, W49-W52, W75-W76.9	Unintentional death resulting from contact with or threat of an (in)animate object, human or plant.	Unintentional bodily damage resulting from contact with or threat of an (in)animate object, human or plant.
Unintentional firearm injuries	**ICD9:** E922-E922.99, E928.7 **ICD10:** W32-W34.9	Unintentional death resulting from contact with a firearm.	Unintentional bodily damage resulting from contact with a firearm.
Other exposure to mechanical forces	**ICD9:** E916-E921.99, E928.1-E928.6 **ICD10:** W20-W31.9, W35-W38.9, W40-W43.9, W45.0-W45.2, W46-W46.2, W49-W52	Unintentional death resulting from contact with or threat of an (in)animate object (not including a firearm), human or plant.	Unintentional bodily damage resulting from contact with or threat of an (in)animate object (not including a firearm), human or plant.
Pulmonary aspiration and foreign body in airway	**ICD9:** 770.1–770.18, E911-E912.09, E913.8-E913.99 **ICD10:** W78-W80.9, W83-W84.9	Unintentional death from inhaling, swallowing or aspirating extraneous materials or substance that enters the airway or lungs.	Unintentional bodily damage from inhaling, swallowing or aspirating extraneous materials or substance that enters the airway or lungs.
Foreign body in eyes	**ICD9:** 360.5–360.69, 374.86, 376.6, E914-E914 09 **ICD10:** H02.81-H02.819, H44.6-H44.799	NA	Unintentional damage from extraneous materials or substance in the orbital structure or eye.
Foreign body in other body part	**ICD9:** 709.4, E915-E915.09 **ICD10:** M60.2-M60.28, W44-W45, W45.3-W45.9	Unintentional death from an extraneous material or substance being within the body, not including the airway, lungs or eyes.	Unintentional bodily damage from an extraneous material or substance being within the body, not including the airway, lungs or eyes.

Injuries definition: damage, defined by cellular death, tissue disruption, loss of homeostasis, pain limiting activities of daily living or short-term psychological harm (for cases of sexual violence), inflicted on the body as the direct or indirect result of a physical force, immersion or exposure, which may include interpersonal or self-inflicted forces.
GBD, Global Burden of Disease; ICD, International Classification of Diseases.

of injury mortality estimation, this process is largely focused on (1) ensuring appropriate accounting for different ICD code versions used for cause of death data classification over time, (2) redistribution of ill-defined causes of death (described in more detail elsewhere) and (3) processing VA studies into usable data that map to the GBD cause hierarchy.[8 9 12] The third general principle for injury cause of death models in GBD 2017 is to develop a diverse set of plausible models. This process is conducted via

Table 3 GBD nature of injury

Nature of injury		
Amputation of lower limbs, bilateral	Fracture of sternum and/or fracture of one or more ribs	Crush injury
Amputation of upper limbs, bilateral	Fracture of vertebral column	Nerve injury
Amputation of fingers (excluding thumb)	Fracture of femur, other than femoral neck	Injury to eyes
Amputation of lower limb, unilateral	Minor TBI	Poisoning requiring urgent care
Amputation of upper limb, unilateral	Moderate/severe TBI	Severe chest injury
Amputation of thumb	Spinal cord lesion at neck level	Internal haemorrhage in abdomen and pelvis
Amputation of toe/toes	Spinal cord lesion below neck level	Effect of different environmental factors
Lower airway burns	Muscle and tendon injuries, including sprains and strains lesser dislocations	Complications following therapeutic procedures
Burns, <20% total burned surface area without lower airway burns	Foreign body in ear	Multiple fractures, dislocations, crashes, wounds, pains and strains
Burns, ≥20% total burned surface area or ≥10% burned surface area if head/neck or hands/wrist involved without lower airway burns	Open wound(s)	
Fracture of clavicle, scapula or humerus	Contusion in any part of the body	
Fracture of face bones	Superficial injury of any part of the body	
Fracture of foot bones except ankle	Dislocation of hip	
Fracture of hand (wrist and other distal part of hand)	Dislocation of knee	
Fracture of hip	Dislocation of shoulder	
Fracture of patella, tibia or fibula or ankle	Foreign body in respiratory system	
Fracture of pelvis	Foreign body in GI and urogenital system	
Fracture of radius and/or ulna	Drowning and non-fatal submersion	
Fracture of skull	Asphyxiation	

GBD, Global Burden of Disease; GI, gastrointestinal; TBI, traumatic brain injury.

the Cause of Death Ensemble model (CODEm) framework, which is the standard, peer-reviewed cause of death estimation process used extensively in the GBD study. CODEm generates a large set of possible models based on covariates suggested by the modeller based on expert input and literature review (eg, alcohol for road injuries) and then runs every plausible model, which can range into the thousands per cause. These models can be conducted in both rate space and cause fraction space and use an assortment of combinations among the user-selected covariates (table 4). Fourth, the predictive validity of each one of these submodels is tested using test-train holdouts, whereby a specific model is trained on a portion of data and tested on a separate portion to determine out-of-sample predictive validity. Once the submodels are conducted and predictive validity is measured, then an ensemble model is developed out of the submodels. The submodels and the ensemble model are then subject to the fifth principle, which is to choose the best-performing models based on out-of-sample predictive validity. The chosen models may be a single cause model or an ensemble of models. Beyond these processes, which have become automated with expert review in the GBD processing architecture, there is also considerable time required by the analysts, modellers, collaborators and principal investigators who are involved in the GBD study. Such processes also come under expert scrutiny via the GBD Scientific Council and the peer-review process in the annual GBD capstone publications.[2–7]

Once submodels and ensemble models have been conducted for each cause in the GBD cause hierarchy, a process to correct for cause of death rates to ensure internal consistency is conducted. Specifically, each subcause within some overall cause is rescaled such that, for example, every subtype of road injuries sums to road injuries deaths overall, and then road injuries and other transport injuries sum to equal the overall transport injuries cause. As this cascades to the overall cause hierarchy and the overall all-cause mortality rates, cause-specific mortality across all causes ultimately equals the overall mortality in the population. An example of an injuries cause of death model with vital registration data (Colombia, females) is shown in figure 1. A similar model with relatively less data is shown in figure 2 (Honduras, females). While data are absent in more recent years in Honduras, the model is still able to follow temporal trends, age patterns and broader geographical patterns by harnessing signals from covariate-based fixed effects (eg, alcohol consumption per capita) and location-based random effects (eg, the regional trends in Central Latin America and patterns in neighbouring countries). All cause of death models from GBD 2017 are publicly available for review (https://vizhub.healthdata.org/cod/). Cause-specific deaths are converted to cause-specific mortality rates (CSMRs) using GBD populations. Once CSMRs are established, years of life lost (YLLs) are computed as the product of CSMRs and residual life expectancy at the age of death. The residual life expectancy is based on the lowest observed mortality rate for each age across all populations over 5 million. For example, if a death from road injuries occurs at age 25 and the residual life expectancy is 60 years, then there are 60 YLLs attributed to that death. If the death had occurred at age 50 with a residual life expectancy of 38 years, then 38 YLLs would be attributed. Life tables used for GBD 2017 are provided in related publications. [7]

Injury incidence, prevalence and years lived with disability

After cause-specific models for each cause of injury in the GBD cause hierarchy are conducted, the non-fatal estimation process is conducted. An overview of this process is depicted in figure 3. In the first stage, we estimate the incidence of injuries warranting medical care using DisMod-MR 2.1 (abbreviated DisMod). DisMod is a meta-regression tool for epidemiological estimation that uses a compartmental model structure whereby a healthy population may become diseased or injured, at which point the individual either remains a prevalent case, goes into remission or dies. DisMod essentially fits differential equations to reconcile the transitions between these different compartments, so that the final posterior estimate for each epidemiological parameter can be explained in the context of the other parameters.

Table 4 Covariates used in GBD cause of death models

Cause	Global or data-rich model	Sex	Number of covariates used	Covariates used
Transport injuries	Global/Data rich	Male	10	Alcohol (litres per capita), Education (years per capita), Lag distributed income per capita (I$), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Rainfall Quintile 5 (proportion), Vehicles–two+four wheels (per capita), Vehicles–two wheels fraction (proportion), Sociodemographic Index, Healthcare Access and Quality Index
Transport injuries	Global/Data rich	Female	10	Alcohol (litres per capita), Education (years per capita), Lag distributed income per capita (I$), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Rainfall Quintile 5 (proportion), Vehicles–two+four wheels (per capita), Vehicles–two wheels fraction (proportion), Sociodemographic Index, Healthcare Access and Quality Index
Road injuries	Global/Data rich	Male	13	Alcohol (liters per capita), Education (years per capita), Lag distributed income per capita (I$), Population 15 to 30 (proportion), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Vehicles–two+four wheels (per capita), Vehicles–two wheels (per capita), Vehicles - 4 wheels (per capita), Vehicles–two wheels fraction (proportion), Log-transformed summary exposure value (SEV) scalar: Road Inj, Sociodemographic Index, Healthcare Access and Quality Index
Road injuries	Global/Data rich	Female	13	Alcohol (liters per capita), Education (years per capita), Lag distributed income per capita (I$), Population 15 to 30 (proportion), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Vehicles–two+four wheels (per capita), Vehicles–two wheels (per capita), Vehicles - 4 wheels (per capita), Vehicles–two wheels fraction (proportion), Log-transformed SEV scalar: Road Inj, Sociodemographic Index, Healthcare access and quality index
Pedestrian road injuries	Global/Data rich	Male	11	Alcohol (liters per capita), Education (years per capita), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Rainfall Quintile 5 (proportion), Vehicles–two+four wheels (per capita), Vehicles–two wheels fraction (proportion), Log-transformed SEV scalar: Pedest, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Pedestrian road injuries	Global/Data rich	Female	11	Alcohol (liters per capita), Education (years per capita), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Rainfall Quintile 5 (proportion), Vehicles–two+four wheels (per capita), Vehicles–two wheels fraction (proportion), Log-transformed SEV scalar: Pedest, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Cyclist road injuries	Global/Data rich	Male	10	Alcohol (liters per capita), Education (years per capita), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Vehicles–two+four wheels (per capita), Vehicles - two wheels fraction (proportion), Log-transformed SEV scalar: Cyclist, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Cyclist road injuries	Global/Data rich	Female	10	Alcohol (liters per capita), Education (years per capita), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Vehicles - two+four wheels (per capita), Vehicles–two wheels fraction (proportion), Log-transformed SEV scalar: Cyclist, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Motorcyclist road injuries	Global/Data rich	Male	10	Alcohol (liters per capita), Education (years per capita), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Rainfall Quintile 5 (proportion), Vehicles–two wheels (per capita), Log-transformed SEV scalar: Mot Cyc, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Motorcyclist road injuries	Global/Data rich	Female	10	Alcohol (liters per capita), Education (years per capita), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Rainfall Quintile 5 (proportion), Vehicles–two wheels (per capita), Log-transformed SEV scalar: Mot Cyc, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Motor vehicle road injuries	Global/Data rich	Male	10	Alcohol (liters per capita), Education (years per capita), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Rainfall Quintile 5 (proportion), Vehicles–four wheels (per capita), Log-transformed SEV scalar: Mot Veh, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Motor vehicle road injuries	Global/Data rich	Female	10	Alcohol (liters per capita), Education (years per capita), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Rainfall Quintile 5 (proportion), Vehicles–four wheels (per capita), Log-transformed SEV scalar: Mot Veh, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Other road injuries	Global/Data rich	Male	8	Alcohol (liters per capita), Rainfall Quintile 5 (proportion), Vehicles–two+four wheels (per capita), Vehicles–two wheels fraction (proportion), Log-transformed SEV scalar: Oth Road, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Other road injuries	Global/Data rich	Female	8	Alcohol (liters per capita), Rainfall Quintile 5 (proportion), Vehicles–two+four wheels (per capita), Vehicles–two wheels fraction (proportion), Log-transformed SEV scalar: Oth Road, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Other transport injuries	Global/Data rich	Male	11	Alcohol (liters per capita), Education (years per capita), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Rainfall Quintile 5 (proportion), Vehicles–two+four wheels (per capita), Vehicles–two wheels fraction (proportion), Log-transformed SEV scalar: Oth Trans, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Other transport injuries	Global/Data rich	Female	11	Alcohol (liters per capita), Education (years per capita), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Rainfall Quintile 5 (proportion), Vehicles–two+four wheels (per capita), Vehicles–two wheels fraction (proportion), Log-transformed SEV scalar: Oth Trans, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Falls	Global/Data rich	Male	7	Alcohol (liters per capita), Elevation Over 1500 m (proportion), Log-transformed SEV scalar: Falls, Sociodemographic Index, milk adjusted(g), Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Falls	Global/Data rich	Female	7	Alcohol (liters per capita), Elevation Over 1500 m (proportion), Log-transformed SEV scalar: Falls, Sociodemographic Index, milk adjusted(g), Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Drowning	Global/Data rich	Male	10	Alcohol (liters per capita), Coastal Population within 10 km (proportion), Education (years per capita), Landlocked Nation (binary), Elevation Under 100 m (proportion), Rainfall Quintile 1 (proportion), Rainfall Quintile 5 (proportion), Log-transformed SEV scalar: Drown, Sociodemographic Index, Lag distributed income per capita (I$)
Drowning	Global/Data rich	Female	10	Alcohol (liters per capita), Coastal Population within 10 km (proportion), Education (years per capita), Landlocked Nation (binary), Elevation Under 100 m (proportion), Rainfall Quintile 1 (proportion), Rainfall Quintile 5 (proportion), Log-transformed SEV scalar: Drown, Sociodemographic Index, Lag distributed income per capita (I$)

Continued

Table 4 Continued

Fire, heat and hot substances	Global/Data rich	Male	9	Alcohol (liters per capita), Tobacco (cigarettes per capita), Education (years per capita), Indoor Air Pollution (All Cooking Fuels), Population Density (over 1000 ppl/sqkm, proportion), Log-transformed SEV scalar: Fire, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Fire, heat and hot substances	Global/Data rich	Female	9	Alcohol (liters per capita), Tobacco (cigarettes per capita), Education (years per capita), Indoor Air Pollution (All Cooking Fuels), Population Density (over 1000 ppl/sqkm, proportion), Log-transformed SEV scalar: Fire, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Poisonings	Global/Data rich	Male	8	Education (years per capita), Opium Cultivation (binary), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Log-transformed SEV scalar: Poison, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Poisonings	Global/Data rich	Female	8	Education (years per capita), Opium Cultivation (binary), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Log-transformed SEV scalar: Poison, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Poisoning by carbon monoxide	Global/Data rich	Male	4	Education (years per capita), Lag distributed income per capita (I$), Sociodemographic Index, Healthcare Access and Quality Index
Poisoning by carbon monoxide	Global/Data rich	Female	4	Education (years per capita), Lag distributed income per capita (I$), Sociodemographic Index, Healthcare access and quality index
Poisoning by other means	Global/Data rich	Male	4	Education (years per capita), Lag distributed income per capita (I$), Sociodemographic Index, Healthcare access and quality index
Poisoning by other means	Global/Data rich	Female	4	Education (years per capita), Lag distributed income per capita (I$), Sociodemographic Index, Healthcare access and quality index
Exposure to mechanical forces	Global/Data rich	Male	7	Alcohol (liters per capita), Education (years per capita), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Sociodemographic Index, Healthcare access and quality index, Lag distributed income per capita (I$)
Exposure to mechanical forces	Global/Data rich	Female	7	Alcohol (liters per capita), Education (years per capita), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Sociodemographic Index, Healthcare access and quality index, Lag distributed income per capita (I$)
Unintentional firearm injuries	Global/Data rich	Male	9	Alcohol (liters per capita), Education (years per capita), Health System Access (unitless), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Log-transformed SEV scalar: Mech Gun, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Unintentional firearm injuries	Global/Data rich	Female	9	Alcohol (liters per capita), Education (years per capita), Health System Access (unitless), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Log-transformed SEV scalar: Mech Gun, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Other exposure to mechanical forces	Global/Data rich	Male	9	Alcohol (liters per capita), Education (years per capita), Health System Access (unitless), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Log-transformed SEV scalar: Oth Mech, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Other exposure to mechanical forces	Global/Data rich	Female	9	Alcohol (liters per capita), Education (years per capita), Health System Access (unitless), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Log-transformed SEV scalar: Oth Mech, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Adverse effects of medical treatment	Global/Data rich	Male	3	Lag distributed income per capita (I$), Sociodemographic Index, Healthcare Access and Quality Index
Adverse effects of medical treatment	Global/Data rich	Female	3	Lag distributed income per capita (I$), Sociodemographic Index, Healthcare Access and Quality Index
Animal contact	Global/Data rich	Male	11	Alcohol (liters per capita), Education (years per capita), Elevation Over 1500 m (proportion), Population 15 to 30 (proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Elevation Under 100 m (proportion), Log-transformed SEV scalar: Animal, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Animal contact	Global/Data rich	Female	11	Alcohol (liters per capita), Education (years per capita), Elevation Over 1500 m (proportion), Population 15 to 30 (proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Elevation Under 100 m (proportion), Log-transformed SEV scalar: Animal, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Venomous animal contact	Global/Data rich	Male	10	Alcohol (liters per capita), Education (years per capita), Elevation Over 1500 m (proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Elevation Under 100 m (proportion), Log-transformed SEV scalar: Venom, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Venomous animal contact	Global/Data rich	Female	10	Alcohol (liters per capita), Education (years per capita), Elevation Over 1500 m (proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Elevation Under 100 m (proportion), Log-transformed SEV scalar: Venom, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Non-venomous animal contact	Global	Male	6	Alcohol (liters per capita), Education (years per capita), Lag distributed income per capita (I$), Log-transformed SEV scalar: Non Ven, Sociodemographic Index, Healthcare Access and Quality Index
Non-venomous animal contact	Data rich	Male	10	Alcohol (liters per capita), Education (years per capita), Elevation Over 1500 m (proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Elevation Under 100 m (proportion), Log-transformed SEV scalar: Non Ven, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Non-venomous animal contact	Global/Data rich	Female	10	Alcohol (liters per capita), Education (years per capita), Elevation Over 1500 m (proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Elevation Under 100 m (proportion), Log-transformed SEV scalar: Non Ven, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Foreign body	Global	Male	10	Education (years per capita), Indoor Air Pollution (All Cooking Fuels), Population Density (over 1000 ppl/sqkm, proportion), Population Over 65 (proportion), Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Foreign body	Global	Female	10	Education (years per capita), Indoor Air Pollution (All Cooking Fuels), Population Density (over 1000 ppl/sqkm, proportion), Population Over 65 (proportion), Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)

Continued

Table 4 Continued

Pulmonary aspiration and foreign body in airway	Global/Data rich	Male	6	Alcohol (liters per capita), Lag distributed income per capita (I$), Mean BMI, Log-transformed SEV scalar: F Body Aspn, Sociodemographic Index, Access and Quality Index
Pulmonary aspiration and foreign body in airway	Global	Female	8	Alcohol (liters per capita), Education (years per capita), Mean BMI, Alcohol binge drinker proportion, age-standardised, Log-transformed SEV scalar: F Body Aspn, Sociodemographic Index, Healthcare access and quality index, Lag distributed income per capita (I$)
Pulmonary aspiration and foreign body in airway	Data rich	Female	6	Alcohol (liters per capita), Lag distributed income per capita (I$), Mean BMI, Log-transformed SEV scalar: F Body Aspn, Sociodemographic Index, Healthcare Access and Quality Index
Foreign body in other body part	Global/Data rich	Male	10	Alcohol (liters per capita), Education (years per capita), Elevation Over 1500 m (proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Elevation Under 100 m (proportion), Log-transformed SEV scalar: Oth F Body, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Foreign body in other body part	Global/Data rich	Female	10	Alcohol (liters per capita), Education (years per capita), Elevation Over 1500 m (proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Elevation Under 100 m (proportion), Log-transformed SEV scalar: Oth F Body, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Environmental heat and cold exposure	Global/Data rich	Male	11	Education (years per capita), Lag distributed income per capita (I$), Population-weighted mean temperature, Elevation Over 1500 m (proportion), Elevation 500 to 1500 m (proportion), Population Density (150–300 ppl/sqkm, proportion), Rainfall (Quintiles 4–5), Sanitation (proportion with access), 90th percentile climatic temperature in the given country-year, Sociodemographic Index, Healthcare Access and Quality Index
Environmental heat and cold exposure	Global/Data rich	Female	11	Education (years per capita), Lag distributed income per capita (I$), Population-weighted mean temperature, Elevation Over 1500 m (proportion), Elevation 500 to 1500 m (proportion), Population Density (150–300 ppl/sqkm, proportion), Rainfall (Quintiles 4–5), Sanitation (proportion with access), 90th percentile climatic temperature in the given country-year, Sociodemographic Index, Healthcare Access and Quality Index
Other unintentional injuries	Global/Data rich	Male	12	Alcohol (liters per capita), Education (years per capita), Elevation Over 1500 m (proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Elevation Under 100 m (proportion), Vehicles–two wheels (per capita), Vehicles–four wheels (per capita), Log-transformed SEV scalar: Oth Unint, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Other unintentional injuries	Global/Data rich	Female	12	Alcohol (liters per capita), Education (years per capita), Elevation Over 1500 m (proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Elevation Under 100 m (proportion), Vehicles–two wheels (per capita), Vehicles–four wheels (per capita), Log-transformed SEV scalar: Oth Unint, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Self-harm	Global	Male	11	Alcohol (liters per capita), Education (years per capita), Population Density (150–300 ppl/sqkm, proportion), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Sociodemographic Index, Healthcare Access and Quality Index, Muslim Religion (proportion of population), Lag distributed income per capita (I$)
Self-harm	Global	Female	15	Alcohol (liters per capita), Education (years per capita), Population Density (150–300 ppl/sqkm, proportion), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Religion (binary,>50% Muslim), Log-transformed SEV scalar: Self Harm, Sociodemographic Index, Major depressive disorder, Risk of selfharm due to major depressive disorder, Healthcare Access and Quality Index, Non-partner lifetime prevalence of sexual violence (female-only), Lag distributed income per capita (I$)
Self-harm	Data rich	Male	11	Alcohol (liters per capita), Education (years per capita), Population Density (150–300 ppl/sqkm, proportion), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Religion (binary,>50% Muslim), Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Self-harm	Data rich	Female	13	Alcohol (liters per capita), Education (years per capita), Population Density (150–300 ppl/sqkm, proportion), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Religion (binary,>50% Muslim), Log-transformed SEV scalar: Self Harm, Sociodemographic Index, Major depressive disorder, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Self-harm by firearm	Global/Data rich	Male	13	Alcohol (liters per capita), Education (years per capita), Population Density (150–300 ppl/sqkm, proportion), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Religion (binary,>50% Muslim), Log-transformed SEV scalar: Self Harm, Sociodemographic Index, Major depressive disorder, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Self-harm by firearm	Global/Data rich	Female	13	Alcohol (liters per capita), Education (years per capita), Population Density (150–300 ppl/sqkm, proportion), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Religion (binary,>50% Muslim), Log-transformed SEV scalar: Self Harm, Sociodemographic Index, Major depressive disorder, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Self-harm by other specified means	Global/Data rich	Male	13	Alcohol (liters per capita), Education (years per capita), Population Density (150–300 ppl/sqkm, proportion), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Religion (binary,>50% Muslim), Log-transformed SEV scalar: Self Harm, Sociodemographic Index, Major depressive disorder, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Self-harm by other specified means	Global/Data rich	Female	13	Alcohol (liters per capita), Education (years per capita), Population Density (150–300 ppl/sqkm, proportion), Population Density (300–500 ppl/sqkm, proportion), Population Density (500–1000 ppl/sqkm, proportion), Population Density (over 1000 ppl/sqkm, proportion), Population Density (under 150 ppl/sqkm, proportion), Religion (binary,>50% Muslim), Log-transformed SEV scalar: Self Harm, Sociodemographic Index, Major depressive disorder, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Interpersonal violence	Global/Data rich	Male	8	Alcohol (liters per capita), Education (years per capita), Opium Cultivation (binary), Population Density (over 1000 ppl/sqkm, proportion), Log-transformed SEV scalar: Violence, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)

Continued

Table 4 Continued

Interpersonal violence	Global/Data rich	Female	8	Alcohol (liters per capita), Education (years per capita), Opium Cultivation (binary), Population Density (over 1000 ppl/sqkm, proportion), Log-transformed SEV scalar: Violence, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Physical violence by firearm	Global/Data rich	Male	8	Alcohol (liters per capita), Education (years per capita), Opium Cultivation (binary), Population Density (over 1000 ppl/sqkm, proportion), Log-transformed SEV scalar: Viol Gun, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Physical violence by firearm	Global/Data rich	Female	8	Alcohol (liters per capita), Education (years per capita), Opium Cultivation (binary), Population Density (over 1000 ppl/sqkm, proportion), Log-transformed SEV scalar: Viol Gun, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Physical violence by sharp object	Global/Data rich	Male	8	Alcohol (liters per capita), Education (years per capita), Opium Cultivation (binary), Population Density (over 1000 ppl/sqkm, proportion), Log-transformed SEV scalar: Viol Knife, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Physical violence by sharp object	Global/Data rich	Female	8	Alcohol (liters per capita), Education (years per capita), Opium Cultivation (binary), Population Density (over 1000 ppl/sqkm, proportion), Log-transformed SEV scalar: Viol Knife, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Physical violence by other means	Global/Data rich	Male	8	Alcohol (liters per capita), Education (years per capita), Opium Cultivation (binary), Population Density (over 1000 ppl/sqkm, proportion), Log-transformed SEV scalar: Oth Viol, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Physical violence by other means	Global/Data rich	Female	8	Alcohol (liters per capita), Education (years per capita), Opium Cultivation (binary), Population Density (over 1000 ppl/sqkm, proportion), Log-transformed SEV scalar: Oth Viol, Sociodemographic Index, Healthcare Access and Quality Index, Lag distributed income per capita (I$)
Executions and police conflict	Global/Data rich	Male	6	Alcohol (liters per capita), Education (years per capita), Lag distributed income per capita (I$), Population Density (over 1000 ppl/sqkm, proportion), Sociodemographic Index, Healthcare Access and Quality Index
Executions and police conflict	Global/Data rich	Female	6	Alcohol (liters per capita), Education (years per capita), Lag distributed income per capita (I$), Population Density (over 1000 ppl/sqkm, proportion), Sociodemographic Index, Healthcare Access and Quality Index

BMI, body mass index.

Similar to the principles described in CODEm, DisMod uses all available data, ranging from incidence data to cause-specific mortality rates from the corrected CODEm results, to produce estimates for every age, sex, year and location. For the purposes of injuries, we established our case definition for non-fatal injuries as injuries that require medical care. This is a necessary case definition as we do not want to consider minor stumbles and falls, for example, that led to no actual bodily harm as injuries for GBD, since they would not have any associated disability. These models are conducted only for injury *causes* as opposed to the nature of injuries references above. Each data input is designated based on type of data—specifically, inpatient data, outpatient

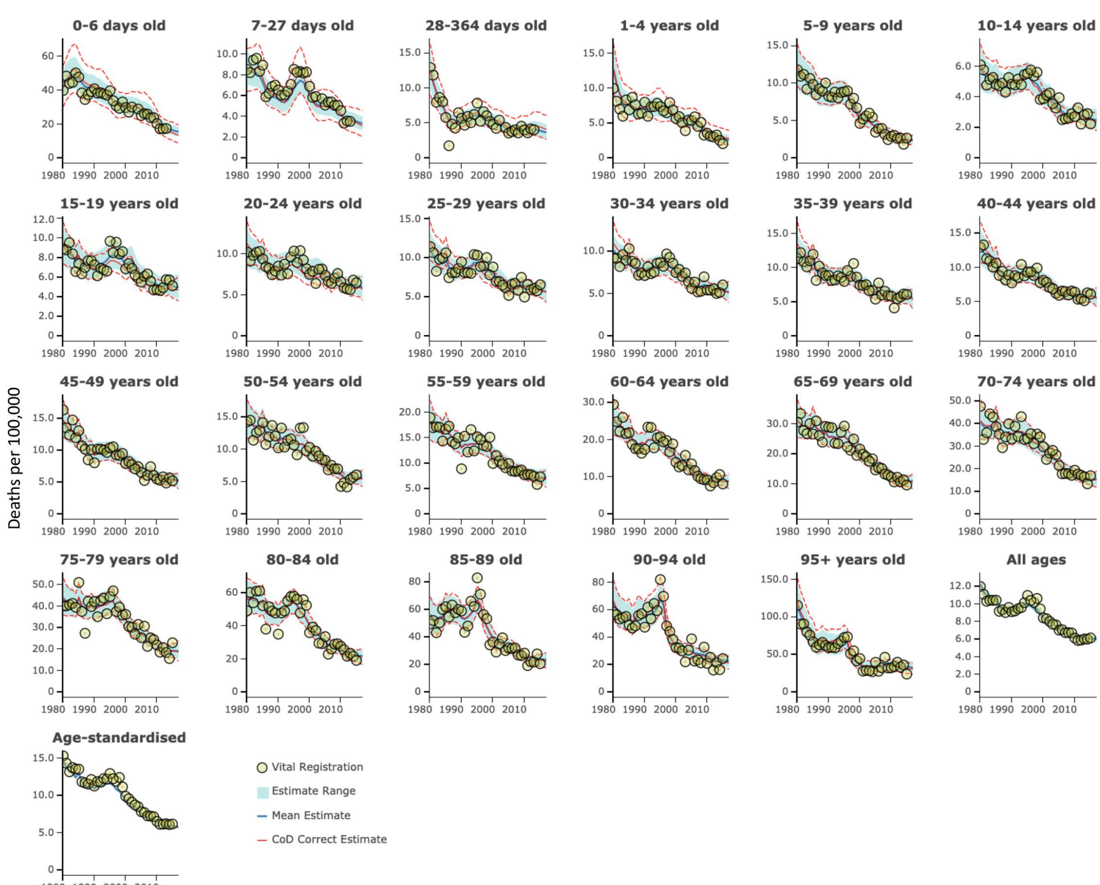

Figure 1 Cause of Death Ensemble model with data points for road injuries in Colombia for females.

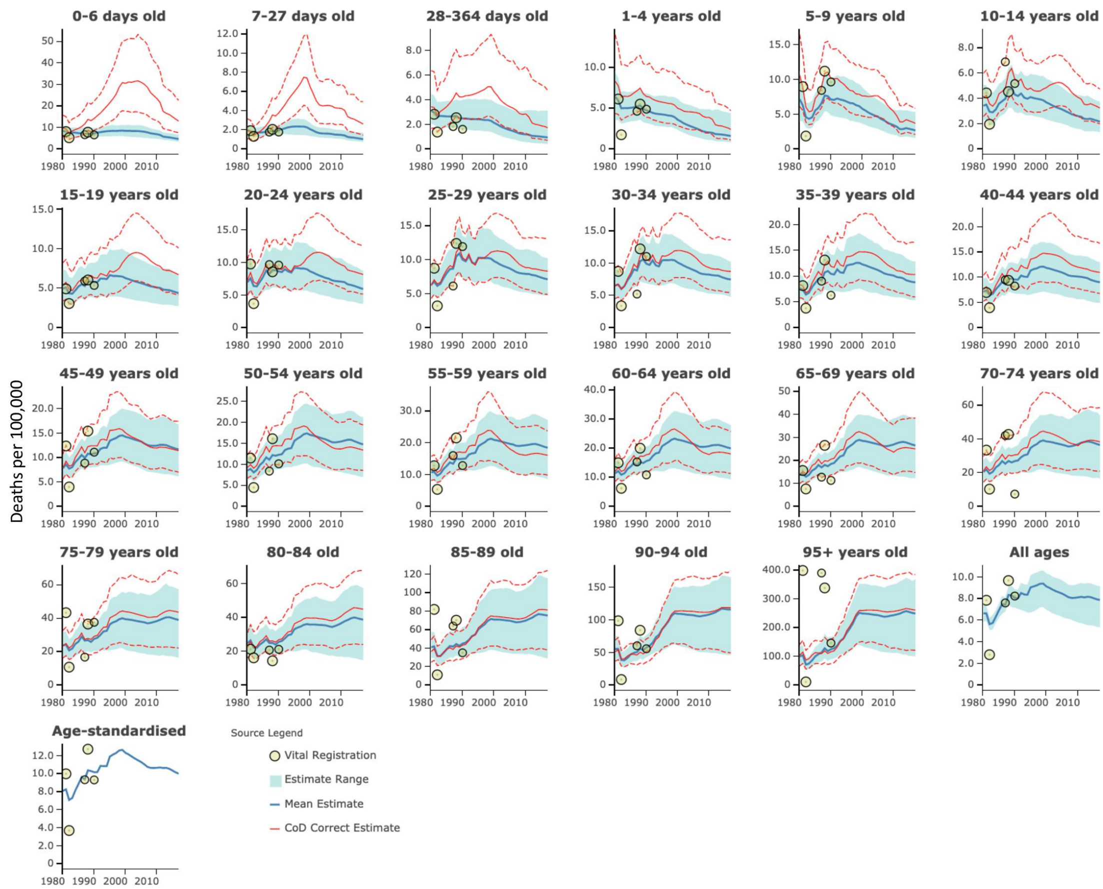

Figure 2 Cause of Death Ensemble model with data points for road injuries in Honduras for females

data, surveillance data, survey data and literature studies that are population-representative. We model incidence rates for hospital admissions for injuries, so the non-inpatient data sources get adjusted according to their classification so that the model inputs are consistent as injuries that warranted or received inpatient medical care. The coefficients measured by DisMod that were used for adjustment are provided in table 5. Input data for injury cause incidence models included sources identified as part of systematic reviews conducted in past GBD cycles, new sources identified by the GBD collaborator network and new sources of clinical data and other injuries data obtained by the core injuries burden estimation team at the Institute for Health Metrics and

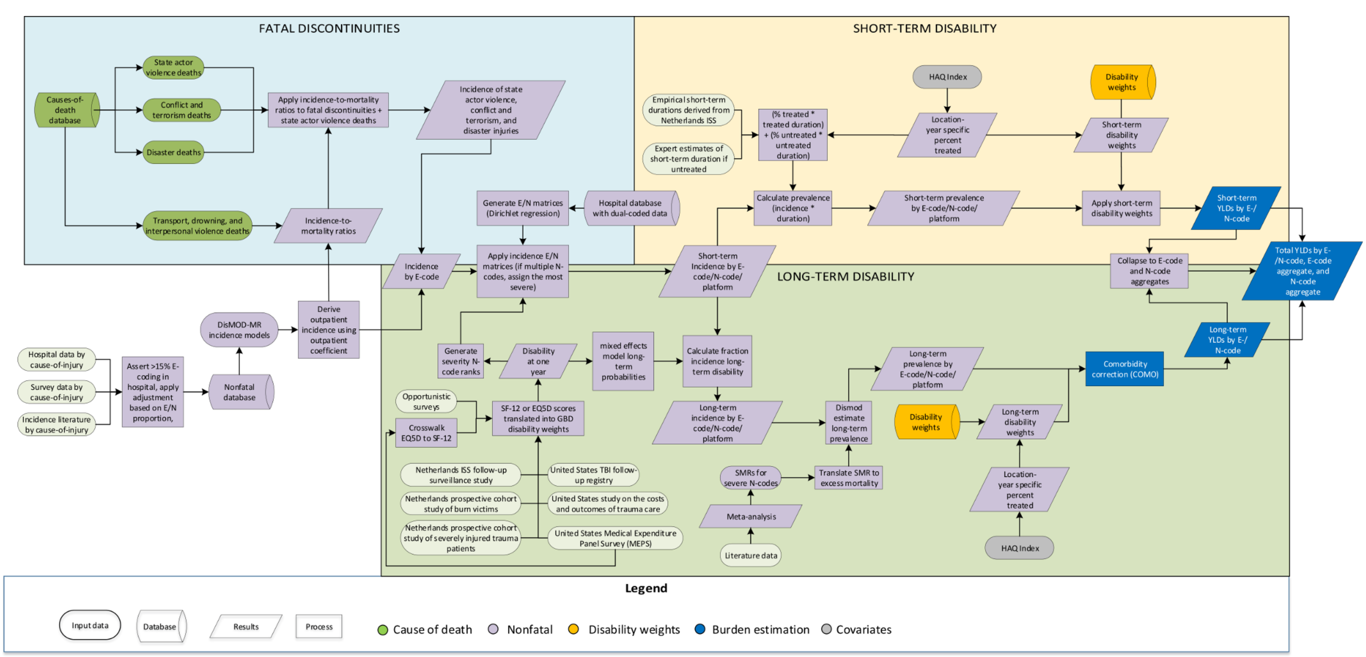

Figure 3 Injuries non-fatal estimation flow chart.

Table 5 Covariates and coefficients used in Global Burden of Disease incidence cause models

Cause	Outpatient coefficient	Injury receiving formal care, inpatient and outpatient coefficient	Injury warranting medical care coefficient
Animal contact	7.04 (7.03–7.04)	7.56 (6.91–8.31)	
Non-venomous animal contact	2.91 (2.91–2.92)	11.21 (10.1–12.38)	
Venomous animal contact	3.14 (3.01–3.34)	4.09 (3.69–4.5)	
Drowning	0.88 (0.87–0.89)	1.01 (1.0–1.05)	30.42 (15.33–51.11)
Falls	6.91 (6.89–6.94)	5.94 (5.5–6.46)	9.73 (9.28–10.22)
Fire, heat and hot substances	3.53 (3.53–3.56)	7.82 (7.24–8.51)	
Pulmonary aspiration and foreign body in airway	3.37 (3.35–3.43)	15.36 (13.93–16.86)	
Foreign body in eyes	931.4 (923.34–934.49)	302.06 (251.14–365.04)	
Foreign body in other body part	1.97 (1.95–2.01)	20.97 (15.55–26.26)	
Interpersonal violence	6.57 (6.56–6.61)	21.43 (13.6–32.79)	46.97 (39.57–53.62)
Assault by firearm	1.36 (1.29–1.44)	1.27 (1.05–1.6)	53.58 (50.65–54.54)
Assault by sharp object	3.18 (2.92–3.5)	2.38 (1.86–3.22)	37.91 (28.3–50.05)
Assault by other means	5.65 (5.44–5.89)	2.44 (2.02–3.2)	
Exposure to mechanical forces	12.4 (12.0–12.82)	33.3 (30.51–36.23)	
Unintentional firearm injuries	2.71 (2.53–2.9)	4.6 (3.49–6.36)	
Other exposure to mechanical forces	12.62 (12.55–12.85)	30.77 (25.74–36.09)	
Adverse effects of medical treatment	1.06 (1.06–1.06)	19.81 (17.29–26.1)	
Environmental heat and cold exposure	3.91 (3.9–3.94)		17.54 (3.91–49.6)
Other unintentional injuries	13.53 (13.46–13.78)		14.95 (9.62–24.12)
Poisonings	3.96 (3.73–4.19)	3.78 (3.4–4.21)	8.47 (4.41–16.64)
Poisoning by carbon monoxide	5.86 (5.68–5.92)		
Poisoning by other means	4.18 (3.9–4.5)		
Self-harm	2.75 (2.75–2.78)	2.5 (2.2–2.83)	
Self-harm by firearm	2.77 (2.42–3.07)	16.94 (2.81–51.06)	
Self-harm by other specified means	1.5 (1.47–1.51)	6.73 (2.78–19.14)	
Other transport injuries	1.65 (1.6–1.77)	1.01 (1.0–1.03)	
Road injuries	3.77 (3.75–3.78)	6.16 (5.65–6.68)	15.44 (13.25–18.1)
Motorcyclist road injuries	1.94 (1.92–1.99)		
Motor vehicle road injuries	4.48 (4.46–4.48)		
Other road injuries	6.9 (6.89–6.96)		
Cyclist road injuries	4.54 (4.33–4.89)		
Pedestrian road injuries	1.94 (1.94–1.96)	15.78 (7.63–36.6)	

Evaluation at the University of Washington. In addition, CSMRs from the corrected CODEm models described above are used in this stage of DisMod modelling. The list of non-fatal injury sources used in GBD 2017 is provided in online supplementary appendix table 2. The completed DisMod models for inpatient incidence for each cause of injury are publicly available at https://vizhub.healthdata.org/epi/.

Once an incidence cause model is constructed for each cause of injury, an extensive analytical 'pipeline' follows which converts injury cause incidence into years lived with disability. First, inpatient incidence is split into inpatient and outpatient incidence using coefficients empirically measured by DisMod. The outpatient coefficients for each injury cause are also included in table 5. Separate pipelines are then conducted for inpatient and outpatient injury incidence—each step below can be considered to have been run for both streams of data, for each cause of injury. After the coefficient is applied, incidence is adjusted by the excess mortality rate measured by DisMod to essentially remove injury cases that died after the injury occurred. Once these deaths are removed from the incidence pool, the resulting steps are applied to these surviving cases of injury. First, each new case of injury is considered to have 47 possible 'natures' of injury that can result. These are the types of bodily injury that are considered to be possible outcomes from a given injury cause. The proportion of new cases of injury that would have some nature of injury as the most disabling outcome is determined based on dual-coded clinical data sources where both the cause and nature of injury were included as ICD codes.[10] Of note, one limitation of this process is that due to computational demands, it is currently only possible to apportion the most disabling nature of injury for each new case of injury. As such, the probability that each nature of injury is the most disabling nature of injury for some cause of injury is modelled in a Dirichlet regression such that the probabilities sum to 1. In other words, each nature of injury has some probability of being the most disabling injury suffered by the victim of some cause of injury, but if multiple natures of injury occurred, then the less disabling injuries are not captured as part of that injury cause's disability. This limitation has been recognised as a limitation of GBD injury burden estimation in various peer-reviewed articles and will likely be addressed in future GBD updates as computational efficiency improves.[3 10]

The probability distributions of each cause-nature are computed separately for each age, sex, year and location. At this point, the analytical stage has the age-specific, sex-specific, year-specific, location-specific incidence of a cause-nature combination, for example, the incidence of road injuries that led to a cervical-level spinal cord injury in males aged 20–24 years in

2017 in Stockholm, Sweden. The next step converts these incidence estimates into short-term and long-term injury incidence estimates, where long-term disability is defined as having a lower functional status 1 year postinjury than at the time of injury. These probabilities were measured using long-term follow-up studies.[14–20] For some natures of injury, such as lower extremity amputation, the probability of being a long-term injury is 1. The probabilities of short-term versus long-term injury for each cause-nature combination are used to split the incidence values into short-term and long-term pipelines. The long-term incidence is then converted to prevalence using the ordinary differential equation solver used in DisMod, which also uses as an input excess mortality estimated for certain natures of injury such as traumatic brain injury and spinal cord injury conducted in a previous systematic review and meta-analysis. The short-term incidence is converted to prevalence by multiplying incidence and duration of injury, where duration of injury was either computed directly from follow-up studies or, in the case of unavailable data, estimated by an expert clinical panel involved in previous iterations of the GBD study. Since access to medical treatment is assumed to affect duration of injury and disability, the GBD Healthcare Access and Quality Index is used to estimate the proportion with and without access to medical treatment on a location-specific basis.[21] The average duration for short-term injury is therefore calculated as the percentage treated multiplied by treated duration added to the percentage untreated multiplied by the untreated duration. The output from this step is the short-term prevalence of each cause-nature combination. Short-term prevalence is subtracted from long-term prevalence at this stage to avoid double counting the same case of injury. Once short-term and long-term prevalence estimates for each cause-nature are computed, then disability weights as derived by the Salomon *et al* process are assigned to each injury nature.[22] Short-term disability weights by injury nature are shown in table 6, which does not include amputations since we assume they cause only long-term disability. The full list of long-term disability weights by injury nature, location and year are provided in online supplementary appendix table 3, which does not include foreign body in respiratory system, foreign body in gastrointestinal and urogenital system, foreign body in ear and superficial injury of any part of body, since we assume these natures of injury do not cause long-term disability. After disability weights are assigned to each injury case, years lived with disability for each cause of injury are calculated as the prevalence of each health state multiplied by the corresponding disability weight and then summed across natures of injury for each cause to compute years lived with disability (YLDs) for each age, sex, year and location for that injury cause. YLDs then undergo comorbidity adjustment used across the GBD study whereby comorbid cases of disease and injury in the population are simulated and adjusted disability weights are computed. These processes are described in more detail in GBD literature.[3] GBD 2017 provided an important methodological update whereby nature of injury results, regardless of cause of injury, could be reviewed in the results from this process; this has enabled more advanced GBD research such as measuring the burden of traumatic brain injury and spinal cord injury, measuring the burden of facial fractures and measuring the burden of hand and finger fractures.[10]

Table 6 Short-term disability weights for each nature of injury

Nature of injury	Short-term disability weight
Spinal cord lesion at neck level	0.7319
Spinal cord lesion below neck level	0.6235
Foreign body in respiratory system	0.4079
Lower airway burns	0.3764
Severe chest Injury	0.3685
Internal haemorrhage in abdomen and pelvis	0.3242
Burns, ≥20% total burned surface area or ≥10% burned surface area if head/neck or hands/wrist involved without lower airway burns	0.3145
Fracture of pelvis	0.2788
Fracture of hip	0.2575
Multiple fractures, dislocations, crashes, wounds, sprains and strains	0.2575
Drowning and non-fatal submersion	0.2471
Asphyxiation	0.2471
Moderate TBI	0.2137
Poisoning requiring urgent care	0.1628
Burns, <20% total burned surface area without lower airway burns	0.1408
Effect of different environmental factors	0.1334
Complications following therapeutic procedures	0.1334
Crush injury	0.1325
Foreign body in GI and urogenital system	0.1143
Dislocation of knee	0.1134
Fracture of femur, other than femoral neck	0.1114
Fracture of vertebral column	0.1106
Minor TBI	0.11
Fracture of sternum and/or fracture of one or more ribs	0.1027
Nerve injury	0.0997
Fracture of skull	0.0714
Fracture of face bones	0.0669
Dislocation of shoulder	0.062
Injury to eyes	0.0543
Fracture of patella, tibia or fibula or ankle	0.0501
Fracture of clavicle, scapula or humerus	0.0349
Fracture of radius and/or ulna	0.0281
Fracture of foot bones except ankle	0.026
Dislocation of hip	0.0159
Foreign body in ear	0.0133
Fracture of hand (wrist and other distal part of hand)	0.0099
Muscle and tendon injuries, including sprains and strains lesser dislocations	0.0075
Contusion in any part of the body	0.0075
Superficial injury of any part of the body	0.0075
Open wound(s)	0.0058

GI, gastrointestinal; TBI, traumatic brain injury.

Sexual violence

Sexual violence follows a different analytical pathway than the other causes of injury. This process is shown in figure 4. We used the same study framework as was developed for other injury rates in the GBD 2017 study to estimate the yearly proportion of the population that experienced at least one episode of sexual violence in the past year, using a case definition of any sexual assault including penetrative sexual violence (rape) and non-penetrative sexual violence (other forms of unwanted sexual touching). To inform the sexual violence estimates, we identified data in 93 countries that met the case definition above. This resulted in 263 site-years of data, which mainly were derived from surveys such as Demographic and Health Surveys and Reproductive Health Surveys. Similar to our other injury models, we used DisMod 2.1 to model prevalence. The

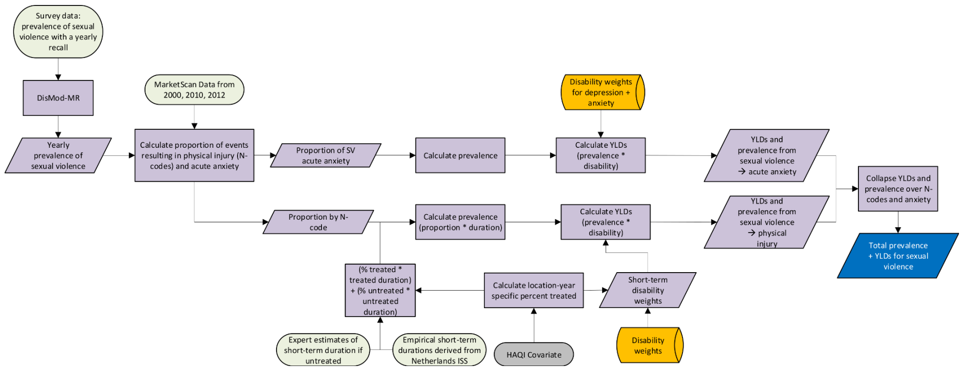

Figure 4 Sexual violence estimation flow chart. HAQI, Healthcare Access and Quality Index.

sexual violence prevalence model used study-level covariates for each type of survey question, for example, we used a study-level covariate to identify surveys that identify penetrative sexual violence only to account for how the overall incidence of sexual violence is greater than this value. This model also used a covariate on alcohol use in litres per capita for each location to help fit the model in data-sparse locations. Once yearly prevalence was measured, sexual violence cases undergo a process by which short-term disability from the physical and psychological harm of sexual violence cases is assigned to each prevalent case; however, long-term sequelae of sexual violence are currently not captured in this process, which has been a known limitation of sexual violence estimation in the GBD framework.

Disability-adjusted life-years

After estimation of cause-specific mortality and YLLs as well as non-fatal health outcomes estimation including YLDs, DALYs are calculated as the sum of YLLs and YLDs for each cause of injury. YLDs are also calculated for each nature of injury category.

GATHER statement

GBD 2017 adheres to the Guidelines for Accurate and Transparent Health Estimates Reporting (GATHER). GATHER is described in more detail in online supplementary appendix 2.

RESULTS

Results for all GBD 2017 injury estimates are available in associated publications as well as online. Specifically, results by age, sex, year, subnational location and nature of injury can be viewed and downloaded online via the GBD Results Tool (http://ghdx.healthdata.org/gbd-results-tool) and GBD Compare (https://vizhub.healthdata.org/gbd-compare/). These results are available in terms of incidence, prevalence, YLDs, cause-specific mortality, YLLs and DALYs, expressed in counts, rates, and percentages. Analytical code and input datasets are available at http://ghdx.healthdata.org.

CODEm models

Model performance metrics for each injury cause model in GBD 2017 are provided in table 7. Model performance metrics for CODEm models include root mean square error (RMSE) for in-sample tests and out-of-sample tests, percentage of data points that correctly predict the trend in-sample and out-of-sample and percentage of data points that are present within the 95% uncertainty intervals (UIs) of the model fit. RMSE in-sample is generally better than RMSE out-of-sample, which is an expected result that also demonstrates the importance of performing out-of-sample predictive validity tests. While the correct trend is predicted in approximately one in five models, this may also be related to more dynamic temporal trends in injury mortality patterns over time. In general, most data points exist within the 95% UI of the model fit (mean: 98.5% in-sample, 98.0% out-of-sample).

Incidence models

Model performance metrics for each injury cause model in GBD 2017 are provided in table 8. These model performance metrics include in-sample coverage and RMSE of estimated results for cause-specific mortality, excess mortality and incidence. There are no performance metrics for CSMR or excess mortality for foreign body in eyes since we do not estimate mortality from this cause of injury. For incidence, the in-sample coverage average was 55.3% across cause-of-injury models and ranged from a low of 26% in falls to a high of 88% in poisoning by carbon monoxide. Incidence RMSE ranged from a low of 1.04 in pedestrian road injuries to a high of 4.86 in foreign body in eye.

DISCUSSION

Many considerable advancements have been made in the measurement of global injury burden since early versions of the GBD Study. Novel datasets, sophisticated statistical modelling and global collaboration have all facilitated the advancement of injury burden measurement science. Many more advancements in future updates should be possible as larger datasets become available and as computational power allows for more detailed measurement processes. Continued global collaboration will be an integral component. Suggested priority items for the advancement of injury burden estimation are as follows:

First, while much of the global injury burden occurs in low-income and middle-income countries, these countries are frequently the most data-sparse. GBD has rigorously attempted to collect all available data, including police records and verbal autopsy studies and inpatient and outpatient records; however, it is likely that additional data sources in data-sparse countries exist. Parties who are aware of additional data sources that could be used in the GBD estimation framework should consider joining the GBD collaborator network to contribute new sources of data to be used in future estimation updates.

Second, computational and data limitations make it difficult to account for the full disability that might be experienced in the setting of multiple injuries. For example, if an individual sustains a below-neck spinal injury and an upper extremity amputation, the amputation is not directly accounted for in the prevalence or YLD estimate of the injury cause to which this disability is attributed. This problem quickly grows in complexity, as one can imagine an event like a road injury leading to multiple contusions and abrasions,

James SL, *et al*. *Inj Prev* 2020;**26**:i125–i153. doi:10.1136/injuryprev-2019-043531

Table 7 Performance metrics for each cause-of-injury CODEm model

Cause	Type	Sex	RMSE in-sample	RMSE out-of-sample	Per cent coverage in-sample	Per cent coverage out-of-sample
Transport injuries	Data rich	Female	0.153062	0.211028	0.999851	0.999395
Transport injuries	Data rich	Male	0.144423	0.202366	0.99978	0.998995
Transport injuries	Global	Female	0.216405	0.338398	0.99951	0.992996
Transport injuries	Global	Male	0.209561	0.327954	0.999347	0.99108
Road injuries	Data rich	Female	0.154916	0.22011	0.999945	0.999642
Road injuries	Data rich	Male	0.147432	0.208989	0.99987	0.999452
Road injuries	Global	Female	0.198002	0.338885	0.999736	0.993674
Road injuries	Global	Male	0.193896	0.321219	0.999332	0.990834
Pedestrian road injuries	Data rich	Female	0.183693	0.327964	0.999776	0.998965
Pedestrian road injuries	Data rich	Male	0.177994	0.323544	0.999688	0.998913
Pedestrian road injuries	Global	Female	0.240151	0.430127	0.999174	0.992328
Pedestrian road injuries	Global	Male	0.247329	0.409191	0.998229	0.990017
Cyclist road injuries	Data rich	Female	0.219965	0.435983	0.999892	0.999106
Cyclist road injuries	Data rich	Male	0.206919	0.500591	0.999876	0.999158
Cyclist road injuries	Global	Female	0.296895	0.528063	0.998384	0.990875
Cyclist road injuries	Global	Male	0.294776	0.527441	0.998702	0.988234
Motorcyclist road injuries	Data rich	Female	0.268406	0.653692	0.999776	0.998805
Motorcyclist road injuries	Data rich	Male	0.195368	0.444714	0.999793	0.998395
Motorcyclist road injuries	Global	Female	0.362655	0.692762	0.998726	0.99082
Motorcyclist road injuries	Global	Male	0.283024	0.502588	0.998804	0.987794
Motor vehicle road injuries	Data rich	Female	0.167766	0.33083	0.99993	0.999335
Motor vehicle road injuries	Data rich	Male	0.160584	0.309726	0.999919	0.999377
Motor vehicle road injuries	Global	Female	0.230946	0.38664	0.99957	0.995355
Motor vehicle road injuries	Global	Male	0.232898	0.378096	0.999353	0.992869
Other road injuries	Data rich	Female	0.408852	1.04171	0.997205	0.970506
Other road injuries	Data rich	Male	0.467256	1.21047	0.994429	0.9463
Other road injuries	Global	Female	0.558784	0.899497	0.994899	0.96375
Other road injuries	Global	Male	0.654189	1.0708	0.984753	0.931697
Other transport injuries	Data rich	Female	0.255843	0.406371	0.999581	0.998655
Other transport injuries	Data rich	Male	0.195575	0.404214	0.999666	0.99863
Other transport injuries	Global	Female	0.31846	0.546918	0.998599	0.991384
Other transport injuries	Global	Male	0.267514	0.49731	0.998444	0.989304
Falls	Data rich	Female	0.162773	0.237492	0.999873	0.999522
Falls	Data rich	Male	0.157114	0.220452	0.999847	0.999492
Falls	Global	Female	0.246877	0.428822	0.99923	0.988577
Falls	Global	Male	0.246101	0.369118	0.999571	0.989585
Drowning	Data rich	Female	0.177905	0.258172	0.999932	0.999782
Drowning	Data rich	Male	0.164617	0.226899	0.999868	0.999373
Drowning	Global	Female	0.238598	0.428467	0.999657	0.992777
Drowning	Global	Male	0.224438	0.361879	0.99961	0.989534
Fire, heat and hot substances	Data rich	Female	0.175426	0.245	0.999962	0.999793
Fire, heat and hot substances	Data rich	Male	0.17054	0.227618	0.999944	0.999737
Fire, heat and hot substances	Global	Female	0.281428	0.401798	0.999483	0.994548
Fire, heat and hot substances	Global	Male	0.289708	0.40982	0.999518	0.99422
Poisonings	Data rich	Female	0.190498	0.283924	0.999901	0.999732
Poisonings	Data rich	Male	0.189747	0.283639	0.999888	0.999668

Continued

Table 7 Continued

Cause	Type	Sex	RMSE in-sample	RMSE out-of-sample	Per cent coverage in-sample	Per cent coverage out-of-sample
Poisonings	Global	Female	0.311328	0.515718	0.99918	0.993385
Poisonings	Global	Male	0.323815	0.529806	0.999166	0.992089
Poisoning by carbon monoxide	Data rich	Female	0.255034	0.352342	0.999119	0.998139
Poisoning by carbon monoxide	Data rich	Male	0.234913	0.328692	0.999486	0.998765
Poisoning by carbon monoxide	Global	Female	0.353393	0.688269	0.998372	0.982832
Poisoning by carbon monoxide	Global	Male	0.305615	0.621778	0.999006	0.983458
Poisoning by other means	Data rich	Female	0.208468	0.470199	0.999861	0.998144
Poisoning by other means	Data rich	Male	0.231395	0.543185	0.999871	0.998948
Poisoning by other means	Global	Female	0.284383	0.555132	0.999746	0.989287
Poisoning by other means	Global	Male	0.288098	0.590913	0.999759	0.990146
Exposure to mechanical forces	Data rich	Female	0.171902	0.29354	0.999636	0.99932
Exposure to mechanical forces	Data rich	Male	0.162641	0.259268	0.999605	0.998955
Exposure to mechanical forces	Global	Female	0.398855	0.54379	0.995672	0.987855
Exposure to mechanical forces	Global	Male	0.325975	0.454021	0.995758	0.985214
Unintentional firearm injuries	Data rich	Female	0.207177	0.502831	0.999619	0.999488
Unintentional firearm injuries	Data rich	Male	0.221533	0.49235	0.999306	0.998449
Unintentional firearm injuries	Global	Female	0.354152	0.591674	0.998979	0.991558
Unintentional firearm injuries	Global	Male	0.355798	0.64953	0.996524	0.980841
Other exposure to mechanical forces	Data rich	Female	0.20287	0.436518	0.999912	0.999795
Other exposure to mechanical forces	Data rich	Male	0.170292	0.318704	0.999896	0.999761
Other exposure to mechanical forces	Global	Female	0.406425	0.538089	0.995379	0.98994
Other exposure to mechanical forces	Global	Male	0.361646	0.472713	0.995528	0.988955
Adverse effects of medical treatment	Data rich	Female	0.186809	0.305147	0.999832	0.999511
Adverse effects of medical treatment	Data rich	Male	0.217278	0.342415	0.999833	0.999577
Adverse effects of medical treatment	Global	Female	0.280204	0.430453	0.999698	0.993818
Adverse effects of medical treatment	Global	Male	0.277028	0.431272	0.999573	0.992957
Animal contact	Data rich	Female	0.277226	0.439671	0.999355	0.998642
Animal contact	Data rich	Male	0.231627	0.414921	0.999863	0.999528
Animal contact	Global	Female	0.401714	0.691306	0.998669	0.987713
Animal contact	Global	Male	0.316647	0.623446	0.9991	0.99176
Venomous animal contact	Data rich	Female	0.417726	0.745234	0.960501	0.956152
Venomous animal contact	Data rich	Male	0.401006	0.761481	0.977149	0.97478
Venomous animal contact	Global	Female	0.634642	0.915323	0.965066	0.949503

Continued

Table 7 Continued

Cause	Type	Sex	RMSE in-sample	RMSE out-of-sample	Per cent coverage in-sample	Per cent coverage out-of-sample
Venomous animal contact	Global	Male	0.449848	0.839185	0.97819	0.96024
Non-venomous animal contact	Data rich	Female	0.304776	0.593881	0.994547	0.991865
Non-venomous animal contact	Data rich	Male	0.304223	0.529077	0.998929	0.998113
Non-venomous animal contact	Global	Female	0.421204	0.680417	0.995082	0.9848
Non-venomous animal contact	Global	Male	0.471148	0.740524	0.998707	0.990622
Foreign body	Data rich	Female	0.170699	0.275966	0.999937	0.999705
Foreign body	Data rich	Male	0.166161	0.263143	0.999798	0.999305
Foreign body	Global	Female	0.216832	0.401408	0.999535	0.992467
Foreign body	Global	Male	0.227414	0.381598	0.999262	0.989838
Pulmonary aspiration and foreign body in airway	Data rich	Female	0.174424	0.374749	0.999979	0.999572
Pulmonary aspiration and foreign body in airway	Data rich	Male	0.178947	0.34741	0.999928	0.999294
Pulmonary aspiration and foreign body in airway	Global	Female	0.267697	0.416038	0.999413	0.993624
Pulmonary aspiration and foreign body in airway	Global	Male	0.286472	0.422915	0.998089	0.990215
Foreign body in other body part	Data rich	Female	0.31229	0.664465	0.99005	0.987846
Foreign body in other body part	Data rich	Male	0.291172	0.629172	0.993547	0.991666
Foreign body in other body part	Global	Female	0.462299	0.749894	0.98392	0.971743
Foreign body in other body part	Global	Male	0.478614	0.759133	0.984301	0.971436
Other unintentional injuries	Data rich	Female	0.266367	0.450437	0.999612	0.999067
Other unintentional injuries	Data rich	Male	0.228051	0.387409	0.999597	0.998959
Other unintentional injuries	Global	Female	0.354782	0.671813	0.997343	0.984969
Other unintentional injuries	Global	Male	0.301256	0.54085	0.997963	0.985982
Self-harm	Data rich	Female	0.157456	0.236415	0.999699	0.999206
Self-harm	Data rich	Male	0.150967	0.223371	0.999688	0.999011
Self-harm	Global	Female	0.219988	0.370761	0.998551	0.986222
Self-harm	Global	Male	0.203341	0.347213	0.999389	0.979274
Self-harm by firearm	Data rich	Female	0.215778	0.439608	0.992476	0.992525
Self-harm by firearm	Data rich	Male	0.19323	0.402898	0.998082	0.997457
Self-harm by firearm	Global	Female	0.311061	0.642889	0.987894	0.971118
Self-harm by firearm	Global	Male	0.316945	0.590367	0.992646	0.977377
Self-harm by other specified means	Data rich	Female	0.162023	0.345661	0.999855	0.998854
Self-harm by other specified means	Data rich	Male	0.235129	0.322581	0.999898	0.999453
Self-harm by other specified means	Global	Female	0.191636	0.38357	0.999636	0.98601
Self-harm by other specified means	Global	Male	0.192311	0.348953	0.999813	0.986603
Interpersonal violence	Data rich	Female	0.224081	0.294307	0.99863	0.996721
Interpersonal violence	Data rich	Male	0.220852	0.298197	0.998132	0.995665

Continued

Table 7 Continued

Cause	Type	Sex	RMSE in-sample	RMSE out-of-sample	Per cent coverage in-sample	Per cent coverage out-of-sample
Interpersonal violence	Global	Female	0.306086	0.450697	0.998456	0.989396
Interpersonal violence	Global	Male	0.307439	0.479452	0.997588	0.981596
Physical violence by firearm	Data rich	Female	0.253283	0.414003	0.998598	0.997318
Physical violence by firearm	Data rich	Male	0.277353	0.501753	0.997843	0.996142
Physical violence by firearm	Global	Female	0.44617	0.621002	0.993619	0.98712
Physical violence by firearm	Global	Male	0.41286	0.679294	0.995867	0.981991
Physical violence by sharp object	Data rich	Female	0.222036	0.393235	0.999815	0.999003
Physical violence by sharp object	Data rich	Male	0.235542	0.463121	0.999796	0.998721
Physical violence by sharp object	Global	Female	0.276474	0.499795	0.999526	0.993622
Physical violence by sharp object	Global	Male	0.332336	0.595217	0.999354	0.990212
Physical violence by other means	Data rich	Female	0.204351	0.336239	0.999954	0.999532
Physical violence by other means	Data rich	Male	0.202192	0.394188	0.999868	0.999051
Physical violence by other means	Global	Female	0.270287	0.410186	0.999719	0.995718
Physical violence by other means	Global	Male	0.285589	0.45387	0.999612	0.992595
Environmental heat and cold exposure	Data rich	Female	0.234754	0.399463	0.999403	0.999073
Environmental heat and cold exposure	Data rich	Male	0.201821	0.309939	0.999658	0.999207
Environmental heat and cold exposure	Global	Female	0.3511	0.639869	0.998595	0.989061
Environmental heat and cold exposure	Global	Male	0.33441	0.528137	0.999336	0.993068
Executions and police conflict	Data rich	Female	0.852242	1.4431	0.49803	0.533053
Executions and police conflict	Data rich	Male	0.970597	1.55607	0.629313	0.628953
Executions and police conflict	Global	Female	1.2422	1.86518	0.541687	0.549016
Executions and police conflict	Global	Male	1.04755	1.95756	0.671496	0.659889

CODEm, Cause of Death Ensemble model.

several fractures in different anatomical sites, a mild traumatic brain injury and a spinal cord injury. There are over 3.6 million permutations of injury if one considers only 10 possible natures of injury, making it difficult to quantitatively measure these relationships by cause of injury and by age, sex, year and location. Future research to address this limitation may focus on simulation studies that model the probability of different comorbid injury combinations to better inform disability weight applications.

Third, more data could be used for nature of injury measurement. Traumatic brain injury and spinal cord injury registries, for example, are not currently directly compatible with the GBD injury estimation framework yet provide rich epidemiological information. Future updates to GBD should focus more attention on incorporating data that measure burden of nature of injury in terms of incidence, prevalence or excess mortality. Incorporating these types of data would require a method to be developed such that estimates were internally consistent across cause-nature distributions. While the methods and data required for this update would be complex, they would represent a large increase in the available data that could be used for GBD injuries estimation.

Fourth, measuring the total burden of sexual violence has proven to be a challenging area of estimation in the GBD framework. As noted in the 'Methods' section of this paper, one known limitation is how long-term sequelae and conditions may not be adequately accounted for in sexual violence burden estimation. In order to attribute burden from major depressive disorder, anxiety disorders, self-harm and substance use disorders, measuring the relative risk of developing these conditions for victims of sexual violence would allow for population attributable fractions to be calculated and DALYs from these conditions to be attributed to sexual violence. While the premise of this methodological update is relatively simple, currently there are relatively few studies to inform these relative risks, and conducting and adding such studies in the future would be recognised as a major achievement in GBD research as it would

Table 8 Performance metrics for each cause-of-injury DisMod model

Cause	Cause-specific mortality rate: in-sample coverage	Cause-specific mortality rate: in-sample RMSE	Excess mortality rate: in-sample coverage	Excess mortality rate: in-sample RMSE	Incidence hazard: in-sample coverage	Incidence hazard: in-sample RMSE
Animal contact	0.95	0.96	0.69	1.14	0.40	1.64
Non-venomous animal contact	0.97	0.98	0.74	1.20	0.53	1.40
Venomous animal contact	0.97	1.13	0.74	1.17	0.48	1.31
Drowning	0.91	0.82	0.84	1.40	0.73	1.61
Falls	0.93	0.66	0.71	1.13	0.26	1.77
Fire, heat and hot substances	0.95	0.59	0.67	0.97	0.50	1.16
Pulmonary aspiration and foreign body in airway	0.92	0.93	0.78	1.29	0.65	1.56
Foreign body in eyes					0.83	4.86
Foreign body in other body part	0.96	1.40	0.74	1.31	0.57	1.39
Interpersonal violence	0.89	0.81	0.64	1.11	0.31	1.77
Assault by firearm	0.93	1.96	0.74	1.07	0.69	1.25
Assault by sharp object	0.92	1.50	0.78	1.05	0.57	1.17
Assault by other means	0.90	0.91	0.75	1.10	0.48	1.33
Exposure to mechanical forces	0.92	0.81	0.61	1.23	0.38	2.01
Unintentional firearm injuries	0.95	1.51	0.75	1.13	0.70	1.17
Other exposure to mechanical forces	0.93	0.84	0.66	1.22	0.41	1.94
Adverse effects of medical treatment	0.92	0.71	0.71	1.48	0.37	1.41
Environmental heat and cold exposure	0.94	1.21	0.73	1.54	0.56	1.52
Other unintentional injuries	0.89	1.31	0.51	1.35	0.50	1.67
Poisonings	0.95	0.90	0.76	1.75	0.58	1.90
Poisoning by carbon monoxide	0.95	0.94	0.81	1.11	0.88	1.17
Poisoning by other means	0.95	0.92	0.79	1.89	0.67	2.04
Self-harm	0.98	0.27	0.76	1.02	0.47	1.32
Self-harm by firearm	1.00	1.28	0.89	1.31	0.86	1.35
Self-harm by other specified means	0.98	0.26	0.83	0.96	0.60	1.06
Other transport injuries	0.96	0.99	0.73	1.43	0.63	1.32
Road injuries	0.91	0.47	0.63	1.10	0.27	1.43
Motorcyclist road injuries	0.96	1.07	0.70	1.13	0.54	1.18
Motor vehicle road injuries	0.94	0.55	0.59	1.12	0.48	1.21
Other road injuries	0.99	1.45	0.78	1.16	0.74	1.19
Cyclist road injuries	0.99	1.13	0.73	1.10	0.59	1.09
Pedestrian road injuries	0.92	0.72	0.62	1.02	0.48	1.04

RMSE, root mean square error .

allow for more accurate estimation of lifetime disability caused by sexual violence. This effort would moreover represent an important contribution to research surrounding the Sustainable Development Goals related to sexual violence and women's rights. [23 24]

Fifth, non-fatal injuries from conflict and natural disaster are challenging to estimate because of data sparsity in areas that are afflicted by these events. Fatalities are estimated after such events, but there is still considerable injury burden among the population that survives. Since data collection systems and hospitals may also be destroyed in these events, it becomes difficult to collect adequate non-fatal injury data. Global collaboration should also focus on identifying sources of data on non-fatal and fatal injury cases in conflict and natural disaster events.

It will be important to monitor the effects of implementing these priorities as injury measurement science continues to evolve. Global collaborations including the GBD enterprise should monitor performance statistics and utilisation of results by research groups and ministries to track how improvements to injury measurement progress over time. Scientific dialogue and collaboration must be a major focus, and the GBD enterprise is a good forum to support this kind of data sharing. For example, a collaborative effort between researchers in Vietnam and the Institute for Health Metrics on Evaluation on developing a study on Vietnam injury burden following GBD 2017 led to identifying the use of the Vietnam National Injury Survey, which was then added for estimation in GBD 2019. Increasing data collection standardisation efforts should be emphasised as a priority in all countries, particularly countries where data coverage on injuries is sparse. Ongoing dialogue via scientific publications and international conferences should also continue to serve as a forum to discuss data and methodological updates that can continue to refine the science of injuries estimation in GBD.

CONCLUSION

Measuring injuries burden in GBD is a complex scientific endeavour that leverages large amounts of data, a complex analytical framework and a global research network. GBD 2017 included more comprehensive detail of injury burden than any other known efforts to date. GBD 2019 and future updates will continue to add detail and refine methods in the interest of providing injury burden estimates that are robust, accurate and timely. Expanded injury data collection efforts will be a critical component of future injury burden estimation.

What is already known on the subject

- Global Burden of Disease (GBD) 2017 provided an extensive peer-reviewed assessment of death and disability.
- GBD 2017 methods have been reviewed and updated iteratively as new methods and data become available.
- Measuring injury burden in GBD 2017 is complex due to differences in measuring cause of injury versus nature of injury and the temporal difference between them.

What this study adds

- This capstone study details key estimation methods that are used for measuring the global burden of injuries as described in related publications in this journal.
- More detailed methods descriptions and model performance metrics from GBD 2017 are provided in this study than in related studies.
- This study also includes suggested future directions for improving injury burden research.

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