THE CORRELATION BETWEEN CRANIAL FRACTURES AND BRAIN TRAUMA

A RETROSPECTIVE STUDY

BY
SINOYOLO SAKAMBANA
SKMSIN001@MYUCT.AC.ZA

Supervisors: Dr Calvin Mole & Dr Shameemah Abrahams

DIVISION OF FORENSIC MEDICINE AND TOXICOLOGY – FACULTY OF HEALTH SCIENCES

UNIVERSITY OF CAPE TOWN

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Abstract

Traumatic brain injury (TBI) is a global public health concern. TBI has been noted to co-occur with cranial fractures, however this is not always case. At present, there is a gap in literature regarding the correlative relationship between the presence of cranial fracture and brain trauma. The knowledge and understanding of this correlation is imperative for autopsy examinations where pathologists have to determine the cause of death of an individual. Furthermore, in cases where the skeleton is the only tissue that is available for examination, anthropologists will be able to apply this knowledge to infer the presence of brain trauma at death. Therefore, the current study aimed to assess the correlation of cranial fracture and brain injury in cases of blunt force trauma. This was achieved through a retrospective review of blunt force head injury cases of blunt force head injury examined at Salt River Mortuary, Cape Town between 01 January 2015 and 31 December 2019.

Co-occurrence of cranial fractures with brain trauma was prevalent in the current study, accounting for 64% of the recorded cases. A significant association was found between age at death and the presence of brain trauma ($p = 0.042$), with majority of individuals with brain trauma ranging between 18 to 49 years of age. Similarly, a significant association was found between the presence of cranial fractures and age ($p < 0.001$). A significant association was found between the presence of cranial fractures and brain trauma to the frontal, parietal and temporal lobes ($p<0.001$). Moreover, fracture type was significantly associated with the presence of brain trauma. Fractures of the cranial base have an increased risk of being associated with traumatic brain injury compared to the fractures in other regions. Individuals presenting with cranial fracture are 4.48 times more likely to have TBI, compared to those without cranial fracture. Specifically, individuals with fracture of the basal region of the cranium are 3.77 times more likely to have co-occurring TBI. Notably, all cases of hinge fractures had associated brain trauma. The data presented in this study can be used for the prediction of the presence of brain trauma, where the presence of cranial fracture is noted.

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List of Abbreviations

BBB – blood brain barrier

BFT – blunt force trauma

CF – cranial fractures

CI – confidence interval

CSF – cerebrospinal fluid

CT – computed tomography

DAI – diffuse axonal injury

EDH – extradural haemorrhage

GCS – Glasgow Coma Scale

HBL – hat brim line

HI – head injury

HREC – Human Research Ethics Committee

IPH – intraparenchymal haemorrhage

LOC – loss of consciousness

OR – odds ratio

POI – point of impact

PTA – post-traumatic amnesia

SAH – subarachnoid haemorrhage

SDH – subdural haemorrhage

SF – skull fracture

SRM – Salt River Mortuary

TBI – traumatic brain injury

USA – United States of America

GCS - Glasgow Coma Scale
PTA - Post-Traumatic Amnesia
LOC - Level of Consciousness

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1. Chapter 1: Literature Review

1.1 Introduction

Traumatic brain injury (TBI) has been reported as a public health concern and the leading cause of death in various countries. In order for a reliable and valid diagnosis of TBI, its severity and contributing factors to be made, the pathophysiology of the injury must be understood (Werner & Engelhard, 2007). This influences subsequent interpretations of the injury and the treatment of patients who may have incurred TBI. Thus, an extensive understanding of its pathophysiology leads to saving lives and addresses the burden of TBI on public health. In forensic medicine and pathology, establishing the role that an injury played in the death of an individual is imperative in determining the cause of the death of the individual and in South Africa, this is a legislative requirement that is governed by the Inquest Act 58 of 1959 (*Inquest Act, No. 58 of 1959*). Due to the weight of findings and interpretations of trauma and injury at autopsy, it is vital that pathologists and medical examiners perform autopsies with as much knowledge and understanding of the associative and correlative relationships between TBI and injuries that can co-occur with TBI, such as cranial fracture. Cranial fractures may or may not be present in the event of head injury and this is important to note as this may influence the subsequent diagnosis and treatment of the injury. In cases where the only tissue that is available is skeletal and an anthropological approach is required, having adequate knowledge of the aforementioned correlation will allow for the determination of whether the individual had sustained TBI where there is evidence of a fracture on the cranium.

Thus, the current study will investigate the correlation between cranial fracture and brain trauma, and the extent of this correlation, while determining the incidence of cranial fracture co-occurring with brain trauma, with an emphasis on blunt force trauma cases.

This literature review will discuss the anatomy of the human head, head injuries, TBI, cranial fractures and their aetiologies as well as, the correlation between types of TBI and cranial fractures and the forensic significance of this correlation.

1.2 The anatomy of the human cranium and brain

The human cranium is comprised of 22 bones making up the neurocranium and the bones of the face (splanchnocranium) (Sutton, 2017). Bones of the cranial vault are flat bones consisting of two layers of cortical bone with a diploe layer of cancellous bone in between. The cranial base consists of more irregular shaped bones, which are robust to fracture (Lynnerup & Klaus, 2019). The bones of the cranium are connected by sutures and when these sutures are fully developed and closed, the bones are immobile (Drake, Vogl & Mitchell, 2009). In children, the primary sutures are only closed after the age of 6 years, thus sutures can be mistaken for cranial fractures in radiography of younger individuals (Nakahara et al., 2006). This is especially true with the presence of accessory sutures, which are common in the parietal and occipital bones (Sanchez et al., 2010).

Additionally, Kroman et al. (2011) reported that the degree of sutural closure impacts the resulting fracture pattern, as the transfer of energy causing the fracture can be interrupted by the presence of sutures, which leads to the fracture being localised.

The primary function of the cranial vault is to protect the brain (Jin et al., 2016). Surrounding the brain are membranous layers known as the maters, collectively called the meninges, which serve to protect the brain from injury (Ellis, 2012). The dura mater is the outer membrane of the brain, and it lies beneath the cranium; it is directly attached to the cranium. The arachnoid mater is an avascular and fragile membrane that lies in direct contact with the dura above it. The arachnoid mater is separated from the pia mater below it by the subarachnoid space (Adeeb et al., 2013). The pia mater is connected to the dura mater and invests the outer surface of the brain (Drake, Vogl & Mitchell, 2009). From the pia mater, extends longitudinal triangular septae that extend into the dura mater internally; where the triangular septae meet at a vertex, the spike-like extension merges with the dura mater (Adeeb et al., 2013). The cranium and meninges encase and protect the brain so that when stress or strain is placed on the head, injury to the brain can be avoided or minimized (Tse et al., 2014).

The brain is made up of soft tissue referred to as grey and white matter, where the glial cells and neurons are found, and it is cushioned by cerebrospinal fluid (CSF). The brain forms part of the central nervous system, and is divided into several regions namely the cerebrum, thalamus and hypothalamus, midbrain, pons and cerebellum, and the medulla oblangata. Each region serves an integral part of cognitive and/or bodily function (Drake, Vogl & Mitchell, 2009). Trauma to different parts of the brain has been associated with neurological consequences resulting in personality changes, mania, generalised anxiety disorder and major depression (Rogers & Read, 2007).

1.3 Head Injuries

Several studies have noted head injuries as common in traumatic and accidental events (Fujiwara et al., 2021; Hyder et al., 2007; Majdan et al., 2011). Trauma can be classified as ballistic, blunt force or sharp force trauma, depending on the object causing the injury (Saukko, 2004). Brink et al. (1998) investigated the pattern of injuries as a result of interpersonal violence and found that the face, head and neck were the most common anatomical site of injury, making up 60% of total injuries. Of total bodily fractures recorded, Brink et al. (1998) reported that 69% were associated with the head region particularly nasal, dental, zygomal and mandibular fractures.

Moreover, in a retrospective study comparing wound patterns in homicide by sharp and blunt force cases, Ambade & Godbole (2006) found that in cases of blunt force injury, the head region was impacted in majority (80.8%) of the individuals. Similarly, in South Africa, Clark et al. (2017) reported that 70% of blunt force homicide cases presented with head injuries in conjunction with other regions, while 23% of the cases presented with head injuries solely.

It is evident that head injuries are a common occurrence in blunt force-related death cases. However, literature surrounding injuries associated with death typically provide a regional (anatomic) perspective of injury distribution but do not provide information about whether the head injury resulted in traumatic brain injury or whether the head injury was associated with the death of the individual.

1.4 Cranial Fractures

The human cranium is a rigid structure that forms part of the skeleton of an individual, which mainly serves to protect and support the brain. The calvarium, mandible and facial bones comprise the cranium where the calvarium components include the vault and base of the cranium and these encase the brain. The disruption of the anatomical continuity of the cranium is known as a cranial fracture and this occurs as a result of an application of force onto the cranium or the impact of the head as it comes into contact with an object or surface, with sufficient force to result in trauma (Wedel & Galloway, 2013). The composition of the cranial bones which allows for the elasticity, strength in tension, rigidity, shock absorbance and flexibility of the cranium, all impact how the cranium responds to the application of force (Kranioti, 2015).

1.4.1 Types of cranial fractures

Types of cranial fractures can be classified according to the location and surface area of the injury, and by their characteristic features such as depressed, comminuted, and linear (Wedel & Galloway, 2013). The type and shape of fracture is reliant on the speed at which the object is moving when it impacts the bone and the force applied at impact (Ruchonnet et al., 2019). Linear, depressed and comminuted fractures are associated low velocity force, although comminuted fractures have been associated with high velocity impact (Kranioti, 2015). High velocity impact is more likely to be associated with more extensive fracturing or perforation of the bone when the bone is impacted by a small, fast-moving object such as a bullet (Stefanopoulos et al., 2015). Multiple cranial fractures of different types may be observed on a single individual as cranial fractures do not always occur in isolation.

Certain fracture patterns have been linked to different types of traumatic events. The hat brim line rule has previously been used to distinguish whether injury was as a result of fall or blow to the head (Kremer et al., 2008; Guyomarc'h et al., 2010). The hat brim line (HBL) rule states that, when the injury is found at the level where the brim of a hat would rest on the head, it is more likely due to a fall while, an injury found above this line is likely due to a blow to the head (Guyomarc'h et al., 2010). Though, Fracasso et al. (2011) reported that BFT from falls will not occur above the hat brim line on condition that the person was (i) standing before they fell; (ii) the fall is from standing height; (iii) the fall was onto a flat surface on the floor and (iv) there are no interceding objects. The HBL rule has been used in isolation, however Guyomarc'h et al. (2010) reported that fractures related to homicides and falls both appear at the hat brim line, where homicide-related blows are categorically found above the line. Guyomarc'h et al. (2010) recommend that the rule be used in combination with the side lateralisation and the number and length of lacerations on the head, which are other criteria that have been tested. The side lateralisation criterion is used to discriminate falls from blows when assessing the occurrence of cranial fractures: a right-sided cranial fracture is more likely with a fall while, a left-sided cranial fracture is more likely with a blow (Kremer & Sauvageau, 2009). This is possibly due to most interpersonal conflict occurring face to face and most of the population being right-handed, therefore impacts to the left-hand side of the victim are more frequent (Kremer and Sauvageu, 2009). Kremer and Sauvageu (2009) explained that since most people are right-handed, the right-sided lateralisation of cranial fractures is the result of right-handed people using their right hand, to break the fall as protection, which causes the right side of the head being most prone to strike the surface.

Because the cranium is the ‘case’ of protection, it is a fair assumption that disruption to it may cause damage to the sensitive and fragile brain that is inside. However, very limited research exists at present, ascertaining the correlative and associative relationship between the presence or extent of cranial fracture and presence of TBI.

1.4.2 Cranial fracture aetiologies

Blunt force trauma is regarded as a low-speed injury. When force is applied, the elasticity of the cranial bones allows for the cranium to absorb the kinetic energy, however there are limits to the elasticity. As loading is increased, bone will undergo elastic deformation until such time where the elastic limit is reached; if the load continues beyond this point, plastic deformation will occur and eventually the bone will fracture (Currey, 1970).

The resulting injury and fracture are influenced by various intrinsic and extrinsic factors including, the tissue and bone biological characteristics, as well as the force applied and the velocity at which this force is applied. The fracture pattern is greatly influenced by the shape and size of the object used for impact (Kranioti, 2015).

When assessing cranial fracture and fracture propagation, it is important to consider these mechanical possibilities: (i) damage to the cranial bone may be localised at or close to the point of impact (POI); fracture formation may initiate far from the POI, due to energy distribution or (iii) the resultant fracture(s) may be a combination of the aforementioned possibilities, particularly in cases of repeated impact to the cranium (Ruchonnet et al., 2019). It is vital to assess whether a fracture occurred ante-, peri- or post-mortem as this impacts the forensic significance of the fracture and it is especially vital for anthropological analyses of the cranium (Fenton et al., 2003). Moreover, it is important to note that the terms ‘ante-, peri- and post-mortem’ are used differently in forensic pathology compared to the anthropological context. The perimortem period in bone tissue relates to the retention of elasticity as a result of collagen and water content – as such the perimortem period refers to a period where bone behaves as if it was fresh, which, may be an extended period following death (Wieberg & Wescott, 2008; Wescott, 2019).

The period of occurrence of a skull fracture (ante-, peri-, post-mortem) can be differentiated based on the characteristics of the fracture and surrounding tissue, such as, evidence of healing in form of osteoblastic and osteoclastic activity (bone reformation) in and around the fracture; this would indicate antemortem trauma (Barbian & Sledzik, 2008). Skeletal trauma that occurred perimortem may be indicated by particular fracture patterning combined with the edge characteristics of the fracture, according to Moraitis et al. (2008), as the trauma occurred on fresh or green bone (recently defleshed bone). Taphonomic changes that may affect the skeletal remains are to be considered when distinguishing the period in which a fracture occurred (Moraitis et al., 2008).

Ren et al. (2020) investigated the influence of skull fracture on TBI under head-ground impacts using simulation and cranial models and found that impact to different locations on the head result in different cranial fracture patterns. This can be influenced by the varied thickness of different cranial bones and each bone’s ability to absorb and dissipate energy. At higher velocities, linear fractures were seen in the frontal and occipital regions of the cranium, while depressed fractures were found in the parietal regions of the cranium (Ren et al., 2020).

Powell et al. (2012) reported a difference in the extent of fracture formation between when the cranium that is struck while it is free-moving and, when a head is at rest on or against a solid and rigid surface, which was investigated using paediatric porcine skulls. A head struck while in free motion is likely to present with a linear or incomplete depressed cranial fracture, whereas a head struck while it is against a rigid surface is likely to present with comminuted fractures with inward bevelling of the cranium (Kranioti, 2015; Ruchonnet et al., 2019). When the head is struck at an angle in relation to the head, a linear fracture is expected; although, this is dependent on where the cranium is struck (Kranioti, 2015).

Previous studies have suggested that a singular linear fracture implies less force was applied compared to the more complex fractures, such as a comminuted fracture (Lovell, 1997; Symes et al., 2012; Saukko & Knight, 2004). Similarly, biomechanical research on cranial impacts has found that more linear fractures were associated with lower impact energy as compared to the depressed comminuted fractures (Raymond et al., 2009; Mole, Heyns & Cloete, 2015). It can be expected that with an increase in impact force, there will be more extensive injury, however, this is not always the case. The energy of impact and the bone’s ability to dissipate the energy influences the extent of injury to the cranium (Fenton et al., 2003). Thus, the type of fracture does not necessarily imply the amount of force applied. Moreover, soft tissue has been noted as a significant factor in the prediction of skull fracture formation (Raymond et al. 2009). As such, the thickness of soft tissue aids in the categorisation of fracture outcome (Raymond et al. 2009).

1.5 Traumatic Brain Injury (TBI)

TBI is an injury to the brain, which occurs as a result of the application of physical and mechanical force, and/or a sudden change in momentum of the cephalic region or the entire human body . The resultant physiological or structural disruption of the brain may be focal, where the initial injury is localised to the area of impact; or diffuse where the injury impacts more than one area of the brain, both of which may result in fatality of the injured individual (Werner & Engelhard, 2007).

1.5.1 Types of TBI

TBI can present in various ways including focal brain damage associated with contact injury causing a contusion, laceration, and/or haemorrhaging in the head; and diffuse axonal injury (DAI) where the injury to the brain is not caused by direct contact with the head, rather as a result of sudden acceleration or deceleration, or swelling of the brain, which causes the shearing of axons in the brain as it moves within the cranium (Mckee & Daneshvar, 2015; Werner & Engelhard, 2007). The initial stages following impact include tissue damage, metabolism, and the disrupted circulation of cerebrospinal fluid (Werner & Engelhard, 2007).

Focal brain damage is caused by an application of blunt or sharp force to the head using an object or by the collision of the head and/or body with a surface that is rigid or sharp enough to cause trauma to the tissue. Additionally, injury to the brain may be coup- or contrecoup. Contrecoup brain injury refers to a contusion that is distant, typically on the opposite side, from the point of impact (Ratnaike et al., 2011). Limited research has been conducted determining the association of cranial fractures and TBI (Yavuz et al., 2003; Tsai et al., 2022 & Ren et al., 2020).

1.5.2 Pathophysiology of TBI

Following the disruption caused by the primary injury to the brain, there is a physiological and biomolecular response in the brain, and this is known as the secondary injury. It is the secondary injuries that determine the patient’s mortality or, morbidity when the patient survives the primary injuries, as they are more progressive (Greve & Zink, 2009). The progression of secondary injuries includes the depolarisation of neurons, cerebral vascular epithelial cells and glial cells, and an increased glutamate concentration that causes an imbalance in the calcium homeostasis. In turn, this imbalance impacts the cellular function in the body resulting in swelling of the brain, loss of bodily function, ischaemia and ultimately, cell death (Greve & Zink, 2009).

Much like the primary injuries, the secondary injuries can be visually identified in brain tissue through post-mortem histology and brain cuts. Rahaman & Del Bigio (2018) investigated the histology of brain trauma and associated hypoxia-ischemia and found that changes in the neuron cells are evident following TBI. The changes include the swelling of the endoplasmic reticulum; the neurons appearing shrunken and dark due to sustaining a contusion or paler due to an oedema, and dead neuron cells presenting with eosinophilic cytoplasm on the brain histology slides (Figure 1). The internal environment of the brain is protected and maintained by the blood brain barrier (BBB) and the autoregulation of cerebral blood flow, however the brain, as an organ, is chiefly protected by the surrounding external structure that is the human cranium.

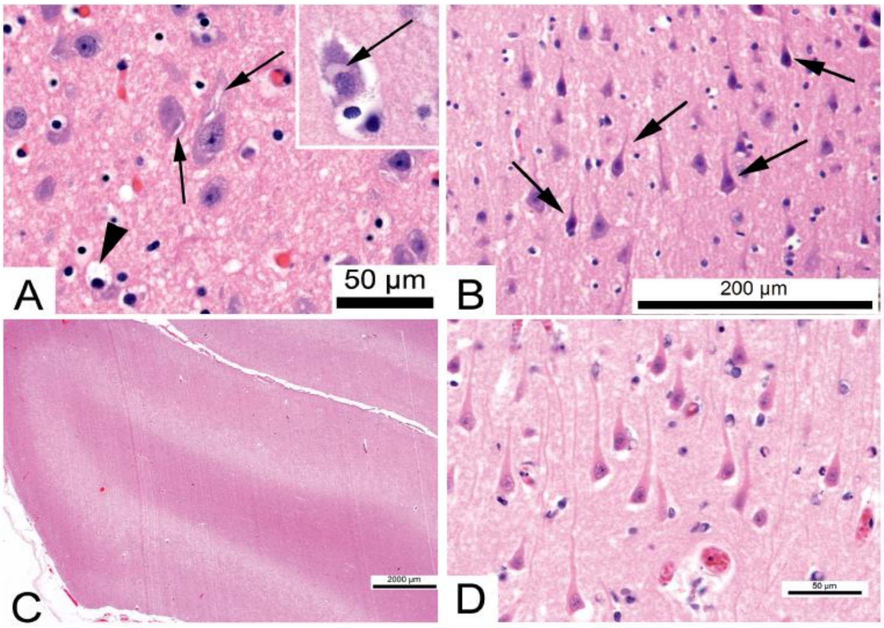


Figure 1: Neuron cell changes in the mature brain, following traumatic brain trauma which caused hypoxia-ischaemia. A) Swollen endoplasmic reticulum (x600); B) Neurons appear shrunken and darker due to sustaining a contusion (x200); C) Swollen neuron cells appear paler due to oedema (x12.5); D) Dead neuron cells presenting with eosinophilic cytoplasm (x600) (Rahaman & Del Bigio, 2018).

1.6 The incidence of TBI and cranial fractures

Globally, TBI has presented with significant incidence and has been noted as a public health issue, due to the high volumes of admissions to hospitals and TBI-related mortalities that are recorded worldwide (Frost et al., 2013). Every year in the United States of America (USA), millions of people are reported to have sustained a TBI and of these, about 52 000 resulted in death (Frost et al., 2013). Although the rates of incidence can be obtained easily, previous literature reported difficulty in determining incidence of TBI (Frost et al., 2013; Wang et al., 2015). This is attributed to the complexity of the injury.

Former studies have reported that the difficulty in assessing and reporting the incidence of TBI lies with the inconsistencies associated with varied methodologies and guidelines used in assessing brain injury globally and locally, and the recording of factors and information related to the injury (Hyder et al., 2007).

Both of these points are valid and can simultaneously be the contributing factors, as ante-mortem diagnosis of severity of TBI has been done using varying methods, namely, the extent of post-traumatic amnesia (PTA), the Glasgow Coma Scale (GCS) and the loss of consciousness (LOC), which have potential for variability that is influenced by the medical doctor or physician’s subjectivity or bias and none of which have been deemed the gold standard at present (Frost et al., 2013).

Wagner et al. (2000) summarised the independent risk factors associated with fatal TBI as male sex, older age, use of alcohol and drugs and participating in contact sports such as American football. Similarly, alcohol consumption at the time of injury is noted as a risk factor by Hyder et al. (2007).

1.6.1 Variation in incidence of TBI between sexes

There has been a notable variation in the incidence of TBI between males and females where previous studies reported that the incidence of TBI is notably higher in males with the average ratio being 2.2:1 (Hyder et al., 2007; Frost et al., 2013). Frost et al. (2013) attributed this to males generally being more involved in contact sports, engaging in risk-taking activities and consuming more alcoholic beverages, all of which are factors that can be associated with the risk of trauma to the head. Tsai et al. (2022) reported that patients that were female and presented with cranial fractures only made up 25.9% of the study sample. However, the likelihood of head injuries presenting with cranial fractures presenting with or without traumatic brain injury has been reported to be equal between the sexes (Carson, 2009).

1.6.2 Significance of the circumstance of injury & related risk factors

Road traffic incidents, falls, accidents, and violence have been reported as leading causes of TBI, majority of which were road traffic incidents and violence (Hyder et al., 2007; Langlois et al., 2006). An increased likelihood of fatality has been reported in individuals that sustained head injury without cranial fracture, through road traffic accidents (Carson, 2009). One possibility is that these individuals suffered DAI, which is likely to result in death due to the shearing and tearing of the axons and does not always present with cranial fractures. According to Yoganandan et al. (2009), DAI can be diagnosed by assessing clinical observations of coma and no ischemic injury visible on computed tomography (CT) or imaging. In the acute stage of TBI, CT is the first imaging test that is carried out; however, CT has low sensitivity for the detection of DAI and as such, this should be considered when performing the scan (Viera & Correa, 2020). Additionally, where no intraventricular and traumatic subarachnoid haemorrhage is found during early imaging, no severe DAI can be deduced (Viera & Correa, 2020).

Chattopadhyay & Tripathi (2010) reported 34.3% of fatalities associated with cranial fracture in India involved blunt force trauma. Cranial fractures due to sharp force were noted in only 10.9% of their cases.

Hyder et al. (2007) reported that, in Africa, road traffic accidents, falls and violence-related injuries as being the most prominent causes of death related to TBI in individuals that are younger than 60 years old. This was attributed to the more active, reckless and poorly thought-out behaviour that is associated with younger generations. Similarly, this was reported by Carson (2009), with the average age reported as 29 years. Although, the proportion of overall fatal TBIs was the largest in individuals 75 years and older in another study (Corrigan, Selassie & Orman, 2010). This may be due to the increased fragility of the human body and its components as an individual ages, thus the skeleton and cranium of an older individual can have less density than that of a younger individual.

In contrast, Frost et al. (2013) reported only 12% of individuals older than 18 years were impacted with TBI. Additionally, cranial fractures were found to be more common in individuals of younger age (with an average of 35 years), irrespective of the mechanism of injury in the study (Carson, 2009).

1.6.3 Impact of alcohol and drug use on the incidence of TBI and cranial fractures

Previous studies reported that in individuals who had consumed alcohol and were under the influence, the risk of sustaining a TBI was significantly higher than those that had not consumed alcohol (Vaaramo et al., 2014; Hyder et al., 2007). Vaaramo et al. (2014) reported that TBI occurred in 57.7% of cases where the individuals had been under the influence of alcohol. Cuthbert et al. (2015) reported that majority of the cases that made up the incidence of TBI were individuals 80 years and older. While, only 22.9% of their sample misused and used alcohol prior to the injury and 12.2% used drugs, increased use of the drugs and alcohol prior to the injury was noted in individuals that were younger than 50 years and less misuse was noted as the age increased.

Gururaj (2004) reported higher rates of mortality and disability in those who sustained TBI while under the influence of alcohol than in those that were not under the influence. Alcohol consumption is often related to dangerous behaviour, as it may cause impaired cognitive function, heightened sense of confidence and reduced reaction time (Schweizer & Vogel-Sprott, 2008). These can all contribute to an individual engaging in reckless behaviour which can result in various types of injuries to the body, including TBI and cranial fractures.

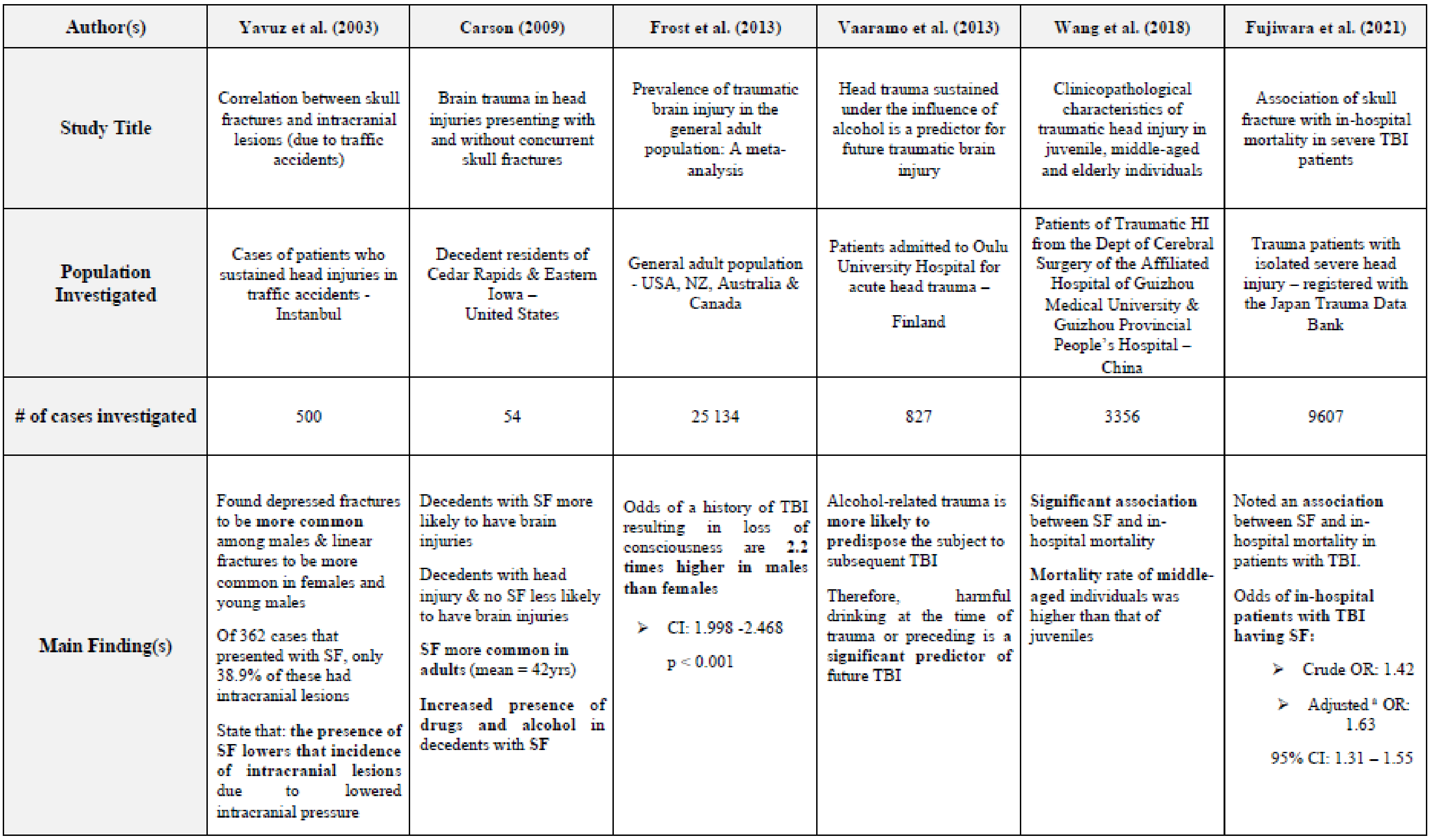
1.7 The correlative relationship between cranial fractures and brain trauma

A cranial fracture serves an indication that there was direct impact to the head. The presence of a fracture does not always imply injury to the brain, in the same way that an absence of a fracture does not imply absence of brain injury. Direct impact to the head can result in intracranial haemorrhaging and brain tissue damage, which can be fatal without emergency medical intervention (Fujiwara et al., 2021). However, it is necessary to gain an understanding of the correlation because it will allow for more efficient clinical care of head injuries to reduce mortality and morbidity and aid in forensic and anthropological investigations involving TBI and cranial fracture. Unfortunately, limited research has investigated this correlation. Table 1 summarises the studies that have previously reported on the correlation between cranial fractures and brain trauma.

Carson (2009) investigated 54 cases of head injuries and found that all cases presenting with cranial fracture except one, had coinciding traumatic brain injury. However, the occurrence of intracranial haemorrhaging, brain swelling, and atlanto-occipital dislocation was varied in individuals that presented with or without fracturing of the cranium (Carson, 2009). Tsai et al. (2022) reported a significant association of compound cranial fractures with the risk of mortality in individuals that have suffered TBI, which was similarly reported by Fujiwara et al. (2021). The presence of cranial fracture in TBI patients indicates greater impact force was applied however, the presence of a cranial fracture may lower the incidence of TBI due to impact energy being absorbed during fracture formation (Tseng et al., 2011; Yavuz et al., 2003).

Fujiwara et al. (2021) suggested that impact that results in cranial fractures can induce neural tissue damage with intensified neuroinflammation than impact that does not result in a cranial fracture. In addition, they reported that neuroinflammation as a result of cytokine release in TBI, may be amplified by the presence of a cranial fracture (Fujiwara et al., 2021). Therefore, the detection of a cranial fracture using CT scans can indicate direct injury (primary) and predict some secondary injuries to the brain. Establishing the extent of the correlation between cranial fracture and brain trauma and the associated contributory factors allows for the determination of whether the head injury resulted in traumatic brain injury or whether the head injury was associated with the death of the individual.

Table 1. Summary of main findings in correlation studies



Author(s)	**Yavuz et al. (2003)**	**Carson (2009)**	**Frost et al. (2013)**	**Vaaramo et al. (2013)**	**Wang et al. (2018)**	**Fujiwara et al. (2021)**
Study Title	Correlation between skull fractures and intracranial lesions (due to traffic accidents)	Brain trauma in head injuries presenting with and without concurrent skull fractures	Prevalence of traumatic brain injury in the general adult population: A meta-analysis	Head trauma sustained under the influence of alcohol is a predictor for future traumatic brain injury	Clinicopathological characteristics of traumatic head injury in juvenile, middle-aged and elderly individuals	Association of skull fracture with in-hospital mortality in severe TBI patients
Population Investigated	Cases of patients who sustained head injuries in traffic accidents - Instanbul	Decedent residents of Cedar Rapids & Eastern Iowa – United States	General adult population - USA, NZ, Australia & Canada	Patients admitted to Oulu University Hospital for acute head trauma – Finland	Patients of Traumatic HI from the Dept of Cerebral Surgery of the Affiliated Hospital of Guizhou Medical University & Guizhou Provincial People's Hospital – China	Trauma patients with isolated severe head injury – registered with the Japan Trauma Data Bank
# of cases investigated	500	54	25 134	827	3356	9607
Main Finding(s)	Found depressed fractures to be **more common** among males & linear fractures to be more common in females and young males Of 362 cases that presented with SF, only 38.9% of these had intracranial lesions State that: **the presence of SF lowers that incidence of intracranial lesions** due to lowered intracranial pressure	Decedents with SF more likely to have brain injuries Decedents with head injury & no SF less likely to have brain injuries **SF more common in adults** (mean = 42yrs) **Increased presence of drugs and alcohol** in decedents with SF	Odds of a history of TBI resulting in loss of consciousness are **2.2 times higher in males than females** ➢ CI: 1.998 -2.468 p < 0.001	Alcohol-related trauma is **more likely to predispose** the subject to subsequent TBI Therefore, harmful drinking at the time of trauma or preceding is a **significant predictor** of future TBI	**Significant association** between SF and in-hospital mortality **Mortality rate of middle-aged individuals** was higher than that of juveniles	Noted an association between SF and in-hospital mortality in patients with TBI. **Odds of in-hospital patients with TBI having SF:** ➢ Crude OR: 1.42 ➢ Adjusted^a OR: 1.63 95% CI: 1.31 – 1.55

*#: Number; OR: Odds Ratio; CI: Confidence Interval; SF: Skull Fracture; TBI: Traumatic Brain Injury; HI: Head Injury; USA: United States of America; NZ: New Zealand; a – Adjusted for age and sex.

1.8 Conclusion

Although literature regarding the correlation between TBI and cranial fractures is limited, a consensus is seen regarding the contributory role played by variables such as the manner and mechanism of death and the use of drug(s) or alcohol. These influence the occurrence and incidence of TBI and cranial fractures directly and indirectly.

Data with regards to the correlation of different types of TBI and cranial fractures is still very limited. Therefore, the knowledge that is lacking could contribute to the examinations and interpretations of head injuries in forensic pathology where a more defined and precise cause of death can be determined. Moreover, this knowledge could contribute to the improvement of the methods that are currently in place for the provision of healthcare, to facilitate the efficient management and treatment of individuals who have suffered a potentially fatal head injury. Thus, the current study is paramount where the results and application of which, will not be limited to forensic medicine but can be applicable to clinical medicine as well. At present, literature and data regarding the correlation of TBI and cranial fractures is limited and there are aspects of this correlation that are yet to be explored. Therefore, this gap in literature and data warrants further studies to be done in this regard.

In addition, future studies have the opportunity to determine the characteristics or patterns of cranial fractures that occur with brain injury. The patterns that are identified can then be used to infer TBI from cranial fractures. This is particularly important in cases where the only tissue that is available is skeletal, and an anthropological approach is required. Having adequate knowledge of the aforementioned correlation will allow for assessing the value of the determination of whether the individual had sustained brain trauma where there is evidence of cranial fractures.

1.9 Aims and Objectives

The aim of this study was to assess the correlation between cranial fractures and brain injuries, while simultaneously determining the incidence of cranial fractures co-occurring with brain injuries.

The objectives of this study were to:

- Identify relevant cases of head injury from the Office Autopsy database
- Perform a retrospective review of autopsy reports pertaining to head injury
- Determine the incidence of cranial fracture and TBI
- Determine the correlation between specific types of brain trauma and cranial fracture

2. Chapter 2: Methodology

2.1 Study Design

This study is a retrospective, cross-sectional correlational study that reviewed medico-legal cases examined at Salt River Mortuary, Cape Town between 01 January 2015 and 31 December 2019. All cases that were recorded with head injury in the Office Autopsy database (HREC: R036/2014) that occurred within the aforementioned 5-year period were reviewed for inclusion in this study. Data regarding the population size was established from the population of suburbs falling within the drainage area of SRM. Ethical approval for the current study was received from the Human Research Ethics Committee of the Faculty of Health Sciences, University of Cape Town (HREC:355/2023) (Appendix A).

Previously, Clark, Mole and Heyns (2017) assessed cases of blunt force homicide that occurred between 2010 and 2014 and cases that were associated with head injuries amounted to 772, which was 93% of the blunt force homicide cases. Thus, assessing blunt force trauma cases that occurred between 2015 and 2019 will assist in comparing trends established, to trends previously noted by Clark, Mole and Heyns~~.~~. However, it is important to note that Clark, Mole & Heyns (2017) focused their study on homicidal blunt force trauma cases of all ages, which is a less restrictive criteria compared to the current study.

The current study was focused on BFT in cases of assaults and falls. Cases of extreme head trauma, such as crushing, were excluded due the extensive damage to the cranium and the guaranteed injury to the brain and difficulty establishing association of fractures and areas/ type of brain injury. Cases that were included were of individuals that are 18 years of age and older and where the cases were noted to have BFT. Additionally, cases of all manners and mechanisms of death, all head injury types and/or fracture types were included, where head injury was the primary injury (Table 2). Where the individual had received medical intervention prior to death, this was noted.

The Office Autopsy database was searched for all cases involving head trauma. Following the application of the inclusion and exclusion criteria, relevant autopsy reports were retrieved and reviewed. The research and review of the digital autopsy reports and ancillary documentation was done at the University of Cape Town (UCT) Health Science Campus, in the Department of Pathology within the Division of Forensic Medicine and Toxicology located in the Falmouth Building, in Anzio Road, Observatory, in Cape Town.

Table 2: Detailed Inclusion and Exclusion Criteria

Include	Exclude
Autopsies conducted between 01 January **2015** and 31 December **2019**	Cases associated with ballistic trauma
Cases of individuals that are 18 years of age and older	Cases of individuals that are younger than 18 years of age
Cases where the autopsy has noted an association with head injury	Cases associated with road traffic accidents or motor vehicle accidents
All manners of death	Cases with severe head injury (crushed) where cranium or head is destroyed
All mechanisms of death with the exception of penetrating and crush injuries	
All types of injury and/or fracture to the skull	
All levels of severity (as noted by GCS & PTA score and LOC)	

*GCS: Glasgow Coma Scale; PTA: Post-Traumatic Amnesia; LOC: Level of Consciousness

2.2 Research procedures and data collection methods

Data collection involved recording information regarding the cause of death (which should be TBI and/or BFT), the manner and mechanism of death and any contributing factors in a Microsoft Excel spreadsheet, with the variables in Appendix B as the categories of calculation. The variables included characteristics such as the circumstance of death, the alleged manner of death, the presence, type and location of injury to the head (externally), the cranial bones and the brain. Following the selection and collection of the cases, the data was deidentified to maintain the anonymity, security and privacy of the deceased during the subsequent statistical analysis and the process of storage and transportation of the collected data.

2.3 Data Analysis

Data validation on a subset (~10%) of data was performed to minimize data recording error. Data was collected by the same individual (myself) for inter rater reliability assessment as well as, by an independent individual (supervisor) and the data was assessed by percentage concordance.

The recorded data was used as aggregated data for subsequent analysis for correlation or association between traumatic brain injury and cranial fracture. All statistical analysis was conducted using Statistical Package for the Social Sciences (SPSS) software, version 28. Alpha was set at 0.05 for all analyses. Statistical analysis of the data was used to determine whether a correlation exists between cranial fractures and brain trauma, the extent of this correlation, and the incidence of cranial fractures and brain trauma occurring simultaneously.

All the data was categorical in nature. In order to determine if there was an association between external head injuries, skull fractures and brain injuries, Pearson's X^2 tests were conducted. Independent t-tests were performed to assess whether there was a significant difference in the ages of individuals with/without head injury, cranial fracture and brain trauma.

Binary logistic regression was performed to assess crude odd ratios and odds ratios adjusted for age and sex, as well as to generate a best subset model. The best subset model was initially generated using the presence of BT as the dependent variable with the main variable categories as co-variates, namely the presence of external HI, presence of CF, CF type and CF site. Ultimately, the CF type was removed from the model as the inclusion of hinge fractures caused an error of calculation.

Incidence was calculated in comparison to the population for the Western Metropole of the City of Cape Town per 100 000 population, based on the population for the drainage area reported in 2011 by Stats SA (2011), as well as the percentage of total intake at the mortuary.

3. **Chapter 3: Results**

The total number of autopsies recorded on the Office Autopsy database for Salt River mortuary, between 2015 – 2019, was 19609, with 12507 of those cases recorded as unnatural deaths. Of the unnatural deaths, 2763 (22.1%) cases were a result of blunt force trauma (Table 3). After the application of this study's inclusion criteria, a total of 719 cases were included in this study. The incidence of cases presenting with a co-occurrence of brain trauma and cranial fractures, in the Western Metropole of the City of Cape Town over 2015 – 2019, was 17.68/100 000 population/year.

Table 3. Cases at Salt River Mortuary per annum (2015 – 2019)

Year	2015	2016	2017	2018	2019	Total
Total Autopsies per annum*	3695	3660	3885	4043	4326	**19609**
Yearly Unnatural Death cases	2989	1734	2482	2609	2693	**12507**
BFT cases	337 (11.27%)	230 (13.26%)	717 (28.89%)	703 (26.94%)	776 (28.82%)	**2763 (22.1%)**

*according to the Office Autopsy database; BFT: Blunt force trauma

Majority of the cases were as a result of homicide (79.8%) while the remainder were accidental (18%) or as result of suicide (1.9%) (Table 4). In a single case, the manner of death was unknown.

Table 4. Manner of death of all study cases

Manner of Death	Number of cases
Homicide	574 (79.8%)
Accidental	130 (18%)
Suicide	14 (1.9%)
Unknown	1 (<1.0%)
Total	719 (100%)

3.1 Age

The mean age at death was 37 years (*SD* ± 16.75 years). Overall, 289 (40.19%) individuals were within the 18 – 29 age group; 218 (30.32%) individuals were within the 30 – 39 age group; 67 (9.32%) individuals were within the 40 – 49 age group; 57 (7.92%) individuals were within the 50 – 59 age group; 40 (5.56%) individuals were within the 60 – 69 age group; 22 (3.06%) individuals were within the 70 – 79 age group; and 26 (3.62%) individuals were within the 80 – 100 age group. Notably, majority of the cases in this study were of the young adult age groups, 18 – 39 years, with a drastic decrease in numbers when it came to the older age groups (>40 years; Figure 2).

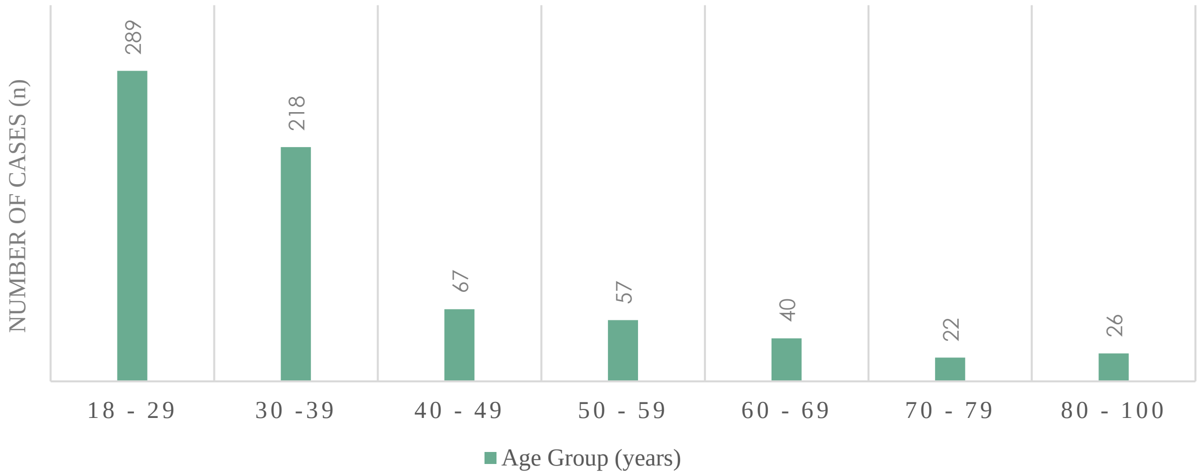


Figure 2: Age distribution of all cases included in the study.

The distribution of age across individuals with cranial fractures and those without, was significantly different (*p* = <*0.001*). Within the 18 – 29 and 30 – 39 age groups, more individuals (71%; n = 360) had cranial fractures than individuals that had no cranial fractures. While in the older age groups, 70 – 79 and 80 – 100 years, there were more individuals (70.83%; n = 34) that presented with no cranial fractures than those that had cranial fractures (29.17%; n = 14). Similarly, the distribution of age across individuals with externally observable head injuries and those without, was significantly different (*p* = *0.010*). Across all age groups, more individuals had externally observable head injuries (97.07%; n = 698) compared to those without head injuries (2.92%; n = 21). The age across individuals with brain trauma and those without, was not significantly different (*p* = *0.947*), statistically.

3.2 <u>Sex</u>

Overall, the study sample consisted of 91% male and 9% female individuals, which was a 10:1 ratio. Of the males in this study, 95.11% (n = 623) presented with the presence of brain trauma and 68.70% (n = 450) presented with the presence of cranial fractures. While a total of 90.63% (n = 58) of the females in this study presented with brain trauma while, only 32.81% of the females presented with cranial fractures. Furthermore, 66.41% (n = 435) of the males presented with a co-occurrence of cranial fracture and brain trauma whereas, only 37.5% (n = 24) of the females presented with the aforementioned co-occurrence (*Figure 3*).

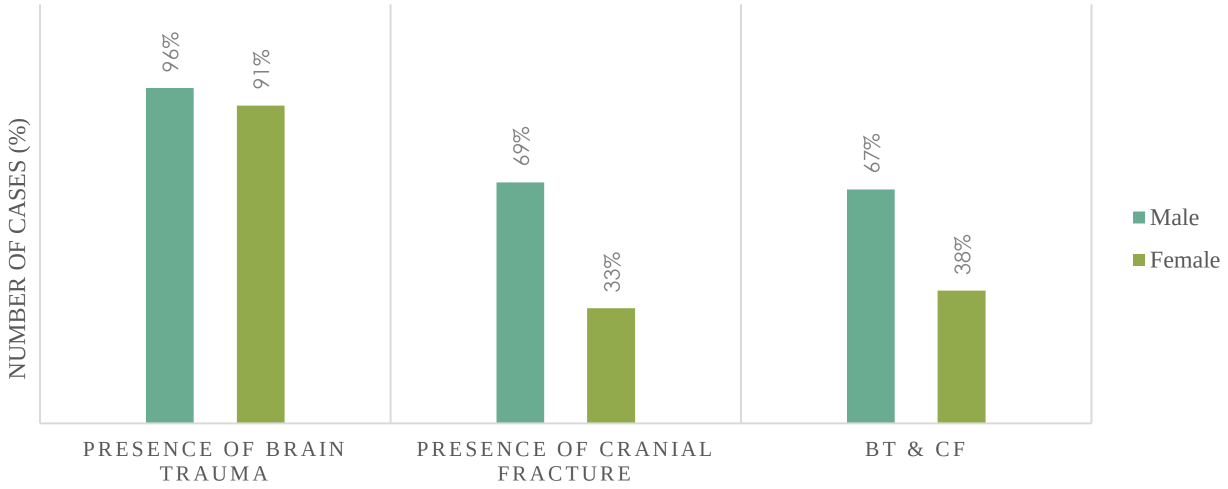


Figure 3: The sex distribution of cases across the presence of brain trauma (BT) and cranial fractures (CF), and brain trauma co-occurring with cranial fracture.

3.3 Brain and cranial trauma

Majority of the cases presented with brain injuries (94.7%; n = 681). Of these brain injuries, the most common primary brain injuries were subarachnoid haemorrhaging (70%; n = 475), brain contusions (61%; n = 416) and subdural haemorrhaging (59%; n = 404). Following these was brain lacerations (23%; n = 156); extradural haemorrhaging was noted in 60 (8%) cases while, intraparenchymal haemorrhaging (burst lobe) was only noted in 23 (3%) cases. The secondary brain injuries, namely brain swelling, and brain herniation were noted in 43% (n = 293) and 24% (n = 167) of the cases with brain injuries, respectively. (*Figure 4*).

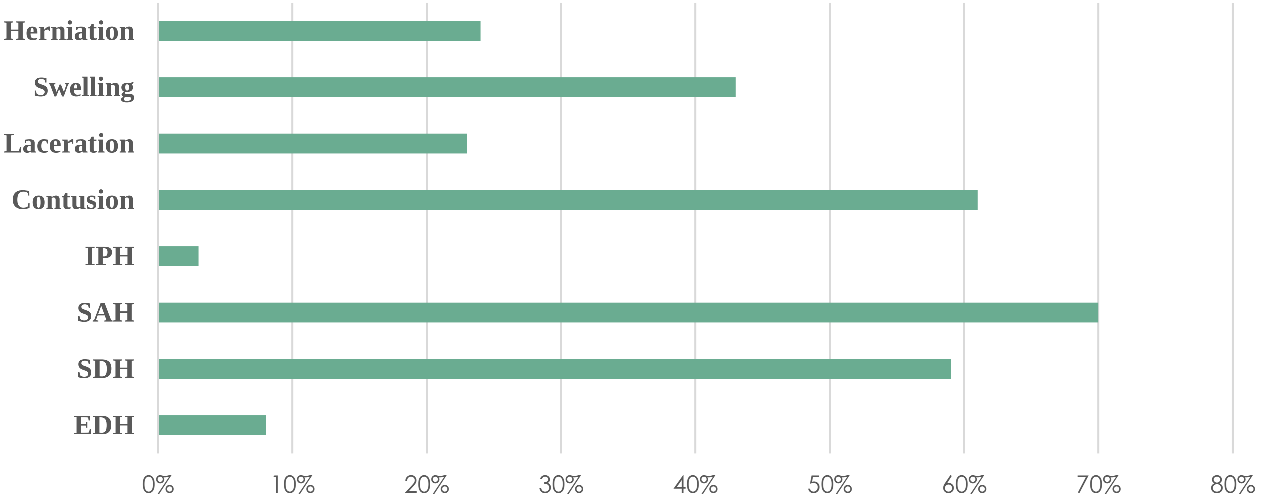


Figure 4: The incidence of brain trauma(s). IPH: Intraparenchymal Haemorrhage; SAH: Subarachnoid Haemorrhage; SDH: Subdural Haemorrhage; EDH: Extradural Haemorrhage

Cranial fractures were noted in 471 (66%) cases. Of the individuals that presented with cranial fractures, the most common fracture type was linear fracture (n = 349; 74%), followed by depressed (n = 171; 36%), comminuted (n = 146; 31%) and hinge (n = 57; 12%) fractures. The percentages of the various fracture types do not add up to 100% in this case due to some of the individuals presenting with more than one fractured region. Fractures were primarily located at the base of the skull (n = 265; 56.26%) followed by the left (n = 261; 55.41%) and right (n = 245; 52.01%) cranium. The least common fractures were frontal and occipital fractures, which were only noted in 183 (38.85%) and 132 (28.03%) cases respectively. A total of 459 (64%) cases presented with cranial fracture(s) and brain trauma simultaneously; 222 (31%) cases presented with brain trauma and no cranial fracture(s), and 12 (2%) cases presented with cranial fracture with no associated brain injury (*Figure 5*). Of the cases that presented with cranial fracture and no brain injury, four presented with scapular lacerations, abrasions and contusions and multiple BFT to the body while one presented with scapular lacerations, contusions and subscapular haemorrhaging and seven presented with scapular abrasions, contusions and subscapular haemorrhaging.

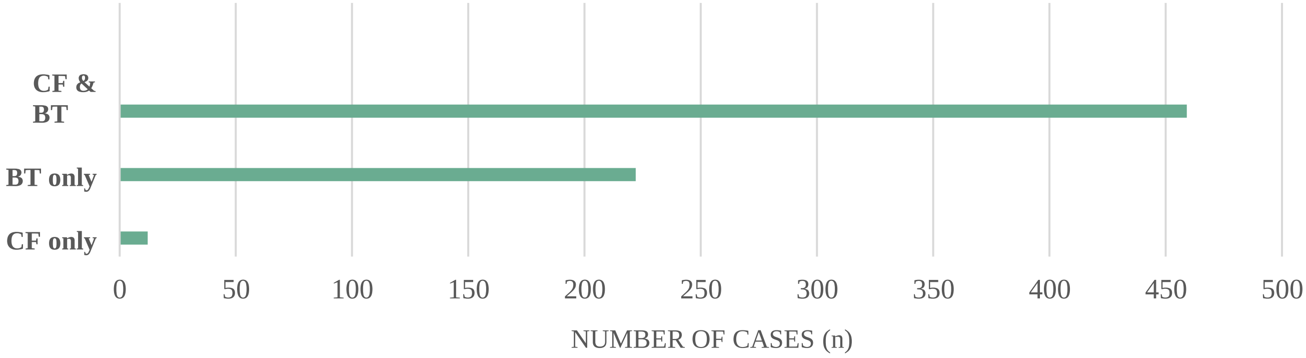


Figure 5: Cases with cranial fractures (CF) co-occurring with brain trauma (BT) (CF & BT); brain trauma with no cranial fractures (BT only), and cranial fractures with no brain trauma (CF only)

Furthermore, the number of cases that presented with a co-occurrence of specific cranial fracture types and brain trauma types was summarised, in figure 6. All the cranial fracture types co-occurred with all the brain trauma types, except for hinge fractures where no extradural haemorrhaging was noted. Overall, linear CFs was the most common fracture type to co-occur with each brain trauma type, followed by depressed CFs which were considerably less than linear fractures, as seen in figure 6. As it relates to brain trauma types and cranial fracture site, all BT types were most commonly associated with fracture(s) to the basal cranial region except for EDH. Interestingly, EDH was commonly associated with fracture to the right temporal bone.

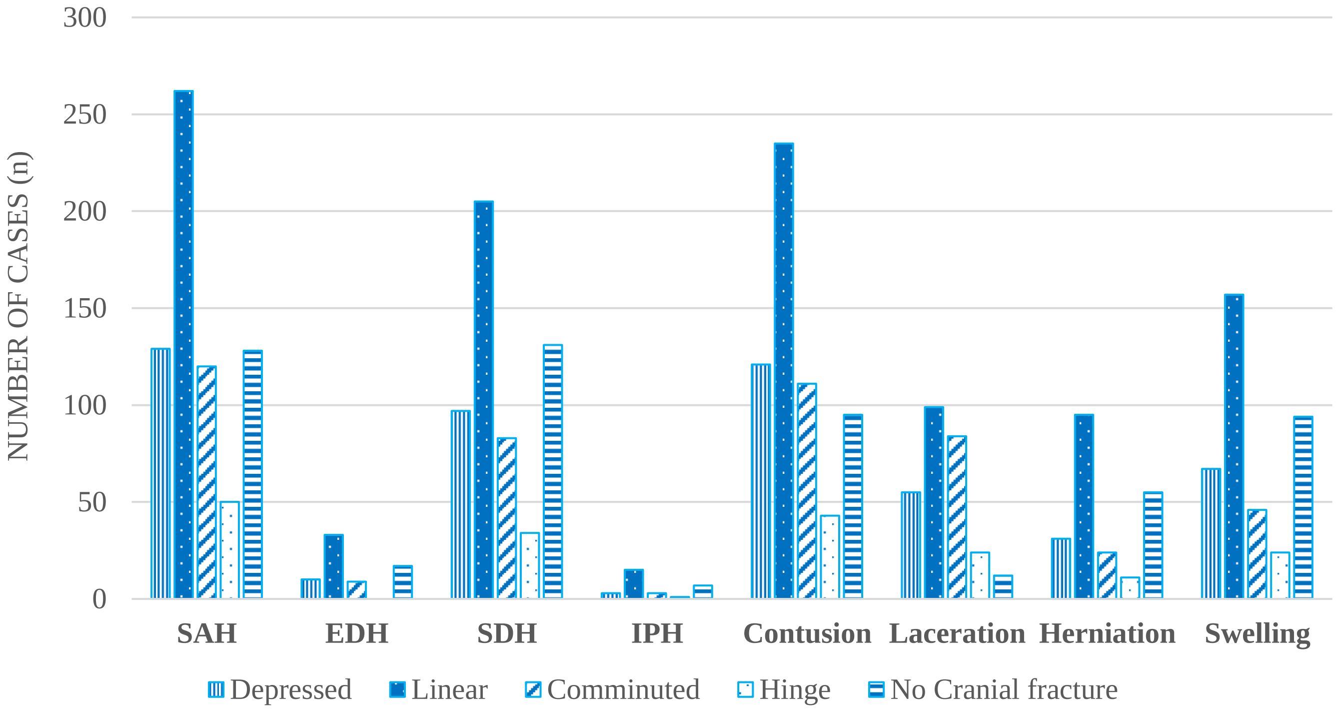


Figure 6: The number of cases occurring with specific brain trauma and cranial fracture simultaneously; SAH: Subarachnoid Haemorrhage; EDH: Extradural Haemorrhage; SDH: Subdural Haemorrhage; IPH: Intraparenchymal Haemorrhage

3.3.1 Association(s) of variables

To assess whether an association exists between specific variables in the study, Chi-squared (X^2) analyses were performed. A significant association was found between the presence of brain trauma and accidental deaths ($p = 0.026$) while, no significant association was found between the presence of brain trauma and homicidal ($p = 0.783$) and suicidal ($p = 0.464$) deaths (Table 5). In contrast, a significant association exists between the presence of cranial fractures and suicidal ($p = 0.007$) deaths, however no significant association was found between the presence of cranial fractures and homicidal ($p = 0.559$) and accidental ($p = 0.519$) deaths (Table 6).

A significant association was found between age and the presence of brain trauma ($p = 0.042$), with majority (n = 482) of the individuals with brain trauma ranging between 18 to 39 years of age. In the older age ranges (60 – 100 years), only 84 (11.68%) individuals presented with brain trauma. Similarly, a significant association between the presence of cranial fractures and age exists ($p = <0.001$) where the number of individuals with cranial fractures in the 30 – 39 age group were more than expected and in the 50 – 59 age group, these were less than expected.

However, no significant association was found between the presence of brain trauma and sex (*p = 0.241*). Likewise, no significant association was found between presence of cranial fractures and sex (*p = 0.372)* (Table 6).

Additionally, a significant association was noted between the presence of brain trauma and the presence of cranial fracture (*p = <0.001*). A significant association was found between the presence of brain trauma and cranial fracture types; in particular, a significant association was found with depressed fractures (*p = 0.049*), comminuted fractures (*p = 0.018*) and linear fractures (*p = <0.001*) individually. The presence of each of these fracture types was more commonly associated with brain injury. Notably, all cases of hinge fractures had associated brain trauma. Associations between brain trauma and variables are presented in table 5.

Table 5. Association(s) with the presence of brain trauma

Variables	*Total cases*	*Cases with brain injury (total BT cases: 681)*	*p-value* (X^2)
Homicidal Deaths	574	543	0.783
Accidental Deaths	130	118	0.026
Suicidal Deaths	14	14	0.464
Age	719	719	0.042
Sex	719	719	0.241
Presence of cranial fracture	471	459	<0.001
Depressed CF	171	167	0.049
Comminuted CF	146	144	0.018
Linear CF	349	341	<0.001
Hinge CF	57	57	0.641

BT: Brain trauma; CF: Cranial fracture; Significant values highlighted in yellow.

Table 6. Association(s) with the presence of cranial fracture

Variables	*Total cases*	*Cases with cranial fracture (total CF cases: 471)*	*p-value* (X^2)
Homicidal Deaths	574	379	0.559
Accidental Deaths	130	82	0.519
Suicidal Deaths	14	4	0.007
Age	719	719	<0.001
Sex	719	719	0.372
Presence of brain trauma	681	459	<0.001

CF: cranial fracture; Significant values highlighted in yellow.

Further X^2 analyses were performed to determine whether an association exists between the types of cranial fracture and brain traumas listed in the study. It is important to note that the different types of cranial fractures were not significantly associated with every type of brain trauma listed; those that were found to be significantly associated were highlighted in table 7. Depressed cranial fractures were significantly associated with subarachnoid haemorrhage (SAH), contusion and lacerations where the presence of depressed fractures resulted in less SAH, contusion and lacerations. Linear and comminuted cranial fractures were both significantly associated with SAH, brain contusions, lacerations, and some secondary brain injuries, namely brain herniations and swelling.

The presence of comminuted fractures resulted in less SAH, contusion, herniation and swelling of the brain, however, the presence of comminuted fractures resulted in more brain lacerations. Similarly, the presence of linear cranial fractures resulted in more SAH, contusion, lacerations, herniation and swelling of the brain. Hinge fractures were significantly associated with SAH, brain contusions and lacerations. Notably, a significant association exists between extradural haemorrhage (EDH) and hinge fractures, despite there being no cases with EDH co-occurring with hinge fractures, thus this is an inverse association.

Table 7. Association(s) between types of brain trauma and types of cranial fracture

	p-value (X^2)							
	EDH	***SDH***	***SAH***	***IPH***	***Brain Contusion***	***Brain Laceration***	***Brain Herniation***	***Cranial Swelling***
Depressed CF	0.176	0.871	0.003	0.219	<0.001	<0.001	0.071	0.632
Comminuted CF	0.286	0.857	<0.001	0.379	<0.001	<0.001	0.030	0.011
Linear CF	0.296	0.181	<0.001	0.104	<0.001	<0.001	0.014	0.025
Hinge CF	0.018	0.583	<0.001	0.518	0.005	<0.001	0.464	0.828

EDH – Extradural haemorrhage; SDH – Subdural haemorrhage; SAH – Subarachnoid haemorrhage; IPH – Intraparenchymal Haemorrhage; CF – Cranial fracture; Significant values highlighted in yellow.

The association between the presence of cranial fracture and trauma to specific brain lobes was analysed. A significant association was found between the presence of cranial fractures and injury to the frontal, parietal and temporal lobes. No significant association was observed between the presence of cranial fractures and injury of the occipital lobe and the cerebellum (Table 8).

Interestingly, a significant association was observed particularly between the left and right frontal lobe and occipital fractures (*$p = 0.007$; $p = 0.030$)* and this is noteworthy as it relates to contrecoup brain injuries. The number of cases that presented with trauma to specific lobes and a presence or absence of cranial fractures are summarised in Table 8.

Cases that did not present with cranial fracture are significantly less compared to cases with associated cranial fracture. An analysis to correlate injury to a specific lobe and fracture to the associated portion of the skull could not be done in this study, however this would be beneficial to assess in the future.

Table 8. Associations between brain lobes and the presence of cranial fracture

Brain Lobe Injury Location	***No Cranial fracture***	***Cranial fracture***	***p-value (X^2)***
Left Frontal Lobe	62	190	<0.001
Right Frontal Lobe	65	184	<0.001
Left Parietal Lobe	17	102	<0.001
Right Parietal Lobe	28	104	<0.001
Left Temporal Lobe	63	238	<0.001
Right Temporal Lobe	62	204	<0.001
Left Occipital Lobe	19	59	0.095
Right Occipital Lobe	18	53	0.182
Cerebellum	38	104	0.066

Significant values highlighted in yellow.

3.3.2 Binary Logistic Regression

Binary logistic regression analyses were performed using crude models and models adjusted for age and sex, to obtain the odds ratios for the presence of brain trauma. The dependent variable was the presence of brain trauma, and the covariates included the presence of cranial fractures, the presence of external head injury (HI), fracture location which was divided into frontal, left region, right region, occipital and basal fracture, and fracture type (depressed, comminuted, linear and hinge fracture). The results of the regression analyses performed are summarised in Table 9. Although all the crude odds ratios were greater than 1, only the odds ratios associated with the presence of cranial fractures and the presence of basal fractures were statistically significantly different from 1. Both these variables are positive predictors of brain trauma and indicate an increased likelihood of the occurrence of brain trauma. Individuals presenting with cranial fracture are 4.48 times more likely to have TBI, compared to those without cranial fracture. Specifically, individuals with fracture of the basal region are 3.77 times more likely to have co-occurring TBI. While fractures to the left lateral region had greater odds ratio of TBI than impacts to the right, this was not statistically different from an OR of one.

Table 9. Binary logistic regression analysis of possible predictors of traumatic brain injuries

	OR	***95% CI***	***p-value (X^2)***	***Adjusted[a] OR***	***95% CI***	***p-value (X^2)***
Presence of CF	4.480	2.219 – 9.044	<0.001	4.813	2.355 – 9.836	<0.001
Presence of HI	1.936	0.434 – 8.633	0.387	1.966	0.435 – 8.893	0.380
Frontal fracture	1.296	0.423 – 3.971	0.650	1.306	0.423 – 4.031	0.643
Left region fracture	2.619	0.859 – 7.987	0.091	2.684	0.881 – 8.182	0.082
Right region fracture	1.911	0.704 – 5.184	0.203	2.042	0.750 – 5.559	0.163
Occipital fracture	1.822	0.408 – 8.137	0.432	1.894	0.425 – 8.438	0.402
Basal fracture	3.775	1.067 – 13.357	0.039	3.937	1.110 – 13.968	0.034

*a – Adjusted for age and sex; OR – Odds Ratio; CI – Confidence Interval CF – cranial fractures; HI – Head injury

When the age and sex of the victims is considered in the predictions, all the odds ratios increased. Notably, the odds of brain trauma occurring increased by more than 0.3 in the presence of a cranial fracture overall while, basal fractures are more likely to predict brain trauma more than a fracture on any other part of the cranium.

Following assessment of crude and sex/age adjusted models, best subsets regression analyses was performed to determine which combination of variables provided the best prediction for the presence of TBI. The regression analyses were performed to establish a model which was most comprehensive and could be best used as an initial step to predict whether a patient is more or less likely to have brain trauma. Thus, the presence of TBI is the dependent variable in each model. To determine the best ‘all subsets’ model, the R^2 value is considered as it represents the goodness of fit of the model. Therefore, the highest R^2 value indicates the best model.

Table 10. Binary logistic regression models trialled for best 'all subsets' model

Models	R^2 value
Presence of CF x Presence of HI	0.078
Presence of CF x Fracture Site	0.111
Fracture Site x Presence of HI	0.111
Presence of CF x Presence of HI x Fracture Site x Age x Sex	0.127
Presence of CF x Presence of HI x Fracture Site x Fracture types x Age x Sex	0.128

CF: cranial fracture(s); HI: head injuries; Best all-subsets model highlighted in green.

Ultimately, the best 'all subsets' model for the prediction included the presence of cranial fractures and externally observable head injuries, fracture locations and types, and sex and age as seen in Table 10. This model had an R^2 value of 0.128 and the equation of the model is as follows:

$$\begin{aligned}\boldsymbol{Log(pres.of\ BT)} &= 0.056\ (pres.of\ CF) + 0.305\ (pres.of\ external\ HI) + 0.118\ (frontal\ fr.)\\ &+ 0.842\ (left\ region\ fr.) + 0.496\ (right\ region\ fr.)\\ &+ 0.520\ (occipital\ region\ fr.) + 1.262\ (basal\ fr.) + 0.308\ (depressed\ fr.)\\ &+ 0.338\ (comminuted\ fr.) + 0.125\ (linear\ fr.) + 2.670\end{aligned}$$

where in each variable, the presence = 1 and the absence = 0; BT – brain trauma, CF – cranial fracture; HI – head injury.

As previously described, all cases that had a hinge fracture, presented with concurrent brain trauma. Thus, this variable would serve as a 100% predictor in any model wherein this variable is included. However, due to the relatively low number of hinge fractures in the sample, this may be an artefact of the sample. As a result, the presence of hinge fractures was not included as a predictor variable in any of the models, although cautiously the data suggests that in the presence of a hinge fracture, there will be associated brain trauma.

4. Chapter 4: Discussion

The incidence of TBI globally has prompted various investigations into the various factors that affect the occurrence, extent and severity of TBI. Thus, it has become of utmost importance to gain knowledge that will aid in reducing the occurrence of TBI and establish more advanced treatment models to reduce the morbidity rate associated with TBI. Various independent risk factors have been associated with fatal TBI including the male gender, older age, use of alcohol and drugs and participating in contact sports such as American football (Wagner et al., 2000; Hyder et al., 2007).

The primary focus of the current study was to investigate blunt force trauma associated with TBI, with an aim to determine the correlation between cranial fractures and brain trauma. Vast knowledge and understanding of the pathophysiology of TBI and the impact of cranial fractures on TBI, is important to move towards prompt and more advanced screening and treatment methods in the event of head injury. Thus, more lives will be saved, and a positive impact will be noted in the global TBI pandemic. Knowledge of the correlation between cranial fractures and brain trauma will be important in the anthropological field as well, where the only tissue that is available for assessment is skeletal and brain trauma is speculated.

4.1 Incidence of TBI-related deaths

At Salt River Mortuary (Cape Town, South Africa), between 2015 – 2019, 12507 unnatural death cases were recorded, of which 2763 (22.1%) cases were a result of blunt force trauma. The most common manner of death in this study was homicides (79.8%; n = 574), making up more than two thirds of the total number of blunt force trauma cases. Similarly, Clark et al. (2017) investigated the prevalence of blunt force trauma and blunt force trauma homicides between 2010 – 2014 and found that 69.1% of the blunt force trauma cases at Salt River Mortuary were classified as homicides. This suggests that the deaths were often a result of violence and intent to injure or cause death. Majority of the cases in the current study were noted as community assaults, which often take place as retaliation to or a means to avenge an unjust act, as deemed by the members of the community (Phoba & Zunza, 2022). Accidental deaths, which in the context of the current study were deaths noted to be due to a fall, made up 18% of the total number of cases, and suicides were only 1.9%, which are considerably less than the homicide cases in this study.

Bertozzi et al., 2020 found that closed head injuries that occurred as a result of non-penetrative impact to the cranium, made up majority (70%) of the TBI cases in their study. Similarly, of the blunt force trauma cases included in the current study from the cases recorded at Salt River Mortuary, 94.7% (n = 719) of the individuals presented with TBI.

Bertozzi et al. (2020) reported that in the United States of America in 2014, a total of 56 800 fatal TBI cases were recorded where, the highest rate of fatal TBI was noted in older individuals (55 years – 75 years and older). This is in contrast to the current study where the mean age at death was 37 years (*SD* ± 16.75 years), with majority of the victims falling within the 18 – 29 and 30 - 39-year age groups. Thereafter, there is a drastic decrease in the number of cases in the remaining age groups. A similar trend was noted in previous South African based literature where Clark et al. (2017) reported that the majority of the blunt force trauma homicide victims were within the 10 – 19 years, 20 – 29 years and 30 - 39 years age groups.

Road traffic, self-inflicted and violence-related injuries were reported as being the causes of death related to TBI in individuals that are younger than 60 years (Hyder et al., 2007). Carson (2009) reported the same results, where the average age was reported as 29 years. Thus, the overrepresentation of the young adult age groups in this study can be attributed to the fact that younger generations have been associated with more reckless, active and poorly thought-out behaviour, as with the previous studies. Notably, majority of the older individuals (60 years and older) had TBI-related deaths as a consequence of an accidental fall. Falls have been reported as the leading cause of accidental deaths in older adults (Stevens, 2005). One in three adults over 65 years and one in two over 85 years will experience a fall and a considerable amount of those will result in injury (Stevens, 2005).

The ratio of male to female was 10.1 in this study where the males made up 91% and the females made up 9% of the total number of cases. More than 95% of the males and 91% of females presented with brain trauma, while 68.7% males and only 32.8% females presented with cranial fractures.

The noteworthy difference in the sex distribution of the cases involved in the study can be attributed to several factors. Males have been reported to engage in more risk-taking behaviour, be more violent and involved in more contact sports, and they are reported to consume more alcoholic beverages than females (Frost et al., 2013).

Morrell and Lindegger (2012) highlighted the integral role that masculinity, and the complexity of masculinity, play in men partaking in more risk-taking behaviour. The necessity of men to showcase their bravery and ‘manliness’ in moments of disagreement has led to more violent and life-threatening behaviour, as aggressive behaviour has been aligned with masculinity (Taylor et al., 2010). The courage to partake in this behaviour is heightened by the consumption and abuse of alcoholic and other mood-altering substances (Taylor et al., 2010; Clark et al., 2017).

In the South African context, particularly in the West Metropole of the City of Cape Town, previous literature reported increased levels of gang violence, wherein more males are often involved (Morrell & Lindegger, 2012; Buur & Jensen, 2004). Similarly, this notion is reinforced by the findings of the current study where the most common circumstance of death among the males was community assault.

4.2 Brain trauma and cranial fractures

Brain trauma was noted in 94.7% of the total cases where the most prevalent type of brain trauma was subarachnoid haemorrhaging (70%) followed by brain contusions (61%), subdural haemorrhaging (59%) and brain swelling (43%). Conversely, Brink (1998) investigated injuries due to interpersonal violence in assault victims of Aarhus, Denmark and found that 34.2% of the cases presented with contusions and only 16% of the cases presented with brain lacerations. Brain lacerations (23%), herniations (24%) and EDH (8%) were noted in less than a quarter of the cases in the current study, however these are still noteworthy. Similarly, previous studies have reported that EDH does not commonly occur in the event of head trauma (Kleiven, 2013). Kleiven (2003) reported EDH in only 6% of the cases.

Al-Sarraj (2016) reported that EDH is often associated with fracture to the squamous temporal bone, which causes damage to the middle meningeal artery that results in the haemorrhage. Likewise, in the current study, EDH was found to most commonly co-occur with fracture(s) to the right temporal bone. In the event of severe TBI, SDHs are significantly more recurrent than EDH, however SAHs are the most common type of haemorrhage, occurring as a result of trauma to the head (Aromatario et al., 2021; McKee & Daneshvar, 2015; Kohli & Banerjee, 2006). Additionally, SDH has been frequently associated with the presence of contusion, SAH and cranial fracture (Al-Sarraj, 2016).

Cranial fractures were noted in 66% of the total cases where the most common fracture type was linear (74%) and depressed (36%) fractures. Comminuted fractures were noted in 31% of the cases and only 12% presented with hinge fractures.

In terms of the site of fractures, fractures occurred primarily on the base of the skull (n = 265; 37%) and left cranium, which involves the left parietal and left temporal bone (n = 261; 36%). It is important to note that fractures do not occur in isolation and the various fracture types can occur simultaneously. Agreeably, Crudele et al. (2019) found that in lethal head trauma cases, cranial base fractures are especially frequent and Kohli and Banerjee (2006) reported cranial base fractures as the most common site of cranial fractures in their study. Interestingly, the cranial base is noted as one of the more resistant areas of the cranium and more protected than the rest of the cranium which suggests that severe head trauma is necessary to cause fracture to the cranial base (Crudele et al., 2019).

The craniofacial skeleton is closely associated with the cranial base of the human skull, through the temporomandibular joint (condylar articulation) of the mandible. Craniofacial fractures, particularly the mandibular fractures, have been associated with basal cranial fractures; this association is rooted in the transference of energy through the mandible, directly to the base of the skull, when a force is applied to the craniofacial region (Pappachan & Alexander, 2012). The mandible is reported to be more sensitive to lateral impacts compared to frontal impacts (Pickrell et al., 2017). This can be attributed to the intricate geometry of the mandible, wherein each area presents with varied levels of failure and tolerance to fracture formation (Pappachan & Alexander, 2012).

In order for a moving object to come to a halt, the kinetic energy with which it was moving has to be dissipated. When the mandibular bone withstands the force that is applied, the resultant energy is transferred to the basal cranium through the temporomandibular joint, and thus relatively minimal mandibular fractures may be associated with significant head injury (Pappachan & Alexander, 2012). Fracture(s) to the cranial base have been associated with haemorrhaging through the ear canal, cerebrospinal fluid leak and hearing loss in surviving patients (Simon & Newton, 2017).

During the treatment and diagnostic period, the presence of periorbital and mastoid battle ecchymosis is reported to be exceptionally predictive of basilar cranial fracture (Simon & Newton, 2017). Periorbital ecchymosis, which is also known as racoon eyes, refers to when blood pools around the eyes, often as a result of injury. Similarly, mastoid battle ecchymosis is the pooling of blood in the mastoid region of the head following injury to the cranium, specifically the middle cranial fossa (Simon & Newton, 2017; Tubbs et al., 2010). In a study investigating the prevalence of basal cranial fractures, Mokolane (2019) found a statistically significant association between the severity of the injury to the head (according to the Glasgow Coma Scale) and the presence of basal cranial fractures as visualised on CT scans.

Likewise, Carson (2009) reported that the severity of injury, scored using the Abbreviated Injury Scale, was significantly greater in individuals with skull fractures than in individuals without skull fractures. The right side of the cranium (parietal and temporal) was fractured in 245 (34%) cases. Frontal fractures were considerably less common with only 183 (25%) cases presenting with frontal fractures. Chattopadhyay and Tripathi (2010) investigated skull fracture and haemorrhage patterns in fatal and nonfatal cases and found that among their cases, the most common fracture site was the frontal, parietal and temporal bones. While occipital fractures were the least common fracture site and the authors proposed that this is possibly attributed to the occipital bone being the thickest of the cranial bone and therefore requires a significant amount of force to fracture (Chattopadhyay & Tripathi, 2010). Similarly, in the current study, the occipital region was the least fractured cranial bone, where only 18% (n = 132) cases showed evidence of occipital fractures.

Brain trauma and cranial fractures co-occurred in 64% of the total cases and significant association was found between the presence of brain trauma and the presence of cranial fracture. Brain trauma in isolation was noted in 31% of the cases while only 2% of cases presented with cranial fractures and no associated brain trauma. Of these cases occurring with cranial fractures only, 76.92% were homicidal deaths while 23.07% were accidental deaths. Thus, brain trauma co-occurring with cranial fractures is exceedingly more prevalent than these occurring in isolation. The likelihood of SAH, SDH and/or EDH occurring is significantly higher, in an individual with skull fracture that co-occurred with TBI (Tseng et al., 2011). Additionally, in the event of TBI, the mortality risk factor is increased when cranial fracture(s) are present (Tseng et al., 2011).

What poses a threat to an individual’s life is seldom the cranial fracture itself, it is the resultant impact and injury to the contents of the cranium that ultimately affect the individual’s life (Saukko, 2004). The presence of cranial fractures increases the occurrence of brain trauma as in the current study, we found that in the presence of cranial fracture, an individual is 4.48 times more likely to have brain injury.

Similarly, Ren et al. (2020) found that an increase the risk of the occurrence of brain contusions may be expected in presence of cranial fracture, particularly under high-impact velocity. However, under medium to high velocities, the presence of cranial fracture decreased the risk of diffuse brain trauma (Ren et al., 2020).

A significant association exists between cranial fractures and brain trauma, markedly, a significant association exists between the specific types of cranial fractures and the types of brain trauma. It is important to note that the presence of a fracture is indicative of the severity of the impact to the cranium as, a significant amount of force is required to cause fracture to the cranial bones (Saukko, 2004). The presence of depressed cranial fractures yielded less SAH, contusion and lacerations and, in the presence of comminuted cranial fractures, more brain lacerations were noted. The presence of linear cranial fractures yielded more SAH, contusion, herniation and swelling of the brain (*Figure 6)*. Interestingly, every case that presented with hinge fracture, presented with brain trauma. Thus, when a hinge fracture is noted in a victim, the brain of the individual is most likely injured as well.

Of the lobes of the brain and in the presence of cranial fracture, the temporal lobes were the most injured followed by frontal lobe, bilaterally. The occipital lobe and the cerebellum were least impacted, with no significant association with cranial fracture (s) noted. This can be attributed to the position of the occipital lobe and cerebellum, on the ventral-caudal section of the brain. These are protected by the occipital cranial bone and the base of the cranium, which have been reported as robust sites (Crudele et al., 2019; Chattopadhyay & Tripathi, 2010).

Importantly, in the current study, occipital fractures were significantly associated with frontal lobe trauma. This reiterates existing literature that report a prevalence of contrecoup injuries, particularly contrecoup injuries involving injury to the frontal lobe due to impact and fracture of the occipital bone (Ratnaike et al., 2011).

A regression analysis indicated a base of skull fracture is more likely to predict the presence of brain trauma, than a fracture to any other site on the cranium, as fracture to this site indicates a large application of force and impact to the head subsequently damaging the site.

When assessing the probability of a victim having brain trauma, the current study found that the most comprehensive model to apply, using the model equation, includes assessing a combination of the presence of cranial fractures and externally observable head injuries, sex and age, fracture locations and fracture types (Table 10). However, it is important to note that there are not always clear clinical indications of the presence of cranial fractures, and this should be considered in the initial stages of treatment, in a clinical medicine context. In accord, Munoz-Sanchez et al. (2009) reported that in surviving individuals who were later confirmed to have mild TBI (GSC: 14 -15) and cranial fracture(s), 63.2% presented with no clinical signs of bone trauma initially. This highlights the importance of considering a comprehensive model of variables when treating a potential case of TBI and that, it is more valuable to consider a multifaceted approach that has been proven, to ensure reliable and efficient examinations.

Most notably, the aforementioned model could play an integral role in challenging anthropological investigations where only skeletonised tissue is available. The model would allow for the understanding and ascertaining of the likelihood of TBI based on the characteristics of the cranial fracture(s) of the victim and this could provide further information regarding mechanism of death in these cases.

4.3 Limitations

Due to the retrospective nature of this study and inclusion/exclusion criteria applied, several limitations should be taken into account when interpreting the data. This study only included individuals that were 18 years or older were included. Thus, the data and results may not be applicable to younger individuals as there are significant biomechanical and structural changes that occur within the cranium as one ages, and these affect the rigidity and robustness of the cranium. These, in turn, affect the degree of protection that the cranial bones can afford the contents of the cranium. Therefore, it would be beneficial to investigate whether contradictory results are seen in the correlation between cranial fractures and brain trauma in individuals that are younger than 18 years. And, to note the impact that the developmental biomechanical differences may have on this correlation.

The severity of TBI in terms of the injury scales such as AIS and GCS, could not be considered in the current study as the determination of this would require the individual to have survived. Some individuals included in this study were hospitalised soon after injury and prior to death, however very few cases recorded the severity of TBI during the period of survival. Assessing the correlation of cranial fractures and brain trauma in surviving individuals would be beneficial, particularly in clinical medicine. This would allow for the impact of the acute injury and the progression of the injury to be monitored, examined and reported on.

The incidence of the co-occurrence of brain trauma and cranial fractures calculated in this study was based on the population statistics that were reported in 2011, as these were the latest available statistics for the Western Metropole of the City of Cape Town at the time of conducting the current study. As the updated population data of the Western Metropole of the City of Cape Town becomes available, assessing the aforementioned incidence and comparing the result to the incidence found in the current study, would provide valuable insight.

The impact of the presence of alcohol and/or other substances at the time of injury could not be assessed as this information was not readily available for every case. It would be interesting to investigate the impact that the presence of alcohol at the time of injury may have on the correlation that has been noted in this study. This is important because apart from the cognitive impairment that alcohol causes, alcohol is known to limit the effectiveness of the coagulating factors within blood and it has been associated with an increased risk of elevated blood pressure (Puddey & Beilin, 2006; Salem & Laposata, 2005). Hyder et al. (2007) reported acute alcohol consumption as a risk factor of TBI, and in accord, Gururaj (2004) reported the severity of TBI being considerably higher in individuals who were intoxicated at the time of injury.

In individuals who have a history of previous TBI, subsequent TBI is likely to be more severe (Dams-O'Connor et al., 2013). However, this is in regard to repeated micro-trauma and accumulation of molecular changes in the brain tissue over time. While this extension may lend itself to future macroscopic brain injury being more severe, limited research has investigated this aspect. Unfortunately, within the scope of this study obtaining detailed medical life histories of all individuals was not possible, Thus, although unlikely, the potential for some of these individuals to have had a greater severity of TBI associated with a particular fracture should be acknowledged.

5. Chapter 5: Conclusion

Blunt force trauma to the cephalic region can result in externally observable head injury, cranial fracture and/or trauma to the brain. In the current study, the correlation between cranial fractures and brain trauma was corroborated and the co-occurrence of cranial fractures and brain trauma was found to be prevalent.

TBI as a result of BFT, was most prevalent in young adults, where the frontal, parietal and temporal lobes are the most commonly injured brain sites, in the presence of cranial fractures. Individuals presenting with cranial fracture are 4.48 times more likely to have TBI, compared to those without cranial fracture. Specifically, individuals with fracture of the basal region of the cranium are 3.77 times more likely to have co-occurring TBI. Furthermore, fractures to the cranial base have an increased risk of being associated with TBI compared to fractures in other regions of the cranium. In addition, in the presence of a hinge fracture, the presence of brain trauma is highly likely, with the exception of EDH. This is because all the cases with hinge fractures had associated brain trauma where hinge fractures were significantly associated with SAH, brain contusion and laceration. Hinge fractures were inversely associated with EDH, and this indicates that the presence of hinge fractures is associated with presenting with no co-occurring EDH.

The data presented in this study can provide useful insight in the process of an autopsy examination for an individual that has suffered or is suspected to have suffered a head injury. The prediction of brain trauma is plausible, using the all-subsets model highlighted in this study. Anthropologically, noting the site and type of a cranial fracture can allow for determining the mechanism of death and gaining more context for the cause and manner of death, even in the absence of brain tissue.

In summation, although the correlation between cranial fractures and brain trauma is scarcely investigated, this study has successfully highlighted the importance and necessity of extensive knowledge of the correlation between cranial fractures and brain trauma and its applicability in multiple fields, while noting the various avenues that future studies can explore as it relates to this correlation.

6. Chapter 6: References

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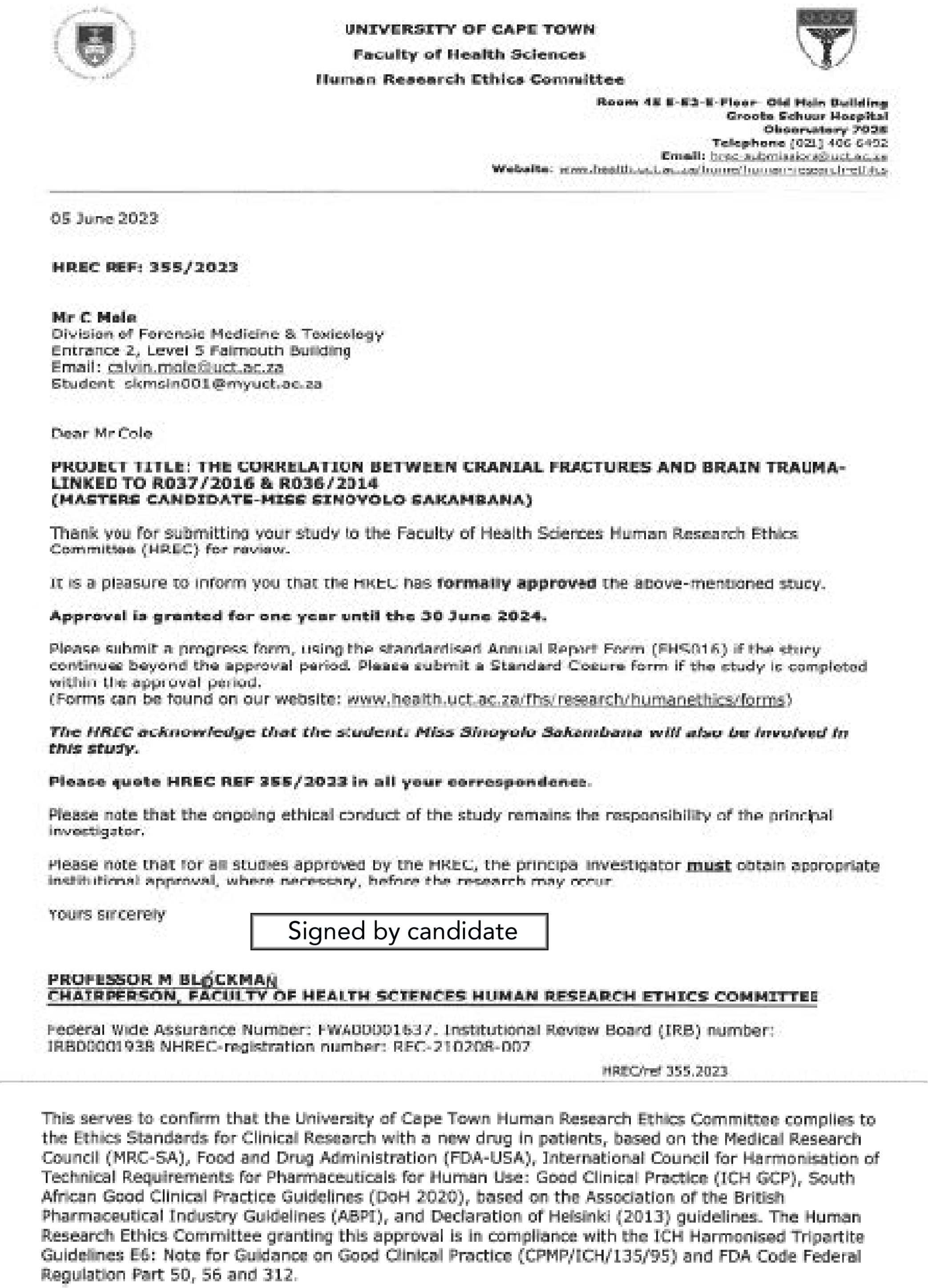
Appendices

Appendix A: Ethical approval



UNIVERSITY OF CAPE TOWN
Faculty of Health Sciences
Human Research Ethics Committee

Room 48 E-53-E-Floor- Old Main Building
Groote Schuur Hospital
Observatory 7925
Telephone (021) 406 6492
Email: hrec-submissions@uct.ac.za
Website: [illegible]

05 June 2023

HREC REF: 355/2023

Mr C Mole
Division of Forensic Medicine & Toxicology
Entrance 2, Level 5 Falmouth Building
Email: calvin.mole@uct.ac.za
Student skmsin001@myuct.ac.za

Dear Mr Cole

PROJECT TITLE: THE CORRELATION BETWEEN CRANIAL FRACTURES AND BRAIN TRAUMA- LINKED TO R037/2016 & R036/2014
(MASTERS CANDIDATE-MISS SINOYOLO SAKAMBANA)

Thank you for submitting your study to the Faculty of Health Sciences Human Research Ethics Committee (HREC) for review.

It is a pleasure to inform you that the HREC has **formally approved** the above-mentioned study.

Approval is granted for one year until the 30 June 2024.

Please submit a progress form, using the standardised Annual Report Form (FHS016) if the study continues beyond the approval period. Please submit a Standard Closure form if the study is completed within the approval period.
(Forms can be found on our website: www.health.uct.ac.za/fhs/research/humanethics/forms)

The HREC acknowledge that the student: Miss Sinoyolo Sakambana will also be involved in this study.

Please quote HREC REF 355/2023 in all your correspondence.

Please note that the ongoing ethical conduct of the study remains the responsibility of the principal investigator.

Please note that for all studies approved by the HREC, the principal investigator **must** obtain appropriate institutional approval, where necessary, before the research may occur.

Yours sincerely

Signed by candidate

PROFESSOR M BLOCKMAN
CHAIRPERSON, FACULTY OF HEALTH SCIENCES HUMAN RESEARCH ETHICS COMMITTEE

Federal Wide Assurance Number: FWA00001637. Institutional Review Board (IRB) number: IRB00001938 NHREC-registration number: REC-210208-007

HREC/ref 355.2023

This serves to confirm that the University of Cape Town Human Research Ethics Committee complies to the Ethics Standards for Clinical Research with a new drug in patients, based on the Medical Research Council (MRC-SA), Food and Drug Administration (FDA-USA), International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use: Good Clinical Practice (ICH GCP), South African Good Clinical Practice Guidelines (DoH 2020), based on the Association of the British Pharmaceutical Industry Guidelines (ABPI), and Declaration of Helsinki (2013) guidelines. The Human Research Ethics Committee granting this approval is in compliance with the ICH Harmonised Tripartite Guidelines E6: Note for Guidance on Good Clinical Practice (CPMP/ICH/135/95) and FDA Code Federal Regulation Part 50, 56 and 312.

Appendix B: Table of Variables

Variable Name	Variable Type	Measurement/Recording
Month of death	Categorical Nominal	mm
Year of death	Categorical Nominal	yyyy
Age (years)	Numerical Continuous	Range: 0 – 100
Sex (Female/ Male/ Unknown)	Categorical Nominal	Coding: 0 – Female 1 – Male 888 – Unknown
Cause of death noted as associated with head injury	Nominal Binary	Coding: 0 – Yes 1 – No 888 – Unknown
Circumstances of death	Categorical Nominal	Coding: 0 – Motor Vehicle 1 – Fall 2 – Blow to the head 888 – Unknown
Alleged Manner of death	Categorical Nominal	Coding: 0 – Homicide 1 – Accidental 2 – Suicide 888 – Unknown
Presence of externally observable head injury	Categorical Binary	Coding: 0 – Yes 1 – No 888 – Unknown
Injury type (to the head)	Categorical Nominal	Coding: 0 – Laceration 1 – Abrasion 2 – Contusion/Bruise 888 – Unknown 999 - Undetermined
Presence of brain injury	Categorical Binary	Coding: 0 – Yes 1 – No 888 – Unknown
Injury type (to the brain)	Categorical Nominal	Coding: 0 – Contusion 1 – Haemorrhage 2 – Herniation 888 – Unknown 999 – Undetermined
Location of injury on head	Categorical Nominal	Free text – Pathologist report
Location of fracture on the skull	Categorical Nominal	Coding: 0 – Left frontal 1 – Right frontal

		2 – Left parietal 3 – Right parietal 4 – Left occipital 5 – Right occipital 6 – Left temporal 7 – Right temporal 8 – Left sphenoid 9 – Right sphenoid 10 – Left zygomatic 11 – Right zygomatic 12 – Left nasal 13 - Right nasal 14 – Left maxillary 15 – Right maxillary 16 – Left mandible 17 – Right mandible 18 – Anterior basal 19 – Mid-basal 20 – Posterior basal 888 – Unknown
Location of injury to brain	Categorical Nominal	Free text – Pathologist report
Position of injury	Categorical Binary	Coding: 0 – Coup 1 – Contra-coup 888 – Unknown 999 - Undetermined
Skull fractures presence	Categorical Binary	Coding: 0 – Yes 1 – No 888 – Unknown
Type of skull fractures	Categorical Nominal	Coding: 0 – Depressed 1 – Comminuted 2 – Linear 3 – Transorbital 4 - Hinge 888 – Unknown
Presence of alcohol and/or metabolites	Categorical Binary	Coding: 0 – Yes 1 – No 888 – Unknown
Presence of drug(s) and/or metabolites	Categorical Binary	Coding: 0 – Yes 1 – No 888 – Unknown