A clinical assessment of the morphometrics of African elephant tusks.

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A clinical assessment of the morphometrics of African elephant tusks.

By

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DECLARATION

I declare that the dissertation that I hereby submit for the Masters of Science degree in Zoology at the University of Pretoria has not previously been submitted by me for degree purposes at any other university.

G. Steenkamp

January 2008

DEDICATION

To Anna and all the others of her species that allowed me the privilege of working on them and helping me to unlock some of their secrets.

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Chapter 1 General Introduction

1.1. INTRODUCTION

The largest land mammal in existence today is the African elephant (*Loxodonta africana*). These animals occur widely throughout sub-Saharan Africa, but are concentrated in the southern and eastern regions (1). Elephants are well adapted to their environment and their habitat ranges from desert in the western parts of Africa through savanna and woodlands (bushveld) to forests (2). These animals are therefore also adapted to utilise a variety of food sources for their survival.

During the past 40 years, veterinarians and zookeepers have been studying dental disease in captive animals. However, the first recorded case of an elephant that developed dental pathology in captivity was an African elephant bull in Exeter 'Change, Strand, London already in 1826 (as cited in 3). Various techniques have been developed to treat the multitude of dental injuries sustained to both African and Indian elephants (*Elephas maximus*) tusks (4-27). Mikota *et al.* reported the incidence of tusk fractures in 69 North American Zoological gardens (27). They found the overall incidence of dental disease to be 6.9% of all the medical conditions that the 379 animals in their database had developed. These dental disorders affected 41% of the animals with tusk disorders affecting 31% of the animals (n=118). Identification of risk factors that may lead to tusk trauma, and the elimination thereof, will therefore go a long way towards increasing the quality of life of these individuals in captivity. Tusk pathology naturally also occurs in wild populations but the incidence thereof is unknown (28).

It is well known that all the proposed treatment modalities of tusk trauma and pathology, as described in the literature (4-27), are not equally successful and a literature review with appropriate recommendations will be pursued in this study. Currently there is no technique whereby veterinarians, zookeepers or conservationists can differentiate between those tusk fractures that need treatment from the ones that do not. Robinson & Schmidt attempted estimating which tusk fractures needed attention based on the distance between the eye and the lip where the tusk exits the alveolus (15). This distance was postulated to be the length of the pulp in the coronal tusk (the part of the tusk that protrudes from the labio-dental fold or lip). This can clearly not be the case in the majority of young elephants as well as in most cows and some bulls, since the total length of the coronal tusk is seldom this long.

Many authors have looked at the morphology of the elephant tusk (29-36) but no one has been able to produce a mathematical formula in order to accurately predict the length of the coronal pulp. In the proposed study, various morphometric characteristics of the tusk will be studied and compared amongst populations in order to establish a relevant model for the determination of pulp exposure.

At present animals with suspected pulp exposure and that are not amenable to conscious handling, need general anaesthesia for a full examination and proper management. Anaesthesia may carry risks for the individual concerned and cost factors must also be considered in every given case. Furthermore, these patients may already be suffering from pain or pain may follow secondarily to trauma inflicted when investigating the pulp under conscious circumstances. In the interest of the safety of both the patient and handlers, when working with an exposed pulp, some form of anaesthesia is therefore advocated.

Innervation of a tooth includes afferent neurons, responsible for the sensory impulses, and autonomic fibers that may play a part in odontogenesis and modulation of the microcirculation (37). The anatomy of the Indian elephant pulp is well documented (38). Sikes also refers to the nerve ending associated with the odontoblast layer in African elephants (39). Recent articles disputed the existence of nerve fibers in the pulp of African elephant tusks, leading to misinformation of clinicians with resultant suffering of elephant patients (40, 41). To settle the dispute a histological description of the innervation of the pulp of an African elephant tusk will be included in this study.

1.2. OBJECTIVES OF THIS STUDY

- A comprehensive literature review on tusk disease and treatment of tusked mammals, concentrating on both African elephants (*Loxodonta africana)* and Indian elephants (*Elephas maximus*),
- A histological description of the innervation of the pulp of an African elephant's tusk
- A proposed model for determining the coronal extent of the tusk's pulp,
- The incidence of elephant tusk pathology in wild elephant populations

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Chapter 2 Oral biology and disorders of tusked mammals

2.1. INTRODUCTION

Mammalian tusks have caught the imagination of many hunters, traders and researchers during the past century. Ivory from elephant tusks, as well as that of hippopotamuses, narwhals, warthogs, boars and walruses, were sold on auctions at the turn of the 18th century (1). By 1910 Bland Sutton estimated that the industrial world required, and obtained, 500 – 600 tons of ivory annually (1). Ivory was used for a variety of products like billiard balls, furniture inlays, bangles, art pieces, piano keys, utensil handles and even complete dentures (2, 3). Hippopotamus ivory was favoured for dentures because of its hardness, followed by walrus ivory (2). Fortunately today, many of these everyday commodities can be manufactured from alternative materials and the demand has therefore decreased. During the 1970's and 1980's elephant poaching for ivory was rife in Africa. This was an easy way of obtaining foreign currency in order to fuel various wars fought on the continent. The banning of the ivory trade in 1989 has gone a very long way to help stabilise the elephant populations in Africa (3). Unfortunately, this has also lead to a decline in income for wildlife conservation in countries that manage their elephant populations well. In most of these countries ivory obtained from natural deaths and those confiscated from illegal hunters are currently stockpiled.

No clear scientific definition of the terminology tusk, tush and ivory has been established and these are often used as synonyms (4-7). The term tush has also been used for the description of the primary incisor tooth in elephants that does not erupt (8). Sperber described a tusk as an elongated anterior tooth that protrudes beyond the occlusal plane out of the mouth. A further distinction was made referring to tusks as either continuously growing canines or incisors of a heterodont dentition (2). It is quite clear at this stage that tusk and tush are colloquial terms that have no broad scientific base and which are used across the board for all species that have teeth protruding from the oral cavity. In fact, Sperber feels the long canine teeth of baboons (*Papio sp.*) deserves to be called tusks (2). The species in the literature where specific teeth have been called tusks are quite varied (Table 2 – 1).

Ivory is another colloquial term that is described as a whitish-yellow dentin structure, seldom covered by enamel, which makes up the tusk of the elephant, hippopotamus, walrus, narwhal and mammoth (4, 5, 7). Raubenheimer *et al*, alluded to the unique pattern of the dentin of elephant tusks and feels the term ivory should be reserved for elephant tusks only (9).

It is beyond the scope of this article to address all dental and oral disease of the species mentioned in Table 2 – 1. This publication will focus mainly on the dental and some oral aspects of the elephant, walrus, various suids and the Hippopotamidae.

2.2. FUNCTIONS OF TUSKS

The diversity in the function of tusks is paralleled only by the variation in the species in which they occur. Where the canines form the tusks, they are often associated with defending the individual (2). This is a phenomenon seen in the Chinese water deer (*Hydropotes inermis*) and musk deer (*Moschus moschiferus*), where the deer species that do not have antlers, develop canines that are long and protruding from the oral cavity. It is also present in the chevrotain (*Tragulus javanicus*) (10). It is possibly an adaptation for their forest habitat.

Apart from physically attacking another individual, tusks can also be used as a defensive shield as in the case with the babirusa (*Babyrousa babyrussa*) (11). Sub adult elephants and narwhals (*Monodon monoceros*) can often be seen to spar with one another, using their tusks as weapons(12-14).

In the walrus (*Odobenus rosmarus*) tusks are used to help with locomotion when they haul out onto the ice (15). The generic name *Odobenus* actually translates into English as 'Tooth walker' (16).

Mate selection on the basis of tusk size has been mentioned in most tusked mammals. In most cases there is an exaggerated sexual dimorphism in these species. According to Tiedermann, it is still not clear whether larger tusked Asian elephant males actually do attract significantly more females (17-19). Incisor tusks of elephants and hippopotamuses are used for foraging and/or digging for food (2, 15, 20). Elephants can often be seen debarking trees with their tusks (12). Asian elephant (*Elephas maximus*) bulls have been reported to debark trees for their tuskless cows (12).

Amongst the Suidae, warthogs (*Phacochoerus aetiopicus*) are well known for their digging behaviour with their canine tusks (21, 22). In other Suidae where the tusk does not exit the oral cavity, rooting is performed by the snout (23).

African elephants will often use their tusks to rest their trunk on (Fig. 2 – 1).

In the Beaked whales of the *Mesoplodon* genus, a single pair of sexually dimorphic tusks is present. It is postulated that the position of these teeth may aid in species recognition of sympatric and otherwise morphologically similar species in this genus (24).

2.3. DENTITION OF TUSKED MAMMALS

Hippopotamidae

The two hippopotamus species have incisors and canines protruding from the oral cavity that can be classified as tusks. They are grazers and have brachyo-and bunodont premolar -and molar teeth (10). There is some discrepancy in the literature relating to the amount of premolars in the hippopotamus (*Hippopotamus ampibius*) (10, 15, 20, 25). Laws described the first premolar tooth, as a deciduous tooth that is lost by about 7 years of age. This tooth is not succeeded by a permanent tooth. For this reason, the permanent dentition of the hippopotamus should reflect 3 premolar teeth only, and not 4, as is generally the case (20).

Suidae

The members of this family usually have canine teeth that may or may not protrude from the mouth, grow continuously and form the tusks. The incisors occlude on each other and form a functional shearing apparatus. Suidae, like the Hippopotamidae, have a relative unspecialised premolar and molar dentition that is brachyo-and bunodont (10). The warthog has a specialised third molar that is necessary to grind the grass and tough rhizomes with associated soil particles (Fig. 2 – 2A). The soil particles increase the abrasivity of the diet (26). This molar erupts continuously throughout life and the rostro-caudal (mesio-distal) length is often longer than the rest of the cheek teeth together (26). The triturating occlusal surface consists of three rows, in a mesio-distal direction, of enamel covered dentin columns, bound by cementum. These columns are formed in the caudal mandible, as in elephants, and then migrate mesially (rostrally) to come into occlusion (Fig 2 – 2B) (26). The Suidae differ from true herbivores as they are omnivorous (10). In the babirusa the maxillary canines do not exit the maxilla through the oral cavity, but erupts dorsally through the maxilla (Fig.2 – 3) (27).

Tayassuidae

The peccaries, or New World pigs, are very closely related to the Suidae. The canines form the tusks in this family, however they rarely protrude from the oral cavity (28). Their cheek teeth are also brachyo-and bunodont (10).

Monodontidae

The narwhal is edentulous apart from 2 maxillary incisors. It is the left maxillary incisor that usually elongates in males to form the magnificent and unique tusk (14, 29).

Ziphiidae

Most species in this family only have 2-4 mandibular teeth that are conically shaped and much larger in the males than the females. Only 2 of the genera display a homodont dentition apart from the tusks (Table 2 – 1) (30).

Odobaenidae

Incisors occur in the maxilla of walruses, however their function is unclear. The maxillary canines are enlarged and form the tusks in this species. All postcanine teeth are uniform in size and have single roots (16, 31). They have a simple crown morphology that is well adapted to their seafood diet that needs to be apprehended and consumed in the water (10).

Dugongidae

The dugong (*Dugong dugon*) is the only member of this family and, like the elephant, has two incisors in the maxilla that develops into tusks (Fig. 2 – 4). These tusks, however, rarely protrude beyond the borders of the oral cavity. Various other characteristics like continuously forming molars, internal genitalia, two mammary glands on the chest, similar heart structure and more makes them close relatives to the Elephantidae (32). Dugongs share the same Paleocene terrestrial mammal ancestor with the Proboscidea and Hyracoidea (33). The dugong is a herbivore and feeds on seagrass and marine algae with its hypsodont molars (33).

Procaviidae

The members of this family, as stated previously, are closely related to the Elephantidae (34). Their incisors have evolved into defensive tusks (34). The premolars are molariform and the molars are lophodont and either brachy-or hypsodont (10). Hyraxes are nonruminant herbivores that can utilise a wide variety of grasses and browsing depending on the environment factors (34, 35).

Elephantidae

Maxillary incisors are the prominent tusks seen in both genera of this family. Elephants do not have any canines and the cheek teeth are hypsodont (10). Most authors describe the first three cheek teeth present, at birth or soon thereafter as deciduous molars (and not premolars). Once they are being replaced, it is with true molar teeth (10, 36-40). Elephant molars are made up of transverse plates of enamel covered dentin, bound together by cementum (Fig. 2 – 5). Each successive molar has a fairly specific number of these transverse plates (laminae) and the tooth is of specific size, both characteristics that are used to determine age (36, 41). These transverse ridges are described by the term lophodont (15). The continuous formation of new molar teeth is unique to the Elephantidae (Fig. 2 – 6) and the Sirenia (42). Sikes have described ageing in African elephants by using a fixed point (foramen mentale {FM}) of the right mandible. The number of a lamina that moves past this fixed point has been correlated to relative age. The operator then first determines which molar is most rostral and can then work out the number of the lamina at the point of the FM. The relative age is then read from a chart (40). The explanation of 'horisontal tooth replacement' for the molars has been disputed (38). Hooijer described the horisontal movement of the elephant teeth as the phenomenon of 'closing the ranks' as seen in many other mammals. This appears to be nothing different than mesial drift as seen in humans, primates and other mammals (38).

2.4. TUSKS

Tusks may vary in size and origin (incisor *vs.* canine) but they all have a similar structure. All tusks grow continuously throughout life (elodont tooth) (15). The distinction between the crown and root of the tusk is not very clear (2). Enamel can partly cover the dentin of a tusk (e.g. hippopotamus and domestic pig canine) or is only apparent for a short period of time after eruption (e.g. hippopotamus and elephant incisors, walrus canines) (Fig. 2 – 7). The root is covered by cementum and, as this tooth erupts past the gingival margin, it will be worn away and disappear with time. Elodont teeth has a large conically shaped pulp with a wide apical opening (Fig.2 – 8) (2, 15). Dentin is deposited throughout the life of the pulp and this leads to the elongation of the tusk (15, 43). In the elephant a central area of the tusk remains unmineralised as the tusk elongates. These are pulp remnants that are compressed coronally as the tusk elongates. With abrasion this unmineralised area is often exposed and it forms a black spot in the centre of the tusk. The pulp can be described as a modified connective tissue organ that contains ground substance, vascular tissue, connective tissue, interstitial fluid, odontoblasts, fibroblasts, nervous tissue and other minor cellular components (2, 44, 45). Wheatherford described the innervation of the

Asian elephant's pulp. It consists of myelenated and non-myelinated nerve fibers which terminates in the odontoblast layer (44). Fagan *et al* disputes this anatomy in the African elephant (36, 45). The author is currently undertaking research in this field.

2.5. DISORDERS OF TUSKS

Trauma

In tusked mammals trauma is the most commonly described of the tusk. Fractures due to falling (46-50), fighting with exhibit mates (51) and trauma by structures in the captive environment (52-60) are probably the most common reason for this in captive elephants. One study of 60 North American zoos revealed an incidence of tusk fractures in 31% of the study animals (n=379) (46). This is significantly higher than 5%, which has been reported for wild populations (61). Inflammation of the tusk sulcus (pericoronitis), unaccompanied by tusk trauma has been described in captive elephants (61). These have been caused by acute or chronic infections in the sulcus, sulcular abscesses or trauma to the sulcus itself (Fig.2 – 9). Pericoronitis is frequently observed in healthy African elephants captured for translocation in the Kruger National Park (Dr. Markus Hofmeyer, BVSc, Skukuza, personal communication, March 2001).

Tusk abrasion and wear due to abnormal digging behavior have been described on several occasions as the inciting cause of pulp exposure in the captive walrus (62-65). Kertesz described pulpitis and pulpnecrosis in a walrus that have abraded his canine on the cement enclosure. The secondary dentinal plug that formed on the inside of the pulp cavity did not extend into the dentinal wall, leaving a gap through which infection spread to the pulp cavity (64).

Tusk fractures with exposure of the pulp has also been described in a captive babirusa (Fig. 2 – 10) (66).

Unerupted/impacted tusks

Single tusked and tuskless elephants have been described in the literature (10, 17, 18, 67-71). The fact that tusklessness occurs more commonly in certain areas or families suggest that this phenomenon is a heritable trait, and has been described as sex-linked (68, 69, 71). Hunting pressures on tusked animals has lead to the demise of large tusk-bearing elephants in the East (18). The impact of hunting pressures on a population and the artificial creation of a higher incidence of tusklessness were clearly demonstrated (70).

Apart from a congenital absence of tusks, failure of a tusk to erupt due to entrapment by the overlying gingival tissue (impaction) can occur (72, 73).

Aberrant growth

Aberrant growth in tusked animals may occur due to trauma to the opposing tooth (74) or because of trauma to the tooth itself (75).

An overgrown tusk is a feature common to most of the tusked species with canine tusks (74). Probably the most common example in museum collections is the circular tusks from wild boars from the South Pacific Islands (2, 74, 76). Circular tusks form when the occlusion between mandibular and maxillary canine is lost. The two canines usually wear each other down and keep the occlusion normal (2, 20, 77). In most of the Suidae and Tayassuidae this also aids in the sharpening of these tusks (Fig. 2 – 11). The exception to this is the babirusa, where the mandibular canines do not make contact with the maxillary canines. In this species the animals have to physically abrade the tusk by rubbing it on trees, enclosure walls or even the keeper's legs (11, 74). The maxillary tusks of the babirusa have been seen to also grow in a circular fashion until it eventually penetrated the skull (74).

Subluxation of canine teeth in the hippopotamus occurs frequently during fighting. This will then lead to overgrowth of the canine, often in a direction out of the oral cavity (20, 77).

Spiral tusks in elephants (Fig. 2 – 12), have been described by many authors (1, 75, 78, 79). This condition, however, has not been seen as a problem in captivity.

Abnormal growth of a tusk in a walrus was recorded several years post extraction (80). Another case of this occurring in a walrus was recently presented at the grand rounds of the Zoo Veterinary Dental Congress in Milwaukee (Prof. G. Willis, DDS, Milwaukee, personal communication, October 2002).

Overeruption has been witnessed by the author in a warthog skull housed in the Transvaal Museum, Pretoria. The root elongated and erupted through the mandibular bone into the oral cavity (Fig. 2 – 13).

Supernumerary tusks

Supernumerary tusks have been reported for most tusk-bearing mammals (10, 29, 74, 81). Exceptions are the beaked whales, chevrotain and other tusk bearing deer, as well as the dugongs (10, 81). To the author's knowledge these have been rarely encountered in captivity.

2.6. TREATMENT PRINCIPLES FOR TUSKS

Prevention

Preventing tusk fractures and stopping excessive tusk abrasion in captivity is one of the challenges that face collections of tusked mammals. Emphasis seems to have shifted from making the captive environment more tusk friendly towards protecting tusks from trauma. Many zoological gardens will routinely reduce tusk length in species like the elephant and babirusa (82, 83). In the elephant, crowns are being used quite regularly on these shortened tusks to prevent further abrasion to them (49, 56-58). This method of tusk protection has been used with promising results in one collection of walruses (63).

The use and type of concrete for floor coverings in elephant enclosures, as well as walrus pools, have been mentioned as hazards to these tusked mammals. Using water under high pressure is often the method of choice when cleaning elephant enclosures. A smooth floor will be cleaned much faster than a floor with corrugations. The latter, however, should be able to give these animals better grip and would hopefully be one way to reduce the incidence of falling in elephants.

Walrus enclosures have received much attention throughout the years (62-64, 84-86). These animals will continuously dig at the pool floor or even at junctions between the wall and observation glass panels. When these animals haul out on ice they use their tusks for locomotion. Pools should be constructed in such a way that the normal locomotory behaviour can be simulated without damage to the tusks.

Babirusas need objects, like trees, in their enclosures to abrade their mandibular tusks on. The maxillary tusks are very brittle and can easily break during fighting. In captivity, their maxillary tusks needs frequent trimming (83).

The canine tusks of the hippopotamus in captivity may require regular trimming if malocclusion has occurred (25, 77).

Elephant tusks with longitudinal or oblique fractures without pulp exposure have been successfully treated with rings or bands (Fig. 2 – 14). These rings protect the tusk from splitting thereby prevent pulp exposure (53, 59).

Gingivectomy

Impacted tusks can cause localised swelling and can be painful to the touch (72). In two recorded cases, normal eruption occurred after excessive gingiva was removed (72, 73).

Partial pulpectomies

Tusked mammals have a very large pulp compared to humans or dogs and therefore can deal better with pulpitis (78, 87-89). Pulpitis may lead to pulp necrosis (Fig. 2 – 15), which in turn very frequently can cause peri-apical abscessation (25, 54, 90, 91). Animals suffering pulpitis may feed poorly, have pain, be aggressive, depressed or unresponsive to handlers and ultimately may die (25, 54, 90-93).

It is evident form the literature that elephant tusks have a great potential to withstand trauma (78, 87-90, 94). Many cases, from as far back as the previous century have been documented where musket balls or spear blades have been walled off within the pulp canal. It is this regenerative/reparative potential that makes these teeth very good candidates for partial pulpectomies. Pulp exposure often leads to excessive or aberrant dentin formation in the pulp (87) (Fig. 2 – 16). Secondary dentin formation in African elephant tusks is well described. In the walrus, secondary dentin is often found throughout the entire length of the pulp canal, with only a small part of the apical pulp free from it. As previously discussed, this dentinal plug, unlike those in elephants, is not attached to the wall of the pulp cavity. This does complicate the use of partial pulpectomies in tusk treatment in the walrus (64).

Before applying a pulp dressing to the exposed pulp, necrotic/inflamed pulp should first be removed and the canal cleaned (52, 56, 95-97). In the literature many different irrigating solutions have been used. These have been listed in Table 2 – 2. The author use copious amounts of lactated ringers solution for lavage, while curetting or amputating necrotic pulp. The depth of pulp to be removed depends on the specific tooth, but generally pulp equal to four times the pulp cavity diameter at the coronal end, should be removed (Dr. Peter Kertesz, BDS, LDS RCS Eng, Milwaukee, Personal communication, October 2002).

In our search for the ideal product we need to find one that is antibacterial, biocompatible and one that stimulates the formation of a hard tissue (secondary dentin) bridge to seal the pulp. The use of paraformaldehyde, usually as formocresol, has been used with success, since 1930. Formocresol fixes the pulp over a period of time, usually with no infection owing to its antibacterial properties. Recently much has been published about the mutagenic, carcinogenic, toxic and tissue destructive effects of formocresol. This product is therefore not a good choice and should not be used because no secondary dentin bridge is formed (98). Twenty-one juvenile elephants were endodontically treated for molar abscessation. In three of these teeth, formocresol and zinc oxide-eugenol (ZOE) were used as filling material. All three endodontic procedures failed as a result of the use of formocresol, ZOE expressed beyond the apex or aditional perforations re-exposing the pulp to the oral cavity. Compared to these three patients, the other eighteen individuals were treated with ZOE and calcium hydroxide (CaOH) with more acceptable results (99).

Zinc-oxide eugenol has been used extensively for indirect pulp cappings, endodontics, cementing agent of bridges and inlays, cement base and temporary restoratives in humans. The free eugenol in the product is responsible for the anaesthetic properties the product has. Unfortunately ZOE is cytotoxic and its value is questioned when used on deep cavities directly on pulp (98). It does however have antibacterial properties and further research is needed to see to what extent the cytotoxicity may negatively impact on the large pulp of elodont teeth.

Calcium hydroxide paste is currently the product of choice for treating exposed pulp in humans. This is also only true for the paste form, as there is no proof yet that the hard setting compounds readily dissociate into the calcium (Ca) and hydroxide (OH) ions, which makes the product effective. The very alkaline pH of CaOH also makes it a very good antibacterial product. CaOH paste initiates an inflammatory reaction in the pulp, an effect that stimulates the hard tissue barrier formation (98). Recently the author used CaOH powder as a dressing agent while successfully performing a partial pulpectomy on an African elephant bull and a babirusa (Figs. 2 – 17A,B, 2 – 18A,B). Three weeks post-surgery there was concern that there may be a septic pulpitis in the elephant. On re-entering the pulp canal, it was clean and a hard tissue bridge was already developing.

The final stage of the partial pulpectomy procedure is to obdurate the coronal opening with a tight sealing filling material. As for sealants, many different techniques have been used with success in the past (Table 2 – 2). An ideal filling material for elodont teeth should be one that gives a good tight seal and wears away with the future tooth wear, is easy to use and cost effective. The measure of success seems to be the continuous growth of the treated tooth, as well as normal looking dentin when the coronal filling material has been worn away, or is lost. Histopathological studies confirming this are lacking.

Currently there is no field technique for determining pulp exposure when fractures occur in elephant tusks. Robinson *et al* attempted this by using the length from the tusk sulcus to the eye (25). This measurement is deemed inaccurate in the Asian elephant cow (82). The author disputes the accuracy of this method, as many African elephants (juvenile, sub-adult or adult) do not have a coronal tusk that is of this described length (Fig. 2 – 19). Research is ongoing to find a suitable model for the determination of pulp exposure.

Extractions

The indications for tusk extractions are varied. This procedure is mostly performed on tusks with complicated fractures that carry a poor prognosis (50, 61, 82, 95, 100) or where the pulp has been exposed due to abrasion (62, 63, 101). In the South Pacific Island maxillary tusk extractions on boars are performed for cultural reasons (2). Disarming of domestic pigs that are kept as pets, is another reason for extracting teeth. These animals are very strong and playful, while they are equipped with razor sharp tusks. In the past, regular trimming of these tusks were done (102). The author has been approached by an owner to remove such a pig's tusks after it has caused damage to their horse for the second time. Complete tusk extraction by the animal itself, has been documented in wild African elephants (103). Recently another such case was reported to me, of a bull African elephant that lost a complete tusk, possibly due to fighting, in the Addo Elephant Park in South Africa (Dr. Markus Hofmeyer, BVSc, Pretoria, personal communication, November 2002). Surgical extraction techniques have been developed to deal with tusks. As an initial means of extraction, a standard surgical extraction through an alveolotomy approach can be used (104). This has been described for various species (Fig. 2 – 20). Extracting tusks is not a procedure to be taken without due consideration since specialised instrumentation is very often needed to perform this type of surgery (25, 61, 100, 105).

The internal collapsing technique is a novel way of extracting tusks (61, 95, 105). The technique is based on the principle of creating a thin walled, hollow tube. Once the tusk is hollow, longitudinal sections are made at the coronal opening, dividing the tusk into four or five segments. A protected chisel is then used to complete the cuts into full-length splits, terminating at the apex of the tooth. Each segment can then be separated from the alveolar bone, with the aid of purpose-made elevators, and folded into the hollow space where it can then be extracted (61, 95, 100).

Steiner *et al* recently presented a unique method of extracting an elephant's tusk with the aid of elastic bands (106). The use of elastic bands was first used in humans suffering from hemophilia. Elastic bands are placed around the tooth and forced apically as far as it would go. This procedure was repeated every second day and more elastics added. The combination of this damage to the periodontal ligament, together with lateral traction daily on the tusk resulted in the exfoliation of this tusk three weeks after the onset of treatment (106).

Walrus tusks have a folded wall. These folds make the use of the internal collapsing technique difficult in this species, but it can however be utilised in selected cases (64).

After the offending tusk is extracted, the empty alveolus should be cleaned of all debris. Curetting the apical area of the alveolus is imperative. Due to the fact that these teeth are elodont, the germinal tissues left behind after extraction should also be removed. Failure to do so will result in regrowth of a tooth or tooth-like structures (80, 107). The technique for walrus extraction, described by Cornell and Antrim does not address this crucial issue (101).

2.7. MISCELLANEOUS ORAL AND DENTAL CONDITIONS UNRELATED TO TUSKS

Partial anodontia

Congenitally missing teeth have been recorded for the hippopotamus and the suids, especially the domestic pig (10, 108, 109). This can be due to premature loss, impaction or failure to erupt as well as true agenisis. In the hippopotamus partial anodontia is described in a first mandibular molar (10). Bodegom and van der Linden described the agenisis of the first lower premolars in three miniature pigs (108). The first premolar tooth in the pig is not heterodont, and will frequently be lost (as was previously discussed for the hippopotamus). This may explain the relative high incidence of absent first premolars in the suids (10, 109). Absent incisors in suids are uncommon, however in two small populatations an incidence of 4% was reported for this phenomenon. In both populations it is speculated, because of their seperation from other populations, that this could be as a consequence of inbreeding (109).

Supernumerary teeth

Supernumerary premolars and premolar roots have been described in the Hippopotamidae (10). This anomaly is also present in the suids but is uncommon (10, 109). In two wild populations the incidence of supernumerary molars in African elephants were 6.1% (37).

Dento-alveolar abscesses

Abscessation due to trauma of the incisors, premolars and molars has been reported in the domestic pig (110-112). The reasons for this are unclear, but the habit of stone chewing and bar biting of domestic suids has a detrimental effect on the premolars

(113). Clipping of tusks in piglets is described as a contributing factor to osteomyelitis in these animals (114). In a herd of 85 elephants, 21 developed mandibular abscessation due to occlusal table perforation of the second molar (99). In a survey of 60 North American Zoos, only 35 out of 375 dental disorders, related to the molars (46). Caries, which may lead to dento-alveolar abscessation, has been documented in the suids (10, 109, 111, 115) and hyrax (*Procavia capensis*) (116). Caries in the hyrax is associated with refined carbohydrate diet as no captive animals were seen with this disease (116). In the domestic pig, swill feeding may contribute to the formation of caries. Even so, the incidence of caries in suids is very low [<3.8 % (109) and <0.4% (111)].

Impaction

From the literature it appears that the Indian elephant is more prone to molar impaction than the African elephant. Impaction of the molar teeth has lead to weight loss, undigested/poorly digested roughage in the faeces and even signs of colic (36, 61, 117, 118). It is important to give elephants a diet of good quality roughage that is abrasive enough to help with molar exfoliation (41). The high incidence of silica in certain diets may cause pulp exposure in molar teeth (61).

In the warthog the third molar tooth continuously erupts for about 3-4 years. In its rostral progression this tooth compresses onto the second and first molar teeth (26, 60). This can be mistaken for impaction.

Periodontitis

Periodontitis is rather common in the domestic and wild pigs. In 2 different studies the incidence varied between 6% and 24 % (109, 111). In suids, periodontitis is commonly associated with the fourth premolar and first molar teeth. Food, bedding straw or foil tops of discarded containers was often trapped between, or around them (21, 111, 113, 118). Canines and incisor teeth were free from periodontal disease (21, 118). One collared peccary skull from the Transvaal Museam, Pretoria, showed tooth loss of the left maxillary second molar, presumably due to periodontal disease (Fig. 2 – 21). It has been speculated that animals in captivity suffer more from periodontal disease than do the wild populations. Samuel and Woodall found no statistical difference between a wild and domestic group of pigs (119). Their domestic group of pigs consisted of skulls from an abattoir, which will contain young animals. This may explain the lower than expected incidence of periodontal disease in this group. The incidence of periodontal disease in the warthog is 9% and in the bush pig 14% (21). Compared to their feral pig study, Woodall found a significant reduction in the incidence of periodontal disease only in the warthog (21). The reasons for this could be the warthogs more abrasive diet as well as the fact that the third molar continue to erupt rostrally, and in so doing, replaces the first 2 molars.

Periodontal disease in elephants is usually associated with impacted molar teeth. Food gets trapped between the molars and creates a favourable environment for periodontal disease (61). Periodontal disease may also occur around tusks if the elephant packs the sulcus with dirt or faeces. This may happen when the animal is suffering from chronic irritation of the sulcus, like sharp tooth fragments after an uncomplicated tusk fracture (120).

Tumours

Tumours in the oral cavity of wild animals are uncommon. Mikota *et al* found 18 tumours in their study population of 379 individuals. None of these tumours were related to the oral cavity or dentition (46). Raubenheimer *et al* described the first odontoma in an African elephant. The tooth affected was the sixth mandibular molar, and this prevented the eruption of this tooth (121). Lindeque reported a mandibular abscess in one of the mandibles he used for ageing the elephants in the Etosha National Park, Namibia (122). On further investigation by the author this appears to be another odontoma and histology is being done to confirm this.

An African elephant was recently shot because of an oral tumour. This was done, unfortunately without taking a biopsy and confirming the diagnosis. The author managed to get hold of the skull after learning of the incident. The individual was 15-18 years old and presented with a mass which the Ranger described as looking like an extra tongue (Fig. 2 – 22). This tumour originated from an 8-cm diameter base, rostro-buccal to the right maxillary molar tooth. It was approximately 40 cm long. What was interesting about this case is the fact that the tumour displaced the maxillary molar in a palatal direction (Fig. 2 – 23), producing a malocclusion with the mandibular molar. This in turn led to decreased wear on the mandibular molar resulting in a crown height higher than the contra-lateral molar.

2.8. SUMMARY

Tusked mammals can be terrestrial or aquatic. Many of these magnificent animals are kept in captivity all over the world. Functions of tusks are paralleled only by the species they occur in. Dental anomalies and disorders of tusks and the rest of the dentition in these mammals are discussed, with and emphasis on the elephant. The tusk anatomy, with its large conically shaped pulp, makes it an ideal tooth for partial pulpectomy treatment in trauma cases where the pulp is exposed. Surgical techniques for tusks have been developed and are discussed. Oral tumours are referred to, but are rare.

2.9. FIGURES

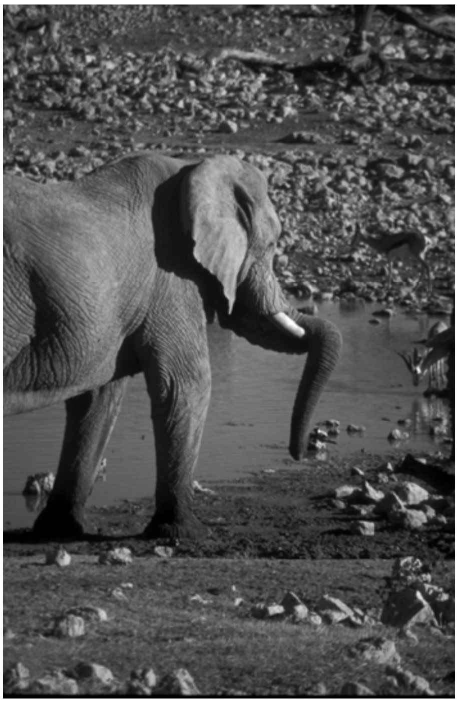

Figure 2 – 1. An African elephant resting at a waterhole, with the trunk draped over the left tusk.

Figure 2 – 2A. The warthog has a specialised third molar (*), possibly adapted for its course diet. The tooth is comprised of three rows of enamel covered dentinal columns bound by cementum. These columns are continuously formed for three to four years.

Figure 2 – 2B. The full warthog third molar in occlusion (*), gradually crushing the second (#) and first molar as it migrates mesially (rostrally).

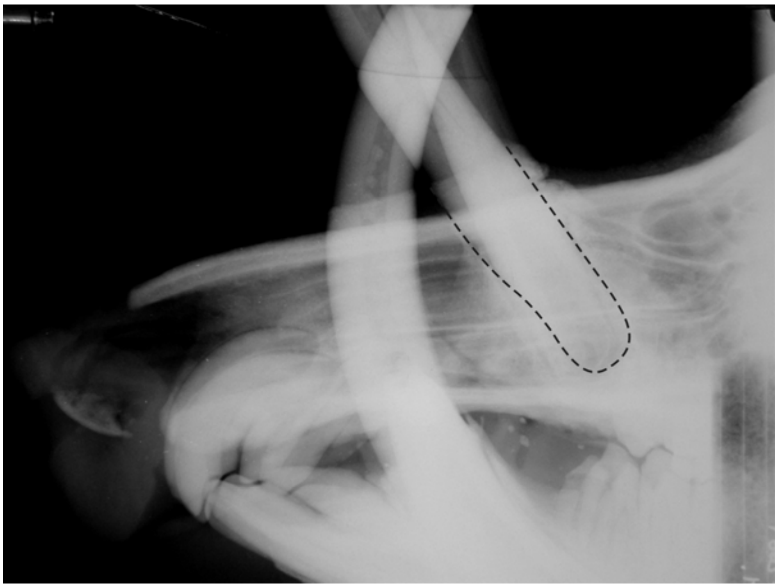

Figure 2 – 3. A lateral radiograph of a babirusa's maxilla. The open apeces of the maxillary tusks are indicated by A. Babirusa maxillary tusks erupt dorsally through the muzzle.

Figure 2 – 4. Rostral view of a dugong skull, showing the large maxillary bone in which two incisor tusks are carried.

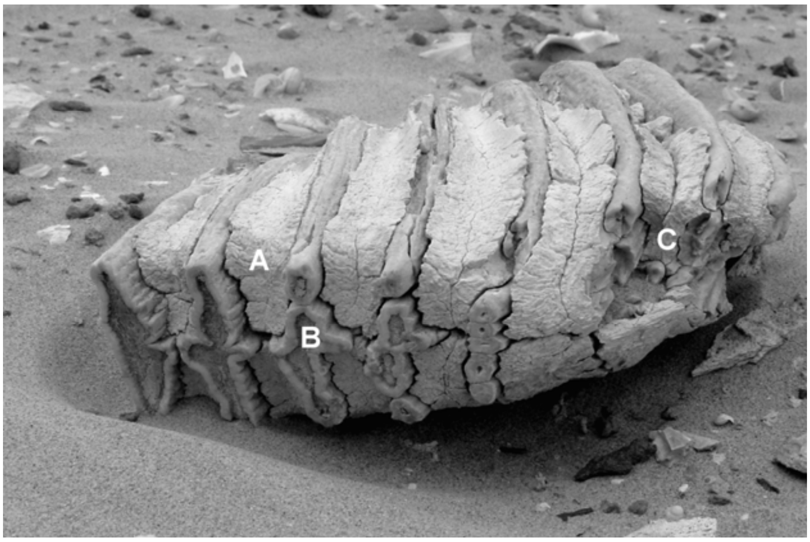

Figure 2 – 5. A weathered African elephant molar found near the East coast of South Africa. On this tooth the components of the molars are clearly visible. The following are identifiable, cementum (**A**), enamel covered dentin lamella (**B**) and the worn rostral portion of the tooth (**C**).

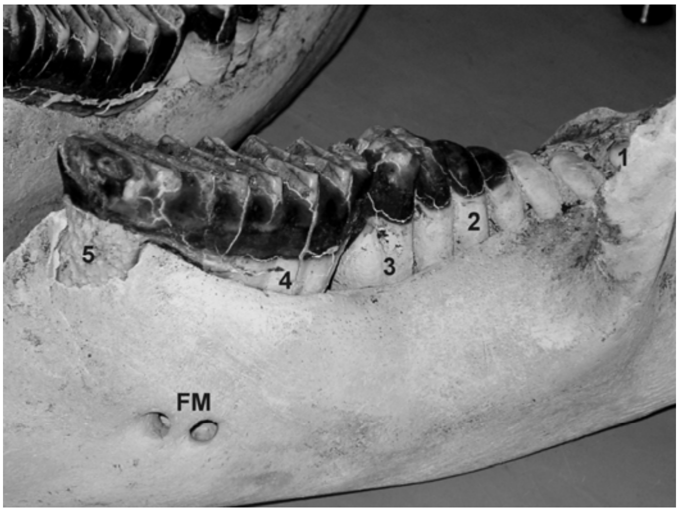

Figure 2 – 6. The continuous development of the elephant molars occurs in the caudal part of the mandible (1). Enamel covered dentin columns are formed and gradually drift mesially (rostral)(2). This process is continuous and as soon as the columns have moved far enough they will come into occlusion (3). Once all lamellae have fused (4), molar formation is complete. As the tooth gradually drifts mesial, the mesial lamellae are lost (5) through wear. The *foramen mentale* has two openings (FM).

Figure 2 – 7. The erupting second incisor of a hippopotamus. There is still an enamel covering (*****) present on this tusk.

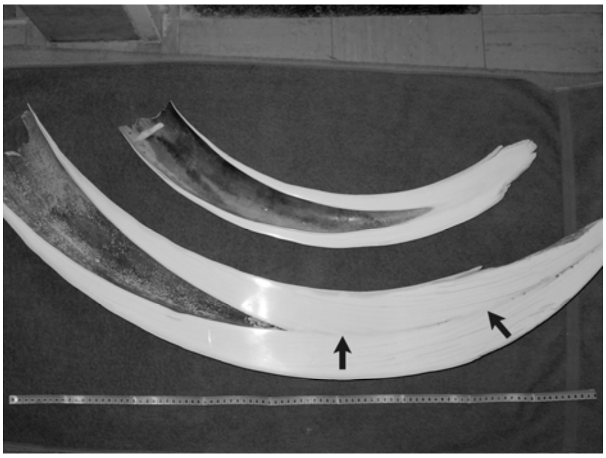

Figure 2 – 8. Longitudinal sections of two African elephant tusks. Clearly visible is the wide apex and conical shape of the pulp chamber. In the larger tusk, the unmineralised central canal is visible.

Figure 2 – 9. Trauma to the coronary band (gingiva) of an African elephant cow, in left lateral recumbency. The cause of the trauma is unknown, but we speculate it may have been caused by another family member's tusk, during transportation. A – Tongue, B – Ventral surface of left tusk (normally covered by alveolar bone and gingiva), C – Coronary band (Gingiva) of the tusk, D – Trauma to coronary band, ventral to left tusk.

Figure 2 – 10. Fracture of a left maxillary canine (tusk) in a babirusa.

Figure 2 – 11. Tusks of a domestic pig. The mandibular canine is long and slender whereas the maxillary canine is short and robust. Continuous wear between these two teeth keeps them sharp.

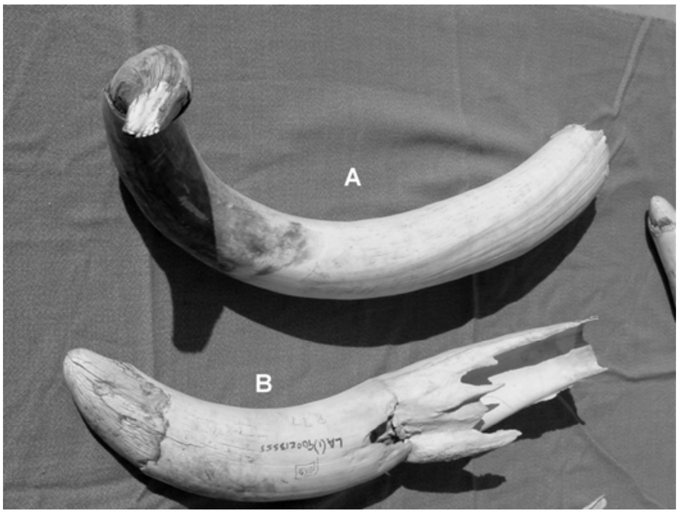

Figure 2 – 12. Two malformed tusks of African elephants, spiral tusk (A) and a dilacerated tusk (B).

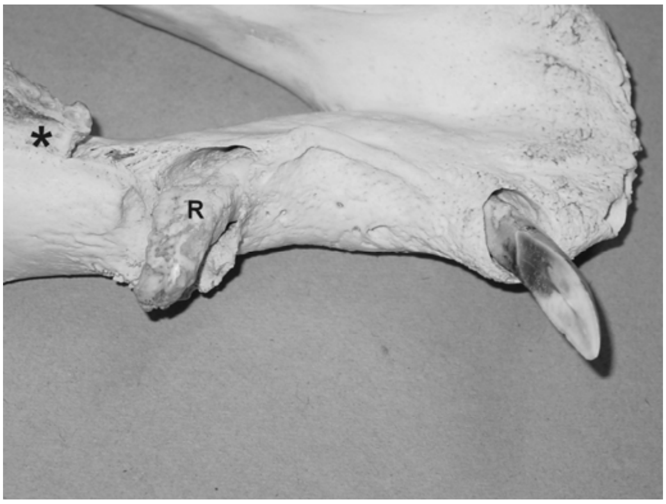

Figure 2 – 13. Supereruption of a warthog's mandibular tusk root (**R**). There is evidence of bone remodelling of the alveolar bone latero-ventral to the root. The mandibular third molar is the only tooth left in the caudal mandible (*).

Figure 2 – 14. A tusk ring applied to a juvenile African elephant in order to prevent further splitting of a longitudinally fractured tusk. The fracture line did not extend into the pulpcanal.

Figure 2 – 15. A complicated fracture of a 6-year-old African elephant's tusk. Pulpnecrosis was present. Purulent material was curetted out of the pulp canal whereafter the canal was thoroughly lavaged before pulp amputation was done.

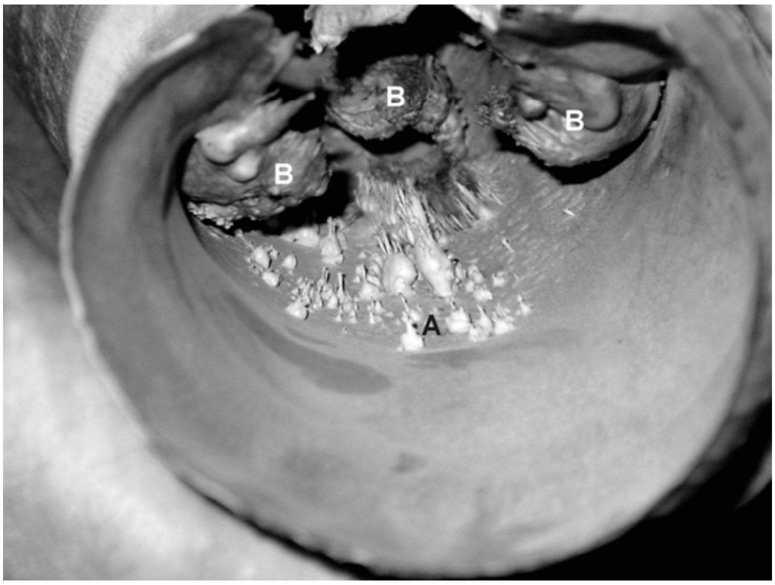

Figure 2 – 16. Looking into the apical opening of a complicated fractured tusk, in a coronal direction. There are several small dentin spicules visible, attached to the tusk wall (**A**) as well as several large dentin structures (**B**), attempting to wall of the infection process.

Figure 2 – 17A. A shortened tusk, after a pulpectomy procedure was performed on a 12 year-old African elephant bull. The tusk suffered an oblique fracture with the fracture line extending below the gingival margin (**A**). At the level of the gingiva, the fracture line was not extending through the pulp cavity anymore.

Figure 2 – 17B. A 15-month follow-up photo of the tusk, treated in 17A. There is loss of the oblique fractured fragment, correlating with where the fracture line extended below the gingival margin. Subsequent to the tooth fragment loss and tusk abrasion, the coronal filling was also lost. The pulp closed by production of secondary dentin before the filling was lost.

Figure 2 – 18A. An 8 year-old babirusa boar suffered a complicated fracture of his right mandibular tusk. A partial pulpectomy procedure was performed, after which the maxillary tusks were shortened.

Figure 2 – 18B. A 14-month follow-up photo of the tusk treated in 18A. The tusk is continuing erupting and the patient appears to have no discomfort.

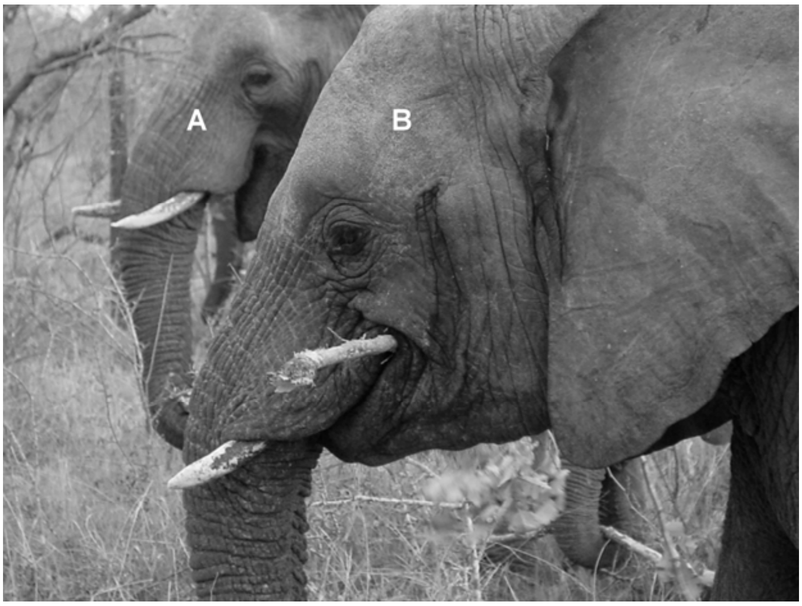

Figure 2 – 19. Two African elephants. Note the distance from the tusk sulcus to the eyes is less than the length of the exposed tusks. Adult cow (*A*) and juvenile (*B*).

Figure 2 – 20. Surgical exposure of the right mandibular tusk in a domsetic pig. The tusk was extracted through a combination of the alveolotomy technique, combined with some internal colloapsing.

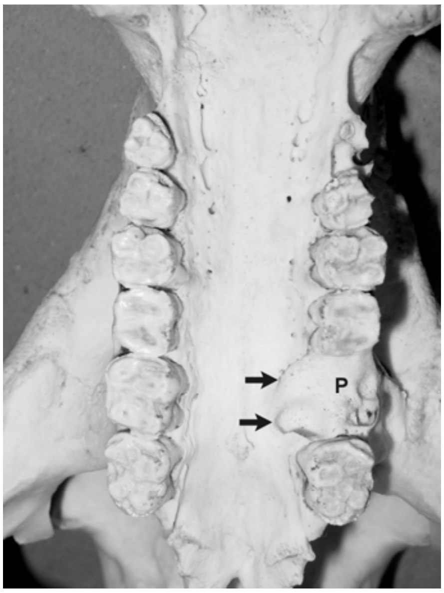

Figure 2 – 21. Palatal view of a Collared peccary skull. There is loss of a second molar on the left (**P**). The palatal borders (>) extend medially and is rounded. This tooth was presumably lost through localised periodontal disease. Alveolar bone loss is also evident on the mesio-distal surface of the first molar's distal root.

Figure 2 – 22. African elephant bull in left lateral recumbency. The mass (**M**) protruding from the oral cavity measured nearly 40 cm. The tongue (**T**) lies ventral to the mass in this photograph. (Courtesy of Dr. Q. Otto, BVSc, Nelspruit, Mpumulanga)

Figure 2 – 23. Skull of an African elephant showing displacement of its maxillary molar due to pressure from a maxillary tumour. The base of the tumour is approximately 8-cm in diameter as delineated on the photograph.

2.10. TABLES

Table 2 – 1.

Tusked mammals, placed in their orders and families. Dental formulae are given and the teeth forming the tusk/s indicated.

I – Permanent incisor, **C** – Permanent canine, **PM** – Permanent premolar, **M** – Permanent molar, **m** – Deciduous molar.

Order	**Family**	**Species**	**Common name**	**Dental formula**	**Tusk**	**Ref**
Artiodactyla	Hippopotamidae	*Hippopotamus amphibius*	Hippopotamus	**I** 2/2 **C** 1/1 **PM** 3/3 **M** 3/3	C+I	(20)
		Choeropsis liberiensis	Pygmy hippopotamus	**I** 2/1 **C** 1/1 **PM** 4/4 **M** 3/3	C+I	(77)
	Suidae	*Sus scrofa domesticus*	Domestic/Feral pig	**I** 3/3 **C** 1/1 **PM** 4/4 **M** 3/3	C	(10)
		Sus scrofa	Wild boar	**I** 3/3 **C** 1/1 **PM** 4/4 **M** 3/3	C	(10)
		Sus scrofa cristatus	Indian wild boar	**I** 3/3 **C** 1/1 **PM** 4/4 **M** 3/3	C	(10)
		Sus verrucosus	Java pig	**I** 3/3 **C** 1/1 **PM** 4/4 **M** 3/3	C	(10)
		Sus verrucosus celebensis	Celebes pig	**I** 3/3 **C** 1/1 **PM** 4/4 **M** 3/3	C	(10)
		Babyrousa babyrousa	Babirussa	**I** 2/3 **C** 1/1 **PM** 2/2 **M** 3/3	C	(10, 26)
		Phachochoerus aethiopicus	Wharthog	**I** 1/2-3 **C** 1/1 **PM** 2/1 **M** 3/3	C	(26)
		Potamochoerus porcus	Bushpig	**I** 3/3 **C** 1/1 **PM** 3/3 **M** 3/3	C	(10)
		Hylochoerus meinertzhageni	Giant forest hog	**I** 1/2 **C** 1/1 **PM** 3/1 **M** 3/3	C	(10)
	Tayassuidae	*Tayassu tayacu*	Collared pecarry	**I** 2/3 **C** 1/1 **PM** 3/3 **M** 3/3	C	(10)
		Tayassu albirostris	White-lipped peccary	**I** 2/3 **C** 1/1 **PM** 3/3 **M** 3/3	C	(10)
	Tragulidae	*Tragulus javanicus*	Chevrotain	**I** 0/3 **C** 1/1 **PM 3**/3 **M** 3/3	C	(10)
	Cervidae	*Moschus moschiferus*	Musk deer	**I** 0/3 **C** 1/1 **PM** 3/3 **M** 3/3	C	(10)
		Hydropotes inermis	Chinese water deer	**I** 0/3 **C** 1/1 **PM** 3/3 **M** 3/3	C	(10)
	Ziphiidae	*Mesoplodon sp.**		All males have 2 mandibular tusks only		(30)

	(Beaked whales)	*Ziphius sp.*		All males have 2 mandibular tusks only		(30)
		Hyperoodon sp.		All males have 2 mandibular tusks only		(30)
		Berardius sp.		All males have 4 mandibular tusks only		(30)
		Tasmacetus shepherdi	Shepherd's beaked whale	34-42/46-56//2 (Males mandibular rostral 2)		(30)
		*Mesoplodon grayi**	Gray's beaked whale	34-44/2 (Males mandibular rostral 2)		(30)
Pinnipedia	Odobaenidae	*Odobenus rosmarus*	Walrus	**I** 1-2/0 **C** 1/1 **PM** 3-5/3-4 **M** 0/0	I	(31)
Sirenia	Dugongidae	*Dugong dugon*	Dugong	**I** 1/0 **C** 0/0 **PM** 0/0 **M** 6/6	I	(32)** (61)***
Hyracoidea	Procaviidae	*Procavia capenisis*	Rock dassie	**I** 1/2 **C** 0/0 **PM** 4/4 **M** 3/3	I	(10)
		Heterohyrax sp.		**I** 1/2 **C** 0/0 **PM** 4/4 **M** 3/3	I	(10)
		Dendrohyrax sp.		**I** 1/2 **C** 0/0 **PM** 4/4 **M** 3/3	I	(10)
Proboscidia	Elephantidae	*Loxodonta africana*	African elephant	**I** 1/0 **C** 0/0 **m** 3/3 **M** 3/3	I	(123)
		Elephas maximus	Indian elephant	**I** 1/0 **C** 0/0 **m** 3/3 **M** 3/3	I	(123)

* There is one exception in this genus, *Mesoplodon grayi*. See later in Table.

** Manatees do not have incisor teeth.

** The molar dentition of the Manatee and Dugong is similar. They may produce up to 40 molars in a jaw during it's life.

Table 2 – 2.

Partial pulpectomy procedures as described in the literature. Species and outcome of various treatment regimes are included. Success is taken as a growing tusk, however this does not indicate histological response to treatment i.e. hard bridge formation (secondary dentin bridge).

Species treated	Flushing Agent	Pulp dressing	Coronal filling materials	Outcome	Reference
African elephant	Does not say	Paraformaldehyde + ZOE	Does not say	No infection and filling in place 2 months post-operative	(124)
African elephant	0.9% NaCl + Povidone-iodine Sterile distilled water	Formocresol	First part of 2 step pulpotomy procedure ZOE + Formocresol	Extraction	(125)
African elephant	None	CaOH (Dropsin)	Glass ionemer + Chemical cure composite	Filling lost in 1 day	(48)
	None	CaO + Type III, low viscosity polysulfide (Omniflex)	Non irritating epoxy (PC7)	Filling lost in 11 days	(48)
		Dropsin + Omniflex	Composite + fast curing epoxy Chrome-Cobalt (Vitallium) crown	Tusk growing	(48)
Asian elephant	3% hypochloride + saline	ZOE and formocresol	ZOE	15 days post-operative filling dropped out	(47)
	None	Gauze	Plaster	Changed weekly initially then 2weekly. – Tusk growing	(47)
African elephant	Hydrogen peroxide + saline	ZOE	Tub and tile sealer + Brass crown	Crown and filling lost in 2 weeks	(56)
	Hydrogen peroxide + saline	None	None	Daily flushings, no growth after 2 years	(56)
	Water	ZOE + Oxytetracycline/ hydrocortisone)	Dental plaster	Abscess, cellulitis formation, filling loosened	(56)
	10% ypochloride, 10% betadine/	None	None	Tooth exfoliated after approximately 4 years and 8 months of treatment	(56)

	hydrogen peroxide				
African elephant	1:10 dilution of povidine iodine Chloromycetin sodium succinate Penicillin G		Set screw + steel impregnated epoxy, nickel-crucible	Tusk growing	(57)
African elephant	Hydrogen peroxide + Iodine	Iodoform gauze soaked in Chloramphenicol	Cork	Tusk growing, 22 months post operative	(52)
African elephant	None	CaOH (Dycal)	Composite restorative + crown	Composite lost, Tusk growing	(57, 97, 126)
Elephants	None	None	Glass ionemer + Composite	None given	(127)
Indian elephant	Saline	CaOH (Pulpdent)	Glass ionemer	Tusk growing 10 weeks postoperatively	(96)
African elephant	None	Penicillin, hemostatic powder & Gelocast R impregnated gauze	De Puy synthetic casting tape (Tuff Stuff R) + metal crown	Filling lost 35 days post-operative	(128)
	None	Penicillin, hemostatic powder & Gelocast R impregnated gauze	De Puy synthetic casting tape (Tuff Stuff R) + metal crown	Filling lost in 12 hours	(128)
	None	BIP	Tuff Stuff R + Chrome steel plate	Filling lost 26 days post-operation	(128)
	None	Iodine + Chloramphenicol + BIP	None	No resolution	(128)
	None	Pine tar and oakum	None	Tusk growing at constant rate, but no dentinal bridge formation	(128)
Babirussa	Saline + 10% Povidone iodine	Sterile polyester gauze	Polyoxymethylene bolt	Tusk growing	(66)
Malaysian elephant	None	Topical antibacterial + CaOH (Dycal)	Glass ionomer + composite + amalgam + Aluminium crown	Tusk growing 18 months postoperatively	(129)
African elephant	None	Gentamycin antibiotic ointment + Bioglass	Composite	Tusk growth 4 weeks postoperatively	(97)

		synthetic bone graft particulate			
Asian elephant	Irrigation in a lateral direction, no drugs mentioned	Dacron membrae impregnated with Whitehead's Varnish and CaOH	Nylon or Delrin rod	Tusk growing	(61) (130)
African elephant (2)	Lactated Ringer's solution	CaOH powder	Intermediate restorative material (IRM) placed.Undercuts made	Tusks growing 6 months post operatively	Author's unpublished data
Babirussa	Lactated Ringer's solution	CaOH powder	Compomer (Dyract)	Filling lost 14 months post operatively, tusk growing	Author's unpublished data

Abbreviations: CaOH, calcium hydroxide; ZOE, zinc oxide eugenol

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Chapter 3 Innervation of the tusk pulp of the African elephant (*Loxodonta africana*)

3.1. INTRODUCTION

The innervation of the dentin-pulp complex of human and certain animal teeth has been investigated and described in great detail (1). Normal pulp tissue usually contains numerous neurovascular structures in a loosely arranged connective tissue stroma. Human dental pulp is known to have a rich sensory and autonomic nerve supply (1, 2). Weatherford and Sikes referred to the pulp innervation of elephant tusks of Indian and African elephants (3, 4). Fagan and others analysed the dental pulp tissue of African and Asian elephants using immunohistochemical stains for the S-100 protein antibody to determine the presence of neural tissue (5). However, they concluded that no nerve fibres, either myelinated or unmyelinated, could be demonstrated in any of the numerous sections taken from the pulp tissue of these elephants. Due to the clinical implications of these results, this study was undertaken to examine the pulp tissue of an African elephant tusk for the presence of neural tissue, and to determine whether S-100 protein antibodies are effective in animal tissue.

3.2. MATERIALS AND METHODS

The formalin fixed extracted pulp of a 2-year-old male African elephant was retrieved from the archives of the Department of Oral Pathology at the Medical University of South Africa and used for this study (Fig. 3 – 1). Longitudinal and transverse sections were cut in the proximal-, mid-, and distal thirds of the elephant pulp tissue. All sections were embedded in paraffin wax after which it was sectioned at 4 µm and stained with haematoxylin and eosin (H&E). Each group of sections was then examined immunohistochemically with antibodies to alpha and beta subunits of the S-100 protein (DAKO) sections to determine the presence of any neural components. Antigen retrieval was performed in a microwave using a microwaveable pressure cooker and citric acid buffer at pH 6. The buffer was brought to boiling point in the pressure cooker by microwaving it at high power for five minutes. The sections were placed in the buffer solution, the pressure cooker sealed and then microwaved for four min on medium high power. The sections were incubated with 3 per cent hydrogen peroxide for five minutes to block endogenous peroxidase activity and then incubated for five minutes with protein blocking agent, 30 minutes with the primary antibody, 20 minutes with the biotinylated secondary antibody, 20 minutes with streptavidin-HRP and four minutes with AEC chromogen, followed by counterstaining with haematoxylin before mounting (Faramount aoueous mounting medium, DAKO). All of the incubation steps were performed at 37 ºC. The antibodies were visualized with a LSAB 2 kit (DAKO). Nerves in a human neck resection sample were used as positive control for the S100-stain.

3.3. RESULTS

On gross examination the pulp tissue consisted of a 23 cm long firm, gelatinous, soft, grey-white tissue mass with a slightly curved long axis (Fig. 3 – 1). Light microscopical examination of haematoxylin and eosin-stained sections showed numerous thin-walled veins and lymphatic channels, as well as small- and medium-sized muscular arteries in a loosely arranged connective tissue stroma with thin, collagen fibres and abundant myxomatous ground substance (Fig. 3 – 2). The cellular composition varied from spindle-shaped fibroblasts to large polyhedral cells with abundant cytoplasm and peripheral cytoplasmic extensions. Positive S-100 staining, defined as red-brown granular staining in the nuclei and cytoplasm of nerve cells, was observed in the human resection tissue used as a positive control.

Various nerve bundles were found in most of the sections of the elephant tusk pulp that we examined. Some nerve bundles were seen in close approximation to the blood vessels, and visualised best on S100 stains of the longitudinally cut sections (Fig. 3 – 3). Small S100-positive nerve bundles were also found away from the vascular structures, especially when examining the transversely cut sections (Fig. 3 – 4).

3.4. DISCUSSION

The pulp tissue of human and animal teeth contains various neurovascular structures and different cell types including odontoblasts, arranged peripherally in contact with the dentin matrix, as well as fibroblasts, undifferentiated and immunocompetent cells scattered throughout the connective tissue stroma and cell-rich zone in the subodontoblastic area.

The elephant tusk is a unique, large, continuously growing, maxillary incisor tooth developed to assist this large mammal in its natural environment. Tusk fractures are common, especially in captive elephants (6). When a tusk is fractured, shortened or traumatically split, the pulp is exposed and more often than not becomes severely infected. Some authors have reported that elephants do not seem to notice or react to an exposed tusk pulp and explain this by the absence of nerve tissue within the dental pulp (5, 7). However, others have seen marked adverse reaction from elephants when performing surgical procedures on the tusk pulp without proper anaesthesia (8). Weatherford described the pulp innervation of an Indian elephant tusk (4), and Sikes also referred to the nerve endings associated with the odontoblast layer in African elephant tusk pulps (3).

The validity of the S-100 stains by Fagan and others (5) in their study was questioned because S-100-protein antibodies are produced mostly for human diagnostic work (9). It was proposed that a positive internal control should be used for this stain in animals, and specifically elephant tissue.

S-100, a marker of neural crest tissue, is a calcium-binding protein that participates in the regulation of intra-cellular calcium homeostasis (10). In neural tissue, the antibody stains both neurons and Schwann cells and is used to demonstrate both myelinated and unmyelinated nerve bundles. S-100, as opposed to other markers of neural tissue like neurofilament protein, has been described in both human (11) rodent (12, 13) and elephant teeth (5). This antibody has also been used in a wide variety of animals for different applications (14, 15). The presence of muscular arteries and veins throughout the elephant tissue implies that autonomic nerve fibres for autoregulation should be present. This has also been demonstrated in great detail in the rat incisor (16) These autonomic nerve fibres could then be used as internal control for staining methods used to search for nerves in the elephant tusk pulp. Therefore, the S100-positive fibres seen in close approximation to the blood vessels (Fig. 3 – 4) most likely represents the autonomic fibres supplying the microvasculature. The small S-100-positive fibres seen distant from the vascular vessels were interpreted as sensory branches (Fig. 3 – 4).

Here are several explanations for the negative S-100 results in the previous study on elephant tusk pulps. The most important one, however, is the technique of antigen retrieval and the enhancement, especially in tissue preserved in formalin for long periods of time. In the present study, a microwave with microwaveable pressure cooker and citric acid buffer at pH 6 were used. Microwaving with citric acid buffer has been shown to enhance the immunoreactivity of various antibodies including S-100 protein (17). The use of heat-mediated antigen retrieval frees protein side-chains which have been masked by formaldehyde fixation, which results in a higher affinity of the antibody for the antigen in question (18).

These findings confirm the presence of nerves in the elephant tusk pulp and clinicians are urged to take proper precaution against causing unnecessary pain when performing surgical procedures on an exposed pulp of an elephant tusk.

3.5. ACKNOWLEDGEMENTS

The authors would like to thank Prof EJ Raubenheimer of Medunsa, for providing the tusk pulp, Professor W.F.P. van Heerden for editing the manuscript and photographs, and Mrs MB Van Heerden and Mrs R Sutherland at the Oral Pathology Department, University of Pretoria, for their laboratory support of such high standard.

3.6. FIGURES

Figure 3 – 1. Macroscopical appearance of the tusk pulp of a two-year old African elephant.

Figure 3 – 2. Thin-walled and muscular vessels in a loosely arranged connective tissue stroma. Haematoxylin and eosin. x 200.

Figure 3 – 3. Longitudinal section of tusk pulp showing autonomic nerve bundles in a close approximation to the blood vessels. S-100 stain. x 200.

Figure 3 – 4. Transverse section of tusk pulp showing sensory nerves not directly associated with blood vessel walls (arrows). S-100 stain. x 150. Insert: Higher magnification of small nerve bundles. S-100 stain. x 400.

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Chapter 4 Estimating exposed pulp lengths of tusks in the African elephant (*Loxodonta africana africana*)

4.1 INTRODUCTION

Tusks are the only maxillary incisors present in African elephants (*Loxodonta africana*). These incisors are continuously growing teeth (elodont teeth) with an open apex (6). The growth rate of tusks varies between the sexes with males possessing large tusks that increases in size, while females have smaller tusks of which the growth rate decreases at the time of puberty (12). The outer mineralized layer of a tusk is ivory, which comprise of dentin not covered by enamel. Ivory has a unique pattern on a cut section. Enamel is only present for a short period of time when the permanent tusk erupts (14). The ivory protects the pulp of the tusk which consists of numerous blood vessels, lymphatic and neural tissue, bound in a loosely arranged connective tissue stroma (2,23).

The tusk anatomy and biology create several potential clinical and management conundrums. Although captive and wild elephants suffer tusk fractures (6,9,19,20), the incidence for captive elephants is higher than that in free-ranging ones (20). Tusk fractures in captivity result from trauma during transporting and offloading of elephants, as well as individuals falling into moats or damaging their tusks against enclosure barriers (19). In many cases, institutions shorten or blunt the tusks (25) to reduce fractures and injury to elephants. Pulp exposure through fracturing or coronal amputation, leads to pain for the elephant (2,3,10) for which various techniques are available for treatment (19). Even so, tusk amputation is a regular option that aims to shorten a tusk without exposing the pulp.

Assessment of coronal pulp length (exposed pulp length) relies on measuring the distance from the lip (labio-dental fold) surrounding the tusk to the eye (15). It assumes a 1:1 ratio between this measure and exposed pulp length. This method is at best a crude guide since it does not consider variation associated with age or sex.

The aim of this study was to find a complimentary and alternative way of estimating the coronal pulp length in African elephants. This will allow veterinarians to evaluate whether a tusk fracture exposed the pulp and assess the need for general anesthesia to treat a fracture. In the case of institutions housing captive African elephants, estimating coronal pulp length from external tusk features may help veterinarians to amputate long tusks without causing pulp exposure.

4.2 MATERIALS AND METHODS

Study populations

Our samples included tusks collected for elephants from two regions. Firstly, the Namibian sample comprised stockpiled tusks originating mainly from the Etosha National Park, but also included individuals from the Caprivi and Khaudum Game Reserves. The elephants in the Etosha National Park in Namibia (22270 km^2, 19ºS 16ºE), live in a dry savanna (16) (annual rainfall: 316-442 mm) (8). This population is stable and comprised 1754-3080 elephants in 2002 (1). The population has a high incidence of tusk fractures but low incidence of tusklessness (20). Authorities removed 316 female elephants from 1983 to 1985, water is provided artificially and the Park is partially fenced (8).

The Khaudum Game Reserve (3841 km^2, 19ºS 20ºE) is partially fenced and has several boreholes that provide water year round (Dries Alberts, personal communication). The Reserve had 993-2939 elephants in 2000 (1) and comprise of dry savanna (16) (annual rainfall: 487±221 mm, Data provided by the Ministry of Environment and Tourism, Tsumkwe, Namibia). Nearly 25% of tusks in Khaudum are fractured, lower than that recorded in Etosha (20).

The 3353-5799 elephants living in the Caprivi Game Reserve (5715 km^2, 18ºS 22ºE) during 1998 (1) are part of a large regional population that spans across several countries. It has no management and elephants are free to move in and out of the Reserve. The vegetation is typically that of a dry savanna (16). Tusklessness is not common in the regional population, but the incidence of fractures is about the same as that noted in the Khaudum Game Reserve (20).

The second population consisted entirely of individuals from the Kruger National Park, SA (Kruger) (19442 km^2, 24ºS 31.5ºE). The elephants in Kruger live in a transition savanna (16) (annual rainfall: 500-700 mm) (22). Here the population comprised 10459 elephants in 2002 (1). The population has a low incidence of tusk fractures and tusklessness (20). Authorities removed 17219 elephants between 1967 and 1996 (21), water is provided artificially (13) and the Park is mostly fenced (24).

Data collection

We made several measurements (Table 4 – 1) of 242 tusks (all natural deaths) from Namibia and collated data for 448 tusks collected during the culling program in Kruger from 1991-1996 (Anthony Hall-Martin, personal communication). All tusk length measurements were measured on the outside curvature of the tusk. Total tusk length (l_t) was the length from the base of the tusk to the incisal edge of the tusk (Fig. 4 – 1). We measured tusk circumference at the base of each tusk (c_b), as well as at the lip margin visible as a brown ring on each tusk (c_l). We also measured tusk diameter using calipers at the same sites as described for circumference (diameter at the base – d_b, diameter at the lip – d_l). Pulp length (l_p) was measured on the inside of the outer curvature of the tusks, using a wire that would follow the shape of the tusk. We determined pulp volume (v_p) using fine river sand and filling the pulp until the sand was level with the rim of the tusk. All lengths and heights are in millimeter, volume in milliliter and weight in kilogram.

We included only 217 of the Namibian tusks since it was not possible to measure all defined parameters on broken or split tusks. For the Kruger group, we included 447 tusks in our study (Table 4 – 1). At the time of sampling, the Kruger observers sexed individuals and assigned ages to them using tooth eruption criteria (7). The collated data for this sample did not include pulp length and tusks were no longer available for further measurements.

Data analysis

To accommodate the missing pulp lengths for the Kruger sample we first tested whether our two samples is one statistical population. We thus tested whether the relationships between the circumference at the base of the tusk (c_b) and at the lip (c_l) and the circumference at the base of the lip (c_l) and pulp volume (v_p) is the same for Namibia and Kruger. For this we used least square regression analyses to find the linear relationships and tested whether the slopes differed using *t*-tests (18). We set intercepts at zero. Proving statistical unity would enable us to predict the pulp length (l_p) for the Kruger tusks. For this purpose, we found the relationship between pulp length (l_p) and circumference at the lip (c_l) for the Namibian population through least square linear regression analyses. We used this relationship to predict the expected pulp lengths (l_p) for tusks that had circumference at lip (c_l) noted in the Kruger data set.

From our measured and predicted variables, we calculated coronal pulp length *i.e.* the pulp that extends into the tusk crown beyond the labio-dental fold also termed the exposed pulp length (e_p) (Fig. 4 – 1). To determine the exposed pulp length (e_p) we subtracted the length of the tusk from its base to the labio-dental fold (l_l) from the total pulp length (l_p) ($e_p.= l_p - l_l,$) using both measured and predicted data. With linear least square regression analysis, we determined the relationship between the exposed pulp length (e_p) and the circumferences at the lip (c_l) in both data sets. The predicted pulp lengths together with the known sex and age data of the Kruger set also allowed us to study the influence of sex and age on exposed pulp length (e_p).

4.3 RESULTS

The Namibian and Kruger relationships between circumference at the lip (c_l) and circumference at the base (c_b) was the same (Etosha: c_b = 0.948c_l, t_{217} = 189.9, p < 0.01; Kruger: c_b = 0.934c_l, t_{447} = 250.2, p < 0.01) (Fig. 2). Confidence intervals of the slope (95% CI: 0.939 – 0.958) for the data measured at Etosha overlapped that for the data collated from Kruger (95% CI: 0.936 – 0.951).

Similarly, there was no difference in the relationship between the circumference at the lip (c_l) and the third root of pulp volume ($v_p^{\frac{1}{3}}$) (Namibia: $v_p^{\frac{1}{3}}$ = 0.038c_l, t_{217} = 128.2, p<0.01; Kruger: $v_p^{\frac{1}{3}}$ = 0.038c_l, t_{447} = 187.6, p<0.01) (Fig. 2). The 95% confidence interval for the slope estimated from the Namibian data (0.037 – 0.039) overlapped that of Kruger (0.037 – 0.038). Given that these results suggest one statistical population, we predicted the pulp length from data collected for tusks at Kruger from the relationship between the circumference at the lip (c_l) and pulp length (l_p) noted in the Namibian population (l_p = $1.584c_l + 72.671$, $t_{216} = 430.9$, $p<0.01$)) (Fig. 4 – 3).

We found no relationship between exposed pulp length (e_p) and circumference at the lip (c_l) ($F_{1,216}=1.352$, $p=0.246$) for the Namibian data set. However, we noted a wide spread of this derived variable ranging from 300mm coronal of the labio-dental fold to 300mm apical of it (Fig. 4 – 4). We could explain some of this variation in exposed pulp length when we separated the derived Kruger data into age and sex categories (Fig. 4 – 5). For the observed Namibian data, the maximum exposed pulp length was 300mm and the upper 95% confidence interval for this group was 255.5mm (Fig. 4 – 4).

4.4 DISCUSSION

Elephants fracture their tusks and do more so in captivity (20). When fractures expose pulp, clinicians may need general anesthesia to treat the tusk. However, general anesthesia in elephants carries the risk of animals having adverse reactions to drugs (4), falling into moats surrounding their enclosures (19) or damaging the enclosures from falling on anesthetic induction and/or recovery (5). Clinicians can minimize these risks by estimating the length of exposed pulp and applying general anesthesia only to those individuals that need treatment. Our study thus focused on finding an externally visible tusk measure from which to estimate the coronal pulp length and compliment the existing guidelines (15). Application of our findings extends further to inform clinical decisions regarding tusk amputations that can prevent complications associated with pulp exposure. We encountered some challenges though since the majority of environment-independent measurements of elephant tusks are within the bony alveolus of the maxilla and obscured when observing a live animal. However, several techniques (*e.g.* digital photogrammetry)

(17) easily allow measures of tusk circumference (c_l) and diameter (d_l) at the lip. We therefore focused on such variables and in particular on circumference at the lip (c_l).

Initially we encountered some analytical constraints due to partially available information for some data sets. Namibia had all the tusk measurements, but little data on the sex and age of the individuals from which the tusks came. Kruger had the sex and age data, but missed some of the morphological tusk measurements required. We thus first needed to evaluate whether we could pool these samples into one statistical population – that allowed us predict the missing data for Kruger. We found two morphological relationships that did not differ between the geographically separated Namibian and Kruger samples irrespective of sex or age. We therefore concluded and treated these two samples as one statistical population for the purpose of this study.

To find a stable, clinically visible measure for exposed pulp length, we focused on the total pulp length (l_p), a crucial variable that was not recorded for Kruger. However, accepting the samples from Kruger and Namibia as a single statistical population allowed us to predict the total pulp length (l_p) for the Kruger samples. We used the relationship between total pulp length (l_p) and the circumference at the lip (c_l) constructed from the Namibian samples to estimate total pulp lengths (l_p) for the Kruger samples from their circumference at the lip (c_l) measurements. That allowed us to calculate a measure of exposed pulp length for both Kruger and Namibia.

We expected older and thus larger elephants to have larger tusks and presumably more exposed pulp beyond the lip margin. However, we found no relationship between exposed pulp (e_p) and the circumference at the lip (c_l) of a tusk. We consider several reasons for this finding. The surrounding soft tissue and associated alveolar bone enlarge with the growing tooth that may result in constant exposed pulp lengths – when elephants increase in size the exposed pulp lengths do not increase at the same rate. As elephants age, they become larger and the surrounding tissue increase due to growth enhancing factors while bone mass increase to accommodate the heavier tooth. Rates of increase in pulp length, tissue and bone volume need to be the same to keep exposed pulp constant when elephant size increase. We have no measures of how tissue and bone volume change with age. However, the large variation in exposed pulp length that we have noted suggest that age related rates of change in pulp length, tissue and bone volume are not the same. Other factors thus most likely influence allometric relationships of exposed pulp length.

Alternatively, our analytical approach to accommodate the shortcomings of our data sets may have masked our results, particularly in the case of Kruger. We concede that the pooling of sex and age may also influence our results. Sex and age differences in exposed pulp length, (e_p) as evident for the values predicted for Kruger, explained some of the variations we noted. Males tended to have a larger variance in exposed pulp length (e_p) irrespective of age than what females have. However, we interpret these sex and age specific patterns cautiously as much of the variation will be removed by the statistical relationship used to predict total pulp length (l_p) from which exposed pulp length (e_p) is calculated.

Furthermore, geographical differences may skew our conclusions. Our relationships for Namibia, from which we predicted exposed pulp lengths for Kruger, came from tusks collected from three widely separated areas spanning a large rainfall gradient. It was not possible for us to separate these tusks. Since the incidence of tusk fractures seem to decrease with rainfall (20), it is not inconceivable that tusk growth and development may differ across a rainfall gradient.

Finally, unknown biological processes may be a more compelling reason for the lack of a relationship between exposed pulp (e_p) and the circumference at the lip (c_l). The maximum exposed pulp (e_p) calculated for tusks from Namibia were 300 mm (Fig. 4 – 4), a relative small value if compared to the total tusk lengths measured in this sample. This surprised us as we expected the total pulp length and therefore exposed pulp length to elongate as the tusk elongates. Given that the volume of the pulp is conical, both the diameter at the base of the tusk (d_b) and the total pulp length (l_p) can influence pulp volume (v_p). Tusks do not only increase in length with age, but the circumference of the tusk also increases. It is likely that the increased pulp volume of older male elephants for instance may be a result of an increase in circumference more than an increase in length. This conceivably influenced our results.

In addition, secondary dentin formation is a well recognized entity (11). It is a life-long continuous, physiologic deposition of dentin that eventually results in reduced pulp volume. Tertiary dentin in contrast is deposited specifically in response to injury of the tooth (11). We therefore also postulate a continuous deposition of dentin, either as a normal physiologic process or as result of trauma/injury or a combination thereof to be responsible for this reduction in pulp volume that affects both the diameter at the base of the tusk (d_b) and the total pulp length (l_p). For instance, the process could result in the reduction of the pulp length even while tusk length and circumference increases. This may explain why we noted a tendency for the range of exposed pulp (e_p) values to reduce, as females get older.

The biological and statistical reasons highlighted above may explain why we did not find a linear correlation between exposed pulp length (e_p) and the circumference at the lip (c_l). What does this mean clinically? The variance noted in exposed pulp defined an upper 95% confidence level of 255.5 mm that serve as a guideline. We therefore propose no tusk to be amputated less than 300 mm from the labio-dental fold, disregarding sex or age of the individual animal. We suggest this guideline as a compliment to the existing index (15).

4.5 ACKNOWLEDGEMENTS

We wish to thank the Namibian Ministry of Environment and Tourism for allowing access to work on their stockpiled elephant tusks. Ian Whyte and Anthony Hall-Martin supplied the data of the Kruger National Park elephants. The South African Veterinary Foundation supported this study financially.

4.6 FIGURES

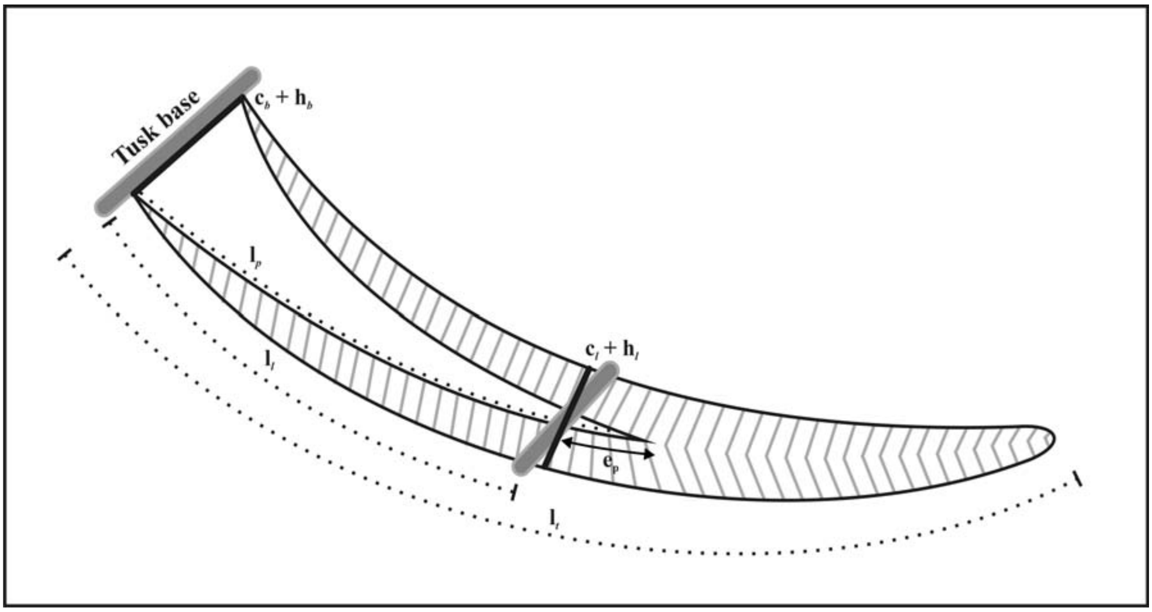


Figure 4 – 1. A diagrammatic illustration of a tusk sectioned longitudinally showing all the length, height and circumference measurements taken on the tusks.

A – Total tusk length

B- Length of tusk to lip

C – Pulp length

D – Height and circumference at base

E - Height and circumference at lip

c_b = circumference at tusk base

c_l = circumference at lip margin

d_b = diameter at tusk base

d_l = diameter at lip margin

e_p = exposed pulp length

l_l = length base of tusk to labial fold

l_p = total pulp length

l_t = total tusk length

v_p = pulp volume

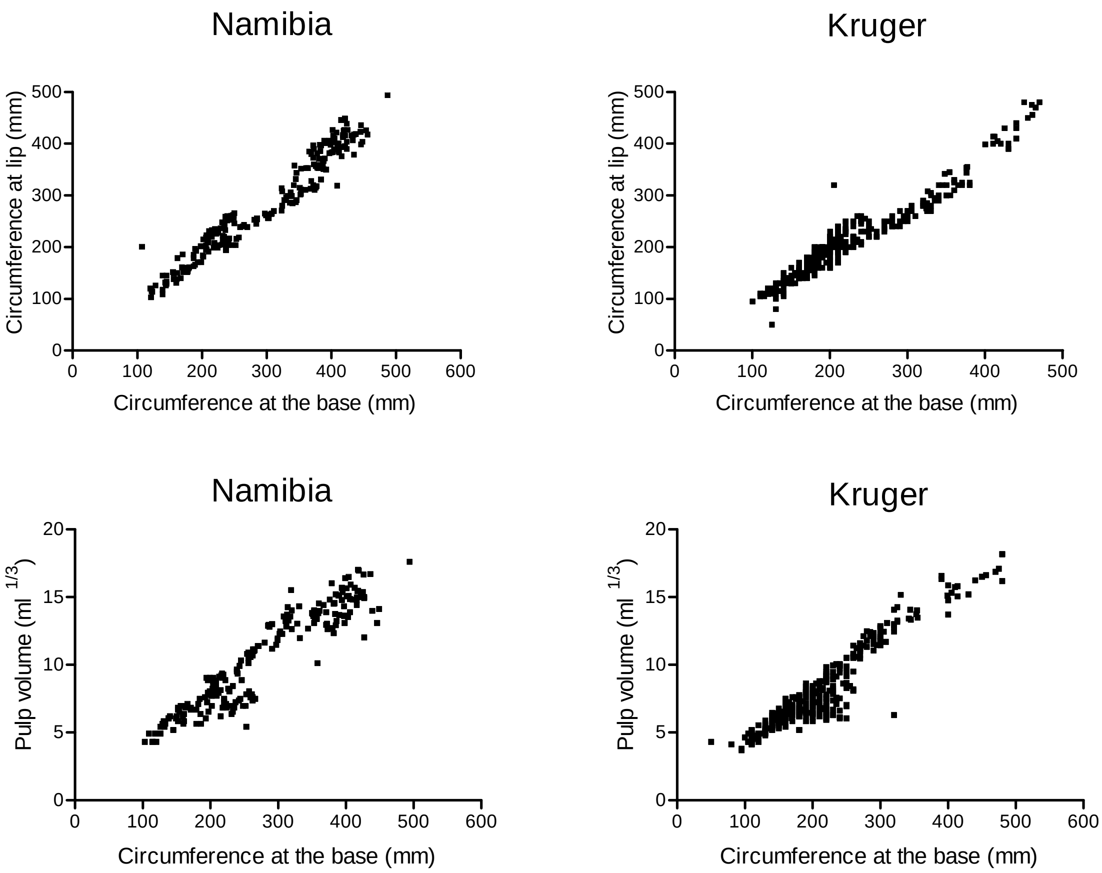


Figure 4 – 2. The relationships between measures of the tusk circumference at base (c_b) and values of tusk circumference at the lip (c_l) as well as the third root of pulp volume (v_p) recorded for samples from Namibia and Kruger. We found no difference between Namibia and Kruger in the respective relationships (see text) and thus pooled the data.

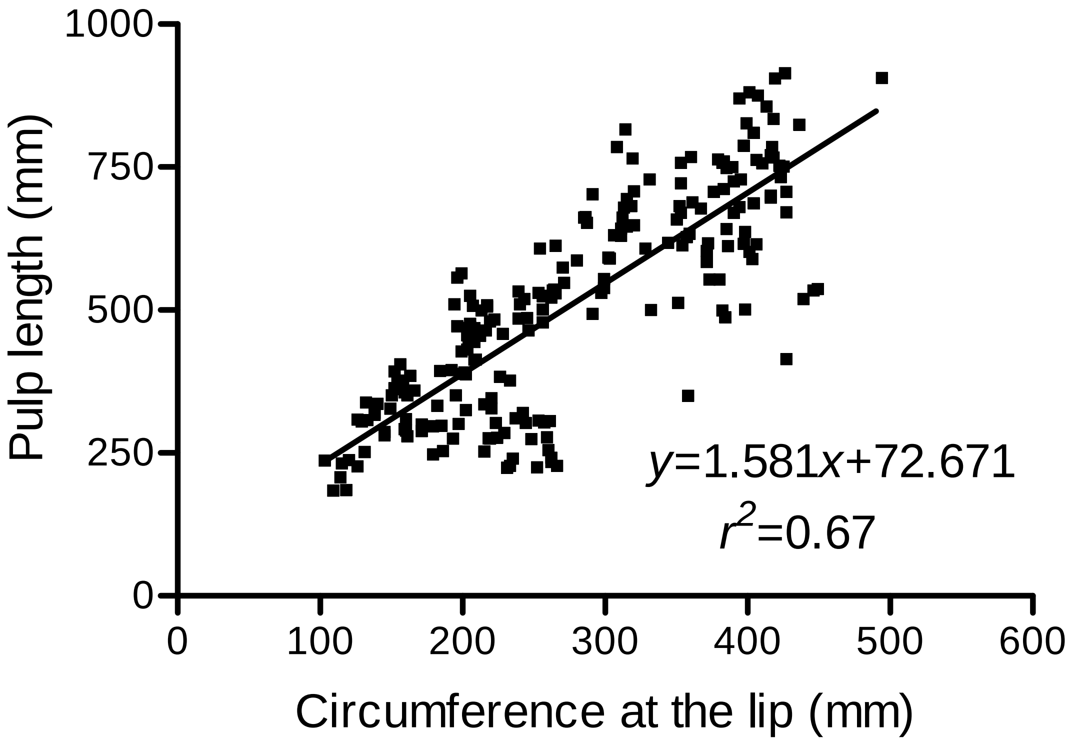
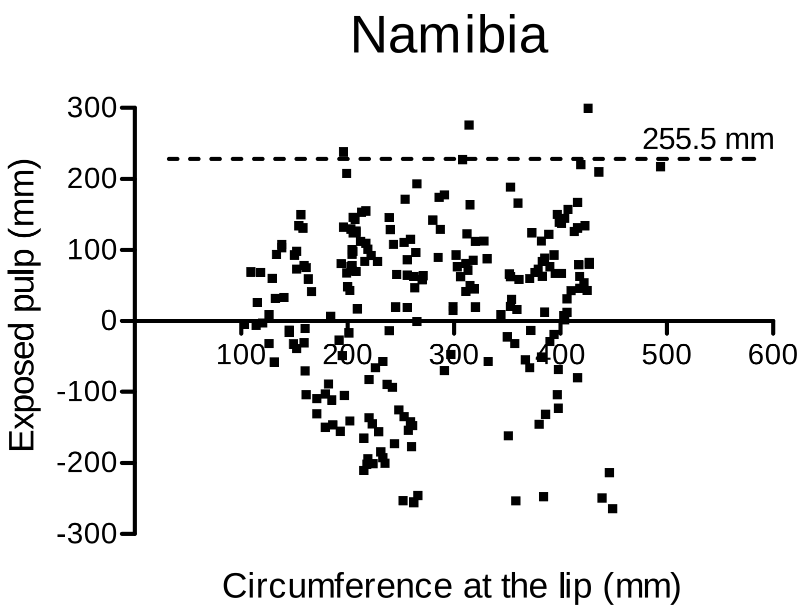


Figure 4 – 3 Relationship between pulp length (l_p) and the circumference at the lip (c_l) established for tusk collected in Namibia. We did not know the sexes from which these tusks came. The relationship allowed us to predict pulp length for tusks collected in Kruger since the tusks from Namibia and Kruger come from the same statistical population (see text and Figure 2).



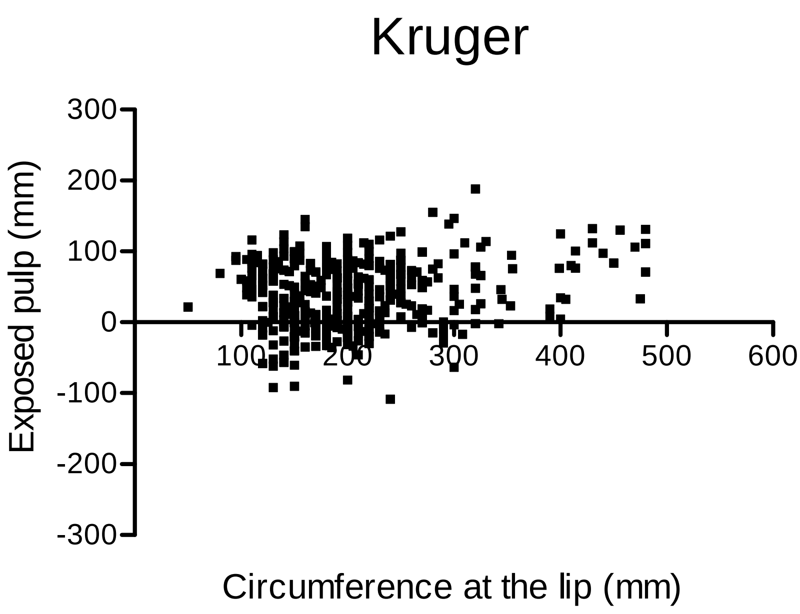


Figure 4 – 4. The length of the exposed pulp (e_p) recorded for Namibia and predicted for Kruger in relation to the circumference at the lip. We did not record any relationship between these variables. The broken line gives the upper 95% confidence interval for exposed pulp in the Namibian data recorded at 255.5mm.

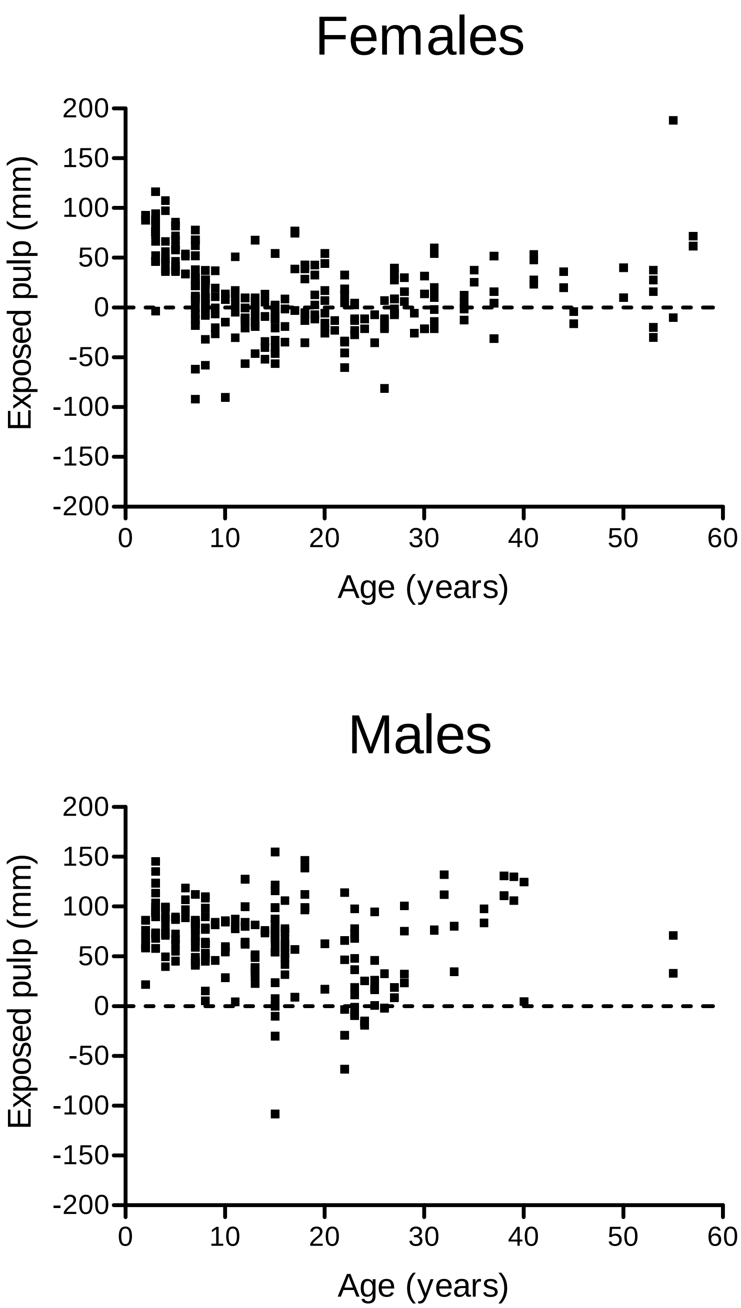


Figure 4 – 5. Sex differences in estimated exposed pulp (e_p) are apparent, while age differences are not well defined for the values we predicted for tusks from Kruger. Males usually have a longer exposed pulp than females, while the variability in females decreased with age.

4.7 TABLES

Table 4 – 1. Data recorded for stockpiled tusks from the Etosha National Park, Khaudum Game Reserve and Caprivi Game Reserve in Namibia, and collated for tusks measured from culled specimens in the Kruger National Park in South Africa (Kruger).

Data Collected	Measurement Description	Unit	Namibia	Kruger
Date	-	-	X	
Age	Estimated from molar teeth	-		X
Sex	Male, female, unknown	-		X
Tusk weight	-	kg	X	X
Total tusk length	Outer curvature	mm	X	X
Length of tusk to lip	Outer curvature	mm	X	X
Exposed (coronal) tusk length	Outer curvature	mm	X	X
Tusk circumference at lip	-	mm	X	X
Tusk circumference at base	-	mm	X	X
Base measurements	Height and width	mm	X	
Pulp length	Inside of outer curvature	mm	X	
Pulp Volume	-	ml	X	X
Number of tusks included			217	447

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Chapter 5 Tusklessness and tusk fractures in free-ranging African savanna elephants (*Loxodonta africana*)

5.1. INTRODUCTION

Tusklessness is common in some African elephant (*Loxodonta africana*) populations. The condition can be inherited (usually bilateral) or acquired (usually unilateral) (1). Incidences vary between populations (1-3), and over time, within populations (4, 5). Elephants that are bilaterally tuskless may act as an early warning sign of genetic drift in a population (6). Tusklessness also increases in heavily poached populations (2). Moreover, tusklessness appears to be sex-linked to females (1, 5, 6).

These observations evoke two outcomes that may both result from genetic drift if the condition has a genetic basis. In the first instance, small populations often created by intense poaching, are prone to genetic drift (7). We may then expect that tusklessness increases over time, i.e. the "tuskless-gene" becomes fixed in the population through drift. If the condition is sex-linked, then we can expect sex-specific relative frequencies to diverge. We should not find any tuskless males.

Secondly, for populations recovering from selective poaching where the residual numbers were relatively high, we may expect that tusklessness decreases over time. The "tuskless gene" is presumably lost from the population also through genetic drift. Here we expect that sex-specific relative frequencies converge onto zero if the condition is sex-linked.

The above expected outcomes evoke a third expectation – small founder populations skewed towards tusklessness or poached populations will have higher incidences of tusklessness than non-disturbed populations. To test these predictions we use observations of 15 populations. One of these is a small population with a skewed founder effect; five experienced intense levels of poaching; two had culling for varying periods which removed elephants non-selectively; and seven are relatively natural.

Acquired tusklessness is the result of a fracture of a tusk below the skin fold surrounding the tusk (labio-dental fold) or avulsion of a tusk. This may inflate the number of elephants that appear to be tuskless. We thus first considered the frequency of tusk fractures in wild populations, because dental disorders are common in captive elephants. Most dental disorders are fractures of the exposed incisors (tusks) − 31% (*n*=350) of the elephants in captivity in 60 North American zoos, had tusk fractures. African elephants comprised 48% (*n*=182) of this sample (8). In the only study on tusk fractures of African elephants in the wild, the incidence was only 5% of all tusks in an unidentified population (9). The incidence of tusk fractures may conceivably be linked to nutritient levels of major food items, humidity or some other factors. We therefore explore how tusk fractures and rainfall correlate as rain is likely to influence these factors.

In the present study we first quantified the incidence of tusk fractures in the 15 African elephant populations and calculated a correction factor for "apparent bilateral tusklessness". We then evaluated our predictions for tusklessness by comparing the incidences in the 15 populations of free ranging African elephants.

5.2. MATERIAL AND METHODS

Digital images of approximately 10 000 African elephants from 15 populations across the African continent (Fig. 5 – 1, Table 5 – 1) in the photographic library of the Conservation Ecology Research Unit at the University of Pretoria were scrutinized. Individual elephants for which either the tusks or the skin covering the tusks at its alveolus were clearly visible were selected. For each individual, we recorded the sex (male, female, unknown), age, presence and fractures of tusks. Age classes were broadly defined as either sub-adult or adult (10). We classified tusks as left or right tusk fractures only when a sharp, clear break was visible. Tusklessness was recorded for left or right tusks, or both.

We calculated the incidence of tusk fractures and used a log-linear model (11) to test for population and sex-specific differences in these. To explore how incidences of fractures vary between populations with different rainfall, we collated rainfall statistics for each population. We assumed that rainfall might serve as an index to some important variable such as nutrient levels of vegetation or humidity that conceivably affect the incidence of tusk fractures. Finally, we use incidences of left and right tusk fractures to calculate the probability that we may observe a fractured left ($p_{f,l}$) or right ($p_{f,r}$) tusk. The probability of observing an elephant with both tusks fractured ($p_{f,l+r}$) is thus the product of these two probabilities.

Incidences of tusklessness were used in a log-linear model (see above) to test for population-, sex- and age-specific differences. We first calculated the probability of observing an elephant with no tusk on the left ($p_{t0,l}$) and right ($p_{t0,r}$) from incidences of tusklessness on the left and right side. As unilateral tusklessness is usually acquired (1), the probability of acquired bilateral tusklessness ($p_{t0,l+r}$) is thus the product of these two probabilities and that of observing two fractured tusks ($p_{f,l+r}$). We use this to correct the frequencies of tusklessness if needed.

5.3. RESULTS

Tusk fractures

The incidences of tusk fractures were variable (Table 5 – 2) and associated with populations, sex and age (Log-linear model goodness-of-fit, maximum likelihood χ^2_{28} = 19.39, p = 0.89). The incidence of tusk fractures depended mostly on the population where the data was collected (Partial Association χ^2_{14} = 1519.61, $p < 0.01$). The populations in the western parts of the range of study areas had higher incidences of tusk fractures. In Etosha National Park, 44.4 % of all tusks had fractures irrespective of sex or age. For the Kaudom Game Reserve, Moremi Game Reserve and Chobe National Park, these values were 17.0 %, 19.2 % and 14.2 % respectively. Populations in the eastern parts of the study area had low incidences of tusk fractures ranging from 0 % to 1.6 % (Table 5 – 2).

The sex of an individual was less important than the population from which samples came, but it also influenced the incidence of tusk fractures (Partial Association χ^2_{2} = 1463.85, $p <$ 0.01). The incidence of tusk fractures was usually higher for males (14.9 %) than for females (11.0 %). The role of age was the least important factor determining incidences once the effects of populations and sex were accounted for (Partial Association χ^2_{1} = 815.63, $p < 0.01$). Incidences of tusk fractures were higher for adults (13.0%) than sub-adults (8.8%) (Table 5 – 2).

The various populations experience different rainfall each year (Table 5 – 1). The incidences of tusk fractures for adult males and females decrease when annual rainfall increases (♂♂: $y = 15790e^{-0.016(x+1)}$, $r^2 = 0.88$, $F_{1,10} = 55.88$, $p < 0.01$; ♀♀: y = 4205e$^-$

$^{0.012(x+1)}$, $r^2 = 0.84$, $F_{1,10} = 74.25$, $p < 0.01$). We recorded similar associations for sub-adults (♂♂: $y = 13000e^{-0.016(x+1)}$, $r^2 = 0.84$, $F_{1,10} = 39.38$, $p < 0.01$; ♀♀: $y = 65640e^{-0.021(x+1)}$, $r^2 = 0.81$, $F_{1,10} = 35.93$, $p < 0.01$) (Fig. 5 – 2).

The median incidence of tusk fractures was 1.31 %, considerably lower than that recorded in captive populations (31%). Only the elephants living in Etosha National Park had higher incidences of tusk fractures (44.4 %) than that of captive elephants.

Tusklessness

The greatest probability of observing acquired bilateral tusklessness was negligibly small at 0.0001 for the elephants in Etosha National Park. We thus made no corrections to our observed tuskless frequencies (Table 5 – 3). The incidence of tusklessness depended on the population sampled as well as the sex of individuals (Log-linear model goodness-of-fit, maximum likelihood $\chi^2_{98} = 81.61$, $p = 0.88$). The origin of samples contributed most to the variation in frequencies of tusklessness (Partial Association $\chi^2_{14} = 639.89$, $p < 0.01$). In the Addo Elephant National Park (small founder population) 91.0% of the adult females were tuskless. Tusklessness amongst adult females ranged from 21.1% to 26.7% in populations that experienced poaching. The incidence of tusklessness in populations that experienced non-selective culling and those that were relatively free from major disturbances were similar and ranged from 0.0% to 3.9% (Fig. 5 – 3).

Incidences of tusklessness also differed with sex (Partial Association $\chi^2_2 = 770.66$, $p < 0.01$) as no males were tuskless. Age was not included in our log-linear model, but more adult females than sub-adult females were tuskless in Addo Elephant National Park and South Luangwa National Park (Fig. 5 – 4).

5.4. DISCUSSION

The incidence of tusklessness varied considerably amongst populations. The population with a small founder size in Addo Elephant National Park had the highest incidence. Three additional populations, all with a poaching history, had relatively elevated incidences. These trends lend support to our prediction - small populations with founder effects and/or poached populations tend to have higher incidences of tusklessness than other populations. In addition, the incidence of tusk fractures varied amongst the 15 populations along an East-West gradient and correlated with annual rainfall. Only the elephants in Etosha National Park (this study) had higher incidences of fractures than captive ones (8).

Fractures of elephant tusks appear to be more common in drier areas − it exponentially increased as mean annual rainfall decreased. The mechanism responsible for this observation may be complex. Stored elephant tusks lose weight due to desiccation (12) and become more brittle (13). We are, however, unsure whether innervated healthy tusks withstand desiccation, particularly at their periphery. It is likely that some level of dehydration could stress such tusks in areas of low annual rainfall. When used by the bearers for defense, debarking of trees or digging in soil, these weakened tusks may have a higher risk of fracturing.

Social constraints as a result of the distribution of resources may add to incidences of fractures, as elephant range patterns centre on water (14), particularly in the dry season (15). With larger aggregations at permanent water in the dry season, hostile social interactions may increase the risk of fracturing tusks. In dryer areas permanent water often comes in the form of small springs or waterholes, sometimes artificially provided, that have access for only a few individuals at a time. Certainly, such interactions in confined space lead to tusk fractures in captivity (8).

Rainfall may well affect important environmental factors such as certain microelements directly or indirectly through vegetation. For instance, various waterholes in the Etosha National Park have high concentrations of fluoride (16). Fluorosis may increase the incidence of tusk fractures due to the fact that it causes brittle teeth, however there are no reports on the effect of fluorosis affecting other species in the Etosha National Park. Nonetheless, it is likely that rainfall affect some key microelement which may influence the chance that a tusk would fracture. On the other hand, warthogs *Phacochoerus africanus*, a possible surrogate for elephants, have tusks that are exposed and used to dig and forage (17). We are not aware of warthogs that suffered from increased tusk fractures in the Etosha National Park. This species furthermore spend some time of day underground, in disused aardvark burrows, which will have a higher humidity than the exposed environment (17).

The frequency of tusk fractures that may reflect on bilateral acquired tusklessness was negligibly small (this study). The incidence of tusklessness is thus unrelated to tusk fractures. However, tusklessness is more common amongst females than males – all males had tusks (this study). This is in stark contrast to that of the Asian elephant *Elephas maximus* – females are tuskless, while the incidence in males varies between populations (18). Tusklessness amongst African elephant males is indeed rare (3, 19) and may diminish with time. One reason is that tuskless males may not mate successfully in the presence of younger, but larger tusked males. Some tuskless males in three Kenyan populations are reproductively active where there are no tusked males left (3). In addition, tuskless females in Amboseli National Park have both tusked and tuskless male and female calves (20).

Furthermore, no tuskless males were born from tuskless females in Addo Elephant National Park (6). Our data may thus suggest a strong female sex-linked trait of tusklessness, but historic observations elsewhere suggest that the condition must be passed on through both males and females.

Such genetic linking suggests that history may play a role in the incidence of tusklesness. This was strong when events in the past selected against elephants that had large tusks. The population in Addo Elephant National Park started with at least 50% of the females without tusks (6). We recorded 90% of all females (91% adults and 84.5% sub-adults) without tusks, lower than the 98% noted in 2001. Non-selective genetic changes, the small size of the population and its isolation lead to the high levels of tusklessness here (6).

Three of the populations in this present study had incidences of tusklessness higher than 20% and all of these have a strong poaching history. Population sizes in the Vwaza Game Reserve, South Luangwa National Park and North Luangwa National Park declined during the 1970s and 1980s (21, 22). In our study, up to 21.1%, 22.9% and 26.7% of the females in these populations had no tusks. In South Luangwa the incidence increased from 10.5% in 1969 to 38.2% in 1989 (5). This change most likely resulted from selective poaching (Douglas-Hamilton *et al*., 1980 in 3). From 1989 to 1993, the incidence declined to 28.7%, possibly as a result of the migration of tusked females from adjacent Game Management Areas (5). However, we found no sub-adult females here that were tuskless. The reduction of tusklessness may in this case also result from genetic processes.

We found published data on high incidences of tusklessness for three other populations – all with a history of poaching. In the Queen Elizabeth National Park, 1.0% of the elephants living here in 1930 had no tusks. By 1988, 10.5% of the females and 9.5% of the males were without tusks (3). At Kasungu National Park, close to the three populations we noted with high frequencies of tusklessness in our study, 8.3% of the females living here in 1978 had no tusks (23). Finally, 10.0 to 15.0% of the elephants at Mana Pools in Zimbabwe were tuskless in 1966. At that time 23.0% of the sub-adults had the condition (19) suggesting that the incidence was on the increase then. As we recorded an incidence of 3.9% and 12.5% for adult and sub-adult females living in the Lower Zambezi National Park close to Mana Pools, incidences of tusklessness may be on the decline, following high frequencies earlier that most likely resulted from selective removal of tuskers.

The rest of the populations that we studied had low numbers of elephants without tusks. Some of these also had poaching histories e.g. Maputo Elephant Reserve (24) and the Kafue National Park (25). However, selective removal of large tuskers from these areas was most likely not as strong as in the other poached populations. Places that had non-selective culling such as Etosha National Park and Kruger National Park had low frequencies of tusklessness. Although we recorded that all adult females had tusks in Kruger, Raubenheimer (2000) reported a 4.2% incidence of tusklessness previously. Overall the incidence of tusklessness was low for those relatively undisturbed populations in our study. The highest value was 3.4% for adult females in the Moremi Game Reserve, and that for females of Amboseli National Park was 2.0% in 1988 (20), similar to a value of 1.5% that we recorded in 2004.

We conclude that the incidence of tusklessness is often a result of history. Selective removal of tusked elephants appears to play a role in determining how frequent tuskless animals occur in populations. The later dynamics of tusklessness then depends on the residual or founder population – if this is small, non-selective genetic change may easily lead to rising frequencies of the condition. However, if the residual population is large, those same genetic changes may lead to a decline in the incidence of tusklessness. Conservation managers may thus only need to consider actions when the incidence of the condition is on the increase. Such a change may serve as an indicator of genetic drift that could later lead to inbreeding depression (6).

5.5. ACKNOWLEDGEMENTS

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5.6. FIGURES

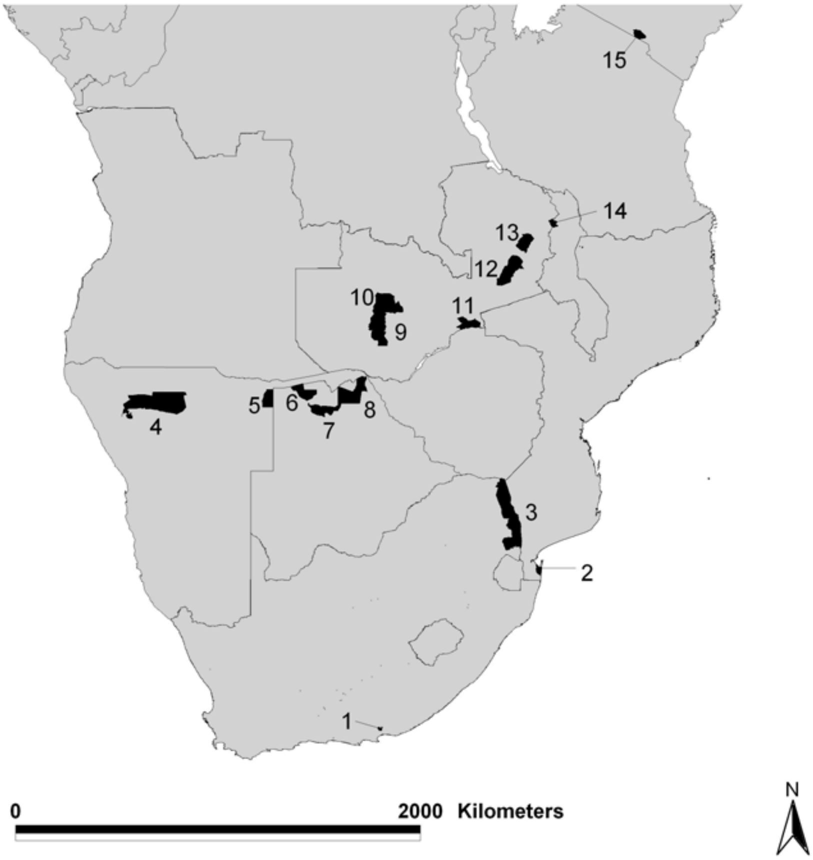

Figure 5 – 1. The locations of populations sampled in our study. 1 – Addo Elephant National Park, 2 – Maputo Elephant Reserve, 3 – Kruger National Park, 4 – Etosha National Park, 5 – Kaudom Game Reserve, 6 – Ngamiland 11, 7 – Moremi Wildlife Reserve, 8 – Chobe National Park, 9 – southern section of the Kafue National Park, 10 – northern section of the Kafue National Park, 11 – Lower Zambezi National Park, 12 – South Luangwa National Park, 13 – North Luangwa National Park, 14 – Vwaza Marsh Game Reserve, 15 – Amboseli National Park.

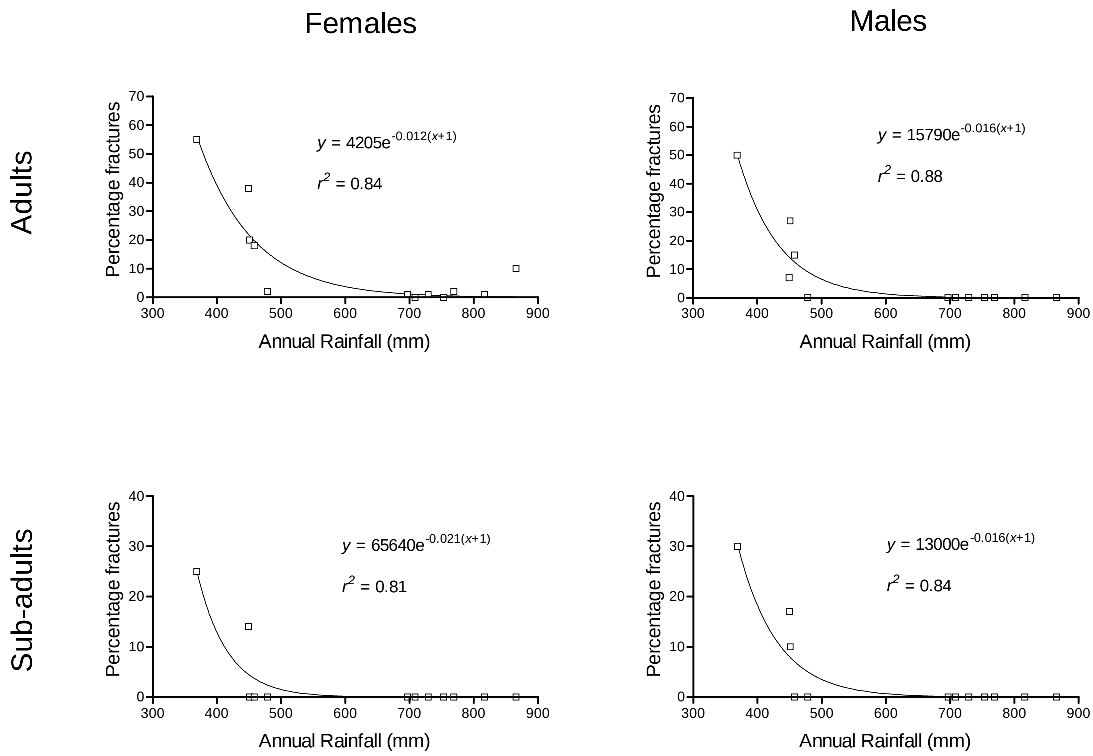

Figure 5 – 2. Change in the percentage tusks fractured recorded for populations with different annual rainfall. The incidence of male and female tusk fractures in a population decreases as annual rainfall increases.

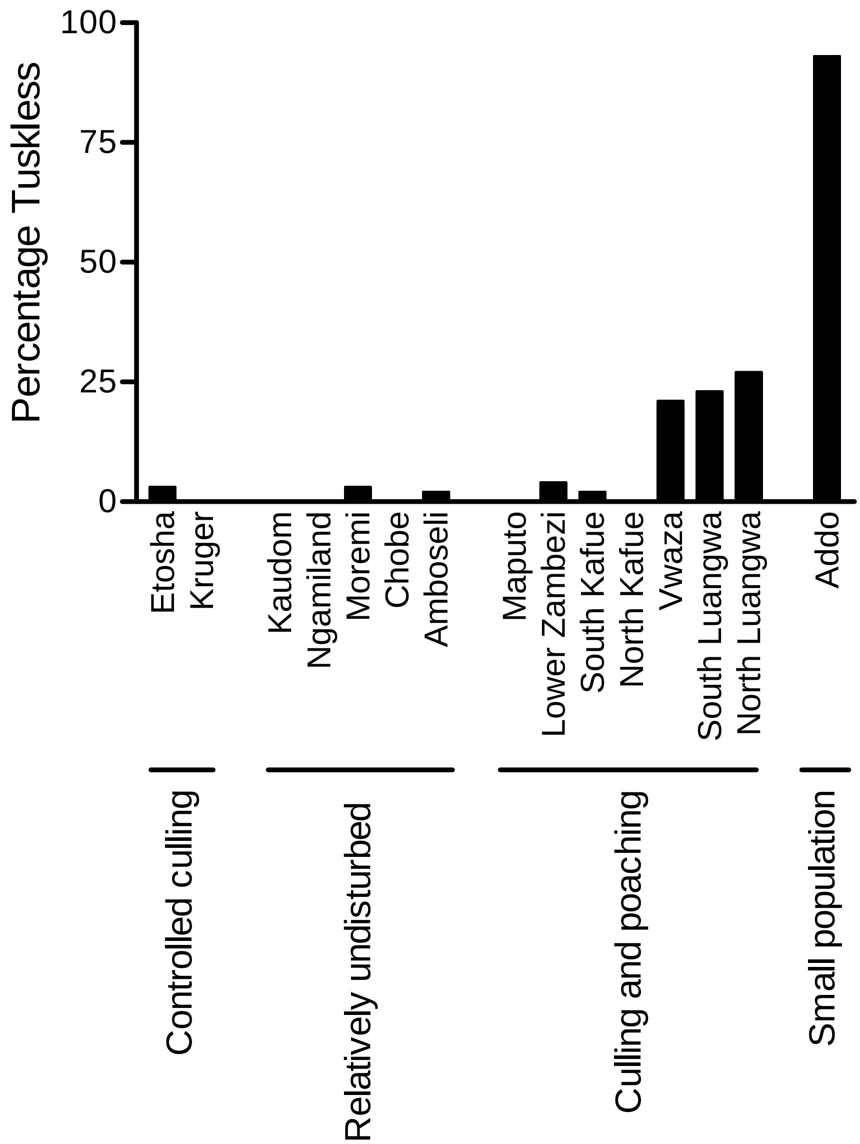

Figure 5 – 3. The association between population features and the incidence of tusklessness amongst adult females. Small populations with a founder effect and some of the populations that experienced intense poaching had higher incidences of tusklessness.

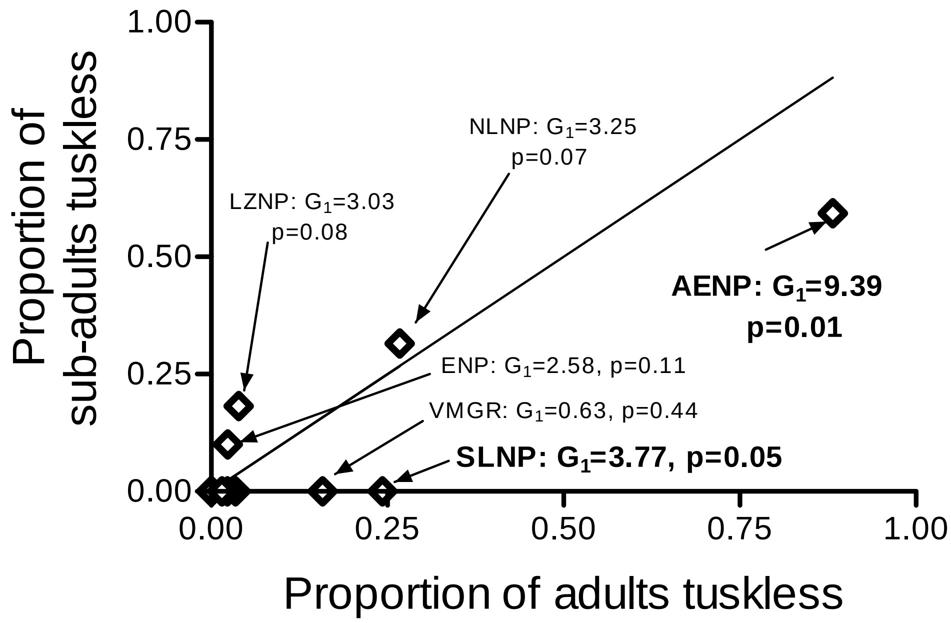

Figure 5 – 4. The proportion of tuskless sub-adult females in relation to adult females in 15 populations. Only two populations had age-specific differences in tusklessness with fewer sub-adults tuskless than adults (marked in bold). LZNP – Lower Zambezi National Park. NLNP – North Luangwa National Park. ENP – Etosha National Park. VMGR – Vwaza Marsh Game Reserve. SLNP – South Luangwa National Park, AENP – Addo Elephant National Park.

5.7. TABLES

Table 5 – 1. A summary of the number of African elephants sampled in 15 populations across seven countries. The years for which rainfall statistics are available and the mean and standard deviation of annual rainfall at each location are noted.

COUNTRY	POPULATION	INDIVIDUALS SAMPLED			RAINFALL	
		Males	Females	Unknown	Years	Annual
South Africa	Addo Elephant National Park	30	44	23	1960-2004	407.9±118.7
	Kruger National Park	29	112	12	1970-2003	478.6±178.0
Namibia	Kaudom Game Reserve	43	81	31	1965-2004	451.0±191.4
	Etosha National Park	11	43	17	1939-2005	368.7±118.7
Botswana	Ngamiland 11	0	12	2	1983-2003	448.2±147.4
	Moremi Wildlife Reserve	24	36	17	1983-2003	449.4±145.5
	Chobe National Park	30	67	5	1983-2003	457.9±137.9
Mozambique	Maputo Elephant Reserve	1	11	2	1980-2003	753.3±230.0
Zambia	Lower Zambesi National Park	1	52	8	1976-2001	798.6±272.2
	Southern Kafue National Park	5	87	1	1983-2003	696.7±185.7
	Northern Kafue National Park	25	95	3	1982-2003	729.1±230.5
	South Luangwa National Park	1	76	4	1983-2003	768.8±186.8
	North Luangwa National Park	7	90	9	1993-2003	816.3±142.2
Malawi	Vwaza Marsh Game Reserve	0	19	3	1983-2001	865.7±278.3
Kenya	Amboseli National Park	40	223	47	1976-2000	346.5±120.0
Totals		247	1048	184	-	-

Table 5 – 2. Frequencies of tusk fractures in samples of elephants taken from 15 populations. t_f denotes the number of fractured tusks in a total sample of n tusks. [a] represents populations where controlled culling took place. [b] represents populations with no intensive management of numbers. [c] represents populations that had high levels of poaching and [d] represents a population with a small founder effect.

Population	Females				Males				Unknown				Total number of tusks	
	Adults		Sub-adults		Adults		Sub-adults		Adults		Sub-adults			
	t_f	n	t_f	n	t_f	n	t_f	n	t_f	n	t_f	n	t_f	n
Etosha[a]	41	75	2	8	5	10	3	10	9	12	0	20	60	135
Kaudom[b]	29	142	0	14	20	74	1	10	-	-	1	60	51	300
NG11[b]	0	18	0	5	-	-	-	-	-	-	0	4	0	27
Moremi[b]	21	55	2	14	2	30	3	18	-	-	1	34	29	151
Chobe[b]	23	131	0	2	6	40	0	20	0	2	0	8	29	203
S-Kafue[c]	1	164	0	2	0	6	0	4	-	-	0	2	1	178
N-Kafue[c]	2	177	0	8	0	38	0	10	-	-	0	6	2	239
L-Zambezi[b]	0	88	0	2	0	2	-	-	-	-	0	14	0	106
S-Luangwa[c]	0	104	0	12	-	-	0	2	-	-	0	8	2	126
N-Luangwa[c]	2	125	0	8	0	14	-	-	-	-	0	12	2	159
Vwaza[c]	4	30	-	-	-	-	-	-	-	-	0	6	4	36
Kruger[a]	5	206	0	16	0	48	0	10	-	-	0	24	5	304
Maputo[b]	0	21	-	-	0	2	-	-	-	-	0	4	0	27
Amboseli[b]	5	384	0	52	2	40	0	40	0	6	1	88	8	610
Addo[d]	0	7	-	-	0	30	0	29	0	6	0	22	0	94

Table 5 – 3. Frequencies of tusklessness recorded for elephants of 15 populations across Africa. T_0 denotes the number of tuskless animals in a total sample of *n*. [a] represents populations where controlled culling took place. [b] represents populations with no intensive management of numbers. [c] represents populations that had high levels of poaching and [d] represents a population with a small founder effect.

Population	Females				Males				Unknown				Total number of animals	
	Adults		Sub-adults		Adults		Sub-adults		Adults		Sub-adults			
	T_0	*n*	T_0	*n*	T_0	*n*	T_0	*n*	T_0	*N*	T_0	*n*	T_0	*n*
Etosha[a]	1	39	0	4	0	6	0	5	0	6	1	11	2	71
Kaudom[b]	0	73	0	8	0	38	0	5	-	-	0	31	0	155
NG11[b]	0	9	0	3	-	-	-	-	-	-	0	2	0	14
Moremi[b]	1	29	0	7	0	15	0	9	-	-	0	17	1	77
Chobe[b]	0	66	0	1	0	20	0	10	0	1	0	4	0	102
S-Kafue[c]	2	86	0	1	0	3	0	2	-	-	0	1	2	93
N-Kafue[c]	0	91	0	4	0	20	0	5	-	-	0	3	0	123
L-Zambezi[b]	2	51	0	1	0	1	-	-	-	-	1	8	3	61
S-Luangwa[c]	17	70	0	6	-	-	0	1	-	-	0	4	17	81
N-Luangwa[c]	23	86	0	4	0	8	-	-	1	1	2	8	26	106
Vwaza[c]	3	19	-	-	-	-	-	-	-	-	0	3	3	22
Kruger[a]	0	104	0	8	0	24	0	5	-	-	0	12	0	153
Maputo[b]	0	11	-	-	0	1	-	-	-	-	0	2	0	14
Amboseli[b]	3	197	0	26	0	20	0	20	0	3	0	44	3	310
Addo[d]	40	44	-	-	0	15	0	15	1	4	8	19	53	97

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Chapter 6 Summary

Dental disease of animals other than the dog cat and to a lesser degree the horse, presents significant challenges to the veterinary care team dealing with these individuals. The oral biology and pathology of many species are unknown or poorly understood. One author referred to the information available to being mostly anecdotal and not scientifically based (1).

Parallel to the development of better understanding of various species' oral cavity is the development of better and safer sedation or general anesthesia procedures or drugs (2-5). These developments are essential to assist the veterinary care team in dealing with a variety of potentially very dangerous species. It remains the duty of the veterinarian to be informed about the known biology and pathology of an individual species before a general anesthesia is performed. This will ensure the safest possible procedure for the animal involved.

The aim of this study was to provide more scientific knowledge regarding the dentition of elephants as well as the treatment thereof. In order to do this the following four objectives were identified:

- A comprehensive literature review on tusk disease and treatment of tusked mammals, concentrating on both African elephants (*Loxodonta africana*) and Indian elephants (*Elephas maximus*),
- A histological description of the innervation of the pulp of an African elephant's tusk

- A proposed model for determining the coronal extent of the tusk's pulp,
- The incidence of elephant tusk pathology in wild elephant populations

6.1. A COMPREHENSIVE LITERATURE REVIEW ON TUSK DISEASE AND TREATMENT OF TUSKED MAMMALS, CONCENTRATING ON BOTH AFRICAN ELEPHANTS (*LOXODONTA AFRICANA*) AND INDIAN ELEPHANTS (*ELEPHAS MAXIMUS*).

When confronted with the largest land mammal, the African elephant, information is available but often disjointed. Many publications regarding the treatment of African or Indian elephants are often just descriptions of single cases. In chapter 2 of this dissertation a comprehensive review of the known oral biology and disorders of elephants, but also the wider tusked mammalian population, is discussed. From the review of tusk treatments in elephants and babirussas, it is clear that the exposed tusk pulp should:

1. not be left untreated.
2. be treated while the patient is either heavily sedated with adequate pain control, or have a general anaesthetic.
3. be copiously lavaged before attempting further treatment. Flushing the pulp cavity with Ringers seems to be adequate.
4. be debrided to remove any necrotic/inflamed pulpal tissue, before further treatment
5. have a pulp dressing containing either calcium hydroxide or even zinc oxide eugenol.

6 have a final restoration that will be able to wear with the tusk. This filling should have an impenetrable seal with the dentin of the tusk in order to prevent contamination of the pulp.

6.2. A HISTOLOGICAL DESCRIPTION OF THE INNERVATION OF THE PULP OF AN AFRICAN ELEPHANT'S TUSK.

A very contentious issue was the presence of nerve fibres within the pulpal tissue or not (6). A histological appraisal of a 2 year-old African elephant pulp, proved beyond doubt that sympathetic as well as parasympathetic nerve fibres were present. This is not unusual as the blood flow as well as various cells within the pulpal tissue is under neurological control. Pain is essential to protect a tooth from exerting forces in excess of what its capabilities are. The data as presented in chapter 3 was corroborated by a further European study (7).

6.3. A PROPOSED MODEL FOR DETERMINING THE CORONAL EXTENT OF THE TUSK'S PULP.

In order for us to determine if a pulp is exposed after a fracture or will the pulp be exposed during a tusk shortening procedure, it is essential to determine the length of the pulp that extends into the crown of the tusk. The current recommended technique is very inaccurate and therefore not useful (8). Various morphometric measurements of tusks were taken and then examined to see which will give the most accurate estimate. Most of the measurements that will not be affected by environment changes, like fractures, are situated within the alveolus and is therefore not available to the veterinarian/zoo keeper for evaluation. The only measurements available were the height of the tusk at the lip and the circumference. No linear relationship between the circumference of the tusk at the lip and the exposed tusk pulp was evident but 2 clusters of data suggested that the pulp in males extended beyond the lip whereas in females they often did not extend beyond the lip. With this current data we can only recommend that no tusk should be amputated shorter then 256 mm in any animal under 20 years of age as well as in females of any age.

6.4. THE INCIDENCE OF ELEPHANT TUSK PATHOLOGY IN WILD ELEPHANT POPULATIONS.

As mentioned before, understanding the biology and pathology of a species is essential to determining what to do with them in captivity. This study showed that elephants in 15 different populations in sub Saharan Africa also suffer from tusk fractures. Tusk fractures are not constant in these populations, but decrease from West to East over Africa. It was only the population in the extreme west (Etosha National park) that had an incidence of tusk fractures greater than published for captive elephants (medical management). The incidence of tusk fractures correlated linearly with the average yearly rainfall in these areas, yielding that drier areas have increased tusk fractures and wetter areas less fractures. It is unclear if this is a humidity effect on the teeth, causing desiccation in drier areas. It may however also have effects on the nutrients available to these animals. This means that we should understand the causes of tusk fractures in captivity better in order for us to focus more on prevention. Together with this, the incidence of tusklessness in these 15 populations was examined. Tusklessness can either be attributed to a small founder population of which many of the individuals were tuskless (Addo Elephant National Park) or to selective culling (poaching) of tusked animals. The latter is present in many African reserves (see Chapter 5), but there are signs, as poaching decreases, that the incidence of tuskless animals is once again decreasing.

6.5. CONCLUSION

The work reported in this dissertation improves our understanding of how elephant tusk fractures in captivity and in the wild differ from one another. It also makes various recommendations of how tusk fractures in this species should be treated. Finally, it shows that the length of the pulp, extending into the pulp cavity of the tusk, can not accurately be predicted using morphometric measurements visible in the live animal. Even though this is the case, a practical recommendation to amputation of tusks is given.

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