REVIEW

Crocodile Attack in Australia: An Analysis of Its Incidence and Review of the Pathology and Management of Crocodilian Attacks in General

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Crocodilians represent one of the oldest constant animal lineages on the planet, in no small part due to their formidable array of predatory adaptations. As both human and crocodilian populations expand, they increasingly encroach on each others' territories, bringing morbidity and mortality to both populations. In this article, the medical and herpetologic literature pertaining to injuries caused by crocodilians is reviewed, and the patterns of saltwater crocodile attacks in Australia from 1971 to 2004 are analyzed. In this review, we examine the features of crocodilians that contribute to explaining their evolutionary success, as well as the potential hazard they pose to humans. Only by understanding their capabilities is it possible to mitigate the potential threat to life and limb.

Key words: crocodile, alligator, attack, bite, Australia

*How doth the little crocodile
Improve his shining tail,
And pour the waters of the Nile
On every golden scale!
How cheerfully he seems to grin,
How neatly spreads his claws,
And welcomes little fishes in,
With gently smiling jaws!*

—Alice in Wonderland by Lewis Carroll, 1866

Crocodilians are among the few species on the planet that cause reflexive fear in humans, perhaps because the fear of being eaten is greater than the fear of being bitten.¹ Many animals will bite, but only a few attack humans as they would other prey items. Fortunately, attacking and eating humans by crocodilians is an uncommon event. We review the features of crocodilians that make them such formidable predators, examine the incidence of saltwater crocodile attacks in Australia, and examine the pathology and management of this entity.

The order Crocodylia comprises 23 species of extant crocodilians within 3 families: Alligatoridae (8 species;

alligators and caimans), Crocodylidae (14 species; “true” crocodiles), and Gavialidae (1 species; Indian gharial)² (Figure 1). Crocodylomorpha, the broad taxonomic grouping that encompasses crocodilians and their known predecessors, can be traced back approximately 240 million years and has diversified into terrestrial, freshwater, and marine environments. The modern Crocodylia originated more than 100 million years ago, and its members have remained relatively unchanged since then. Crocodilians share their early archosaurian origins with dinosaurs and hence are more closely related to birds than other reptiles.³ The word *crocodile* is derived from the Greek word *krokodeilos*, which translates literally into pebble worm (*kroko* means pebble and *deilos* means worm or man), presumably referring to the appearance of a crocodile's skin. The word *alligator* comes from the Spanish for lizard, *el lagarto*.⁴

Modern crocodilians are geographically widespread in warm temperate and tropical climates.⁵ The 2 species of alligator, the Chinese alligator (*Alligator sinensis*) and the American alligator (*Alligator mississippiensis*), are distributed in more temperate climates and are exposed to relatively cold conditions during winter.

It would seem that humans may have always had a healthy respect for crocodilians, judging by the paleon-

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Crocodylus porosus *Alligator mississippiensis* *Gavialis gangeticus*

tologic evidence that suggests that crocodilians preyed on human ancestors.⁶ Crocodilians feature in the traditions and myths of many cultures around the world. For example, crocodiles (*Crocodylus porosus*, *Crocodylus johnstoni*) figure prominently in the dreamtime stories of a number of aboriginal clans in northern Australia⁷⁻⁹ and are of totemic significance to this day. To the Iban people of northern Borneo, it is taboo to kill crocodiles, except where one has killed a human.^{10,11} The Por people of the Cardomom Mountains in Cambodia revere Siamese crocodiles (*Crocodylus siamensis*), and the killing of one is believed to cause an ancestor's forest spirit to bring illness and death to the person or family responsible.¹² In ancient times, Nile crocodiles (*Crocodylus niloticus*) in Egypt were worshipped and associated with the crocodile-deity Sobek, at the shrines of Kom-Ombo in Upper-Egypt, and in Crocodilopolis (Fayum).¹³ The crocodile was thought to be responsible for the rains that overflowed the Nile River and left behind the rich mud that fertilized the land. At the same time, they were feared for their destructive power.^{14,15} Early explorers reported the fear that Native American Indians showed toward alligators.¹⁶

More recently, humans have had the advantage. The overexploitation of crocodilians for their skins after World War II resulted in two thirds of the species being placed on Appendix I of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) in 1973.¹⁷ No international trade is permitted under Appendix I (except animals derived from registered captive-breeding operations). Today, because of the efforts of conservationists, researchers, skin traders, and others, many crocodilian populations around the world have recovered.¹⁸ The success of many of these management programs has led to increased interactions and conflicts between people and crocodilians, often promoting a negative reaction to their successful population recovery. In some countries, wildlife authorities have specific programs to remove nuisance alligators or problem crocodiles to improve public safety (eg, Australia, United States, Zimbabwe).

With regard to unprovoked attacks on humans, 3 species are perhaps the best known—the American alligator, the Nile crocodile, and the saltwater or estuarine crocodile (*C. porosus*). A number of other crocodilian species have been less commonly implicated in attacks

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Figure 1. Dorsal and lateral views of a true crocodile (saltwater crocodile, *Crocodylus porosus*), alligatorid (American alligator, *Alligator mississippiensis*), and gavialid (Indian gharial, *Gavialis gangeticus*). Adapted from Webb and Manolis.⁸

on humans, including the black caiman (*Melanosuchus niger*),^{19,20} Morelet's crocodile (*Crocodylus moreletii*),^{21–23} American crocodile (*Crocodylus acutus*),^{24,25} mugger (*Crocodylus palustris*),²⁵ and the Indian gharial (*Gavialis gangeticus*).²⁶ Two cases of directed attacks by Australian freshwater crocodiles (*C. johnstoni*) (in 1988 and 1990)²⁷ appear to have been cases of mistaken identity, since this species is generally considered harmless unless provoked.

The incidence of crocodile attacks in many countries is extremely difficult to quantify. Undoubtedly, many more people have been attacked by crocodilians than have been reported. At the turn of the century in the United States, current thinking was that crocodilians would not attack humans unprovoked.^{28–30} This widely accepted opinion changed in 1973 with the death of a 16-year-old girl attacked by a 4-m-long alligator.³¹ Since then, more detailed records on alligator attacks have been kept,³² although with nowhere near the accuracy or detail of the record keeping of other animal attacks, such as the International Shark Attack File. The worst mass attack by crocodiles was said to have been on the night of February 19, 1945, when allegedly approximately 1000 Japanese soldiers found themselves pinned down in a mangrove swamp separating Ramree Island from the Burmese mainland. According to the British naturalist Bruce Wright, who was then a member of the British Armed Forces, only 20 Japanese allegedly escaped alive from the saltwater crocodiles.³³ The veracity of this report has subsequently been called into question.³⁴ A 5.8-m-long saltwater crocodile (named Whiteback due to distinctive white markings on his back) gained considerable notoriety in Sarawak, Malaysia, after killing 13 people.³⁵

Accurate data collection concerning animal attacks does not usually occur until a species is protected and formal monitoring is introduced. The situation with saltwater crocodiles in northern Australia is no exception, and most detailed information on attacks has been recorded since the species was legally protected in the states or territories in which it occurs (Western Australia in 1969, Northern Territory in 1971, and Queensland in 1974).⁸ Even so, detailed information on some attacks is not always available, and attacks that do not result in injury are not usually recorded.

A review of crocodile attacks in northern Australia would not be complete without a brief summary of the features of crocodilians that make them such formidable predators.

The crocodile as a predator

Crocodilian notoriety stems in part from their prominent teeth, the number of which varies between species.³⁶

Saltwater crocodiles possess between 64 and 66 teeth: 17 to 18 teeth on each side of the upper jaw (premaxilla and maxilla) and 15 on each side of the lower jaw (mandible). Designed to grab and hold onto prey, the teeth are constantly replaced through the animal's life. Massive pterygoid muscles³⁷ close the jaws with enormous force, and being bitten has been described like being hit with a hammer, patients often only realizing later that they have sustained a penetrating injury. Even bites from small specimens can have serious consequences.

Recently, investigators measured the bite force of various crocodilian species, with particular attention to series of different sized American alligators and saltwater crocodiles. These results indicated that a 300-kg, 3.65-m-long American alligator could exert a force of just under 1000 kg, equal to the force required to lift a small utility vehicle.³⁸ Such forces can easily crush turtle shells and have been reported to be able to crush a pig's head with ease.⁸ They also found that biting force was proportional to size.

As in most vertebrates, the depressor muscles that open the crocodilian's jaws are much weaker than those that close the jaws, and it is common folklore that a strong elastic band can prevent even large crocodilians from opening their jaws. With relatively undifferentiated teeth, crocodilians waste little time processing prey before swallowing it. The jaws and teeth crush flesh, carapace, and bone enough to render prey small enough to be swallowed. Larger prey items are broken into smaller chunks by rolling the entire body (termed the *death roll*) and also by using a whipping action of the head.³⁹ Contrary to what might be assumed by their large size, crocodilians are surprisingly agile and explosively fast over short distances. Some species have been observed "galloping" at speeds up to 17 km/h (10.6 mph),⁴⁰ and even large crocodilians can move rapidly across land at speeds of up to 10 km/h (6.2 mph). The ability to move very quickly over a short distance (eg, an entire body length in less than half a second) contributes to their success as ambush predators.

Most adult crocodilians are threatened only by other crocodilians and humans. Generally, the larger species of crocodilians see humans as a potential food source. The average maximum size of male saltwater crocodiles is 5 m, and some individuals may exceed 6 to 7 m.^{10,41} Nile crocodiles typically average 3.5 m in length, although some males may reach 5 m.⁴² Male American alligators average approximately 3 m, and some occasionally reach 4.5 m.⁴³

The success of crocodilians as predators is due largely to the shape of their body and their ability to expose only a small part of it (the head), while the bulk of the body remains hidden underwater. The positioning of the

internal nares behind the palatal valve and the development of a secondary palate have been instrumental in their success, enabling this minimum exposure posture of eyes, ears, and nostrils above water that lends a crocodilian its stealth profile.⁸ A palatal valve at the back of the tongue serves to seal the mouth off from the palate and trachea, enabling the jaws to be opened fully underwater without allowing water to enter the throat and trachea.

This minimum exposure posture leaves the well-developed sense organs exposed and continually sensing the environment.³⁶ Daytime vision is good, and night vision is enhanced by a layer of guanine crystals in the retina (the tapetum lucidum) that reflect light that enters the eye back over the visual sensory cells a second time.^{36,44} Crocodilian hearing apparatus is the most developed of all reptiles, and its sensitivity is on a par with most mammals. Research has also shown their olfactory and gustatory senses to be highly developed. Recent studies of sense organs in the skin around the jaws (dermal pressure receptors) show the organs' ability to detect very subtle pressure changes in the water—alligators could detect a droplet of water hitting the surface near their head through the resulting pressure waves alone.⁴⁵

Crocodilians can remain underwater for extended periods, which allows them not only to drown prey but also to remain concealed. The amount of time that an animal can stay underwater without surfacing increases with increasing body size. Although most crocodiles stay underwater for an average of 15 minutes per dive, large crocodiles (>4 m in length) are able to stay underwater for up to 2 to 3 hours.⁴⁶ Following a voluntary dive, heart rate decreases markedly and can drop to as low as 1 to 2 beats/min. Unlike other reptiles, crocodilians have a 4-chambered heart that possesses unique valves both within the heart (cog valve) and in the twin aortas leaving it (foramen of Panizza).⁴⁷ The heart's structure serves to divert oxygenated blood flow away from peripheral and nonessential organs during diving, maximizing available oxygen to the brain and other vital organs. Crocodilian hemoglobin has 12 unique bicarbonate binding sites, allowing far more oxygen to be released from the molecule for a given oxygen tension than from the human equivalent. A hybrid human-crocodilian hemoglobin (Hb-Scuba) has been developed and has potential as a synthetic hemoglobin.⁴⁸

One characteristic that is relevant to the analysis of crocodile attacks is that crocodilians will intentionally eat stones, which are stored within the stomach. These stones appear to act as gastroliths to assist in the breakdown of ingested food,⁸ although a hydrostatic function has also been suggested.⁴⁹ The propensity of crocodilians to retain heavy objects in the stomach means that

items such as bullets and lead shot imbedded in prey or carrion remain in the stomach well after the food has been completely digested. A coroner's examination of crocodilian stomach contents that contain human remains may become "complicated" if such items are also present (Figure 2).⁸

Literature review methods

A review of the available literature on Australian crocodile attacks was completed from a variety of sources. The extensive records at Crocodylus Park (Darwin, Northern Territory) were cross-referenced against a Nexis/Lexis and NewsText electronic search of newsprint articles. Crocodile attack has only been coded as a separate injury mechanism since the introduction of the *International Classification of Diseases, Tenth Edition* in 1997, but data from the National Injury Surveillance Unit were further cross-referenced to the newsprint data. The medical literature was searched using the PubMed database for all references to *crocodile* or *alligator*. The herpetologic literature was searched using the Biosis Previews, Zoological Record, and Wildlife and Ecology Studies Worldwide databases for crocodile or alligator attacks. Finally, the Google search engine was used to search for all instances of *crocodile attack* or *alligator attack*. All references obtained using this search strategy were then subsequently hand searched for further relevant references.

Analysis of attacks

There have been 62 definite, unprovoked attacks by wild saltwater crocodiles, resulting in injury or death to humans, between 1971 and 2004 (Table 1). One attack on a researcher (collecting crocodile eggs, 1986), 2 attacks on wildlife rangers (capturing crocodiles, 1993 and 2002), and 1 attack on a crocodile farmer (collecting crocodile eggs, 2004) that occurred during their work with wild crocodiles were excluded. Likewise, attacks by captive crocodiles were excluded from the analysis.

The Northern Territory, which contains the largest wild population of saltwater crocodiles within Australia, has accounted for most (63%) attacks, followed by Queensland (24%) and Western Australia (13%) (Table 1). Notwithstanding the relatively low number of attacks during the 34-year period, there has been a tendency toward increasing numbers of nonfatal attacks over time (from 0.1 per year in 1971 to 1980 to 3.3 per year in 2001 to 2004) and relatively stable numbers of fatal attacks over time (mean, 0.5 per year) (Table 2).

The wild population of saltwater crocodiles in the Northern Territory has increased from an estimated 3000

Figure 2. Radiographs of postmortem *Crocodylus porosus* and *Homo sapiens* (to similar scale). In the circumstances of this case, it was important to establish whether the victim had been shot before having been consumed by the animal. One shot was used by a police officer to dispatch the animal. **Left,** The police bullet can be seen in the crocodile's head. **Right,** The torso has been transected by the force of the crocodile bite, but no additional projectile can be identified.

Table 1. Saltwater crocodile attacks in the wild, in northern Australia, 1971–2004

Attack type	No. (%) of attacks			
	Northern Territory	Queensland	Western Australia	All states
Fatal	10 (25.6)	5 (33.3)	2 (25.0)	17 (27.4)
Nonfatal	29 (74.4)	10 (66.7)	6 (75.0)	45 (72.6)
Total	39 (62.9)	15 (24.2)	8 (12.9)	62

to 5000 in 1971, when the species was protected after 26 years of unregulated hunting, to 50 000 nonhatchlings in 1984⁵⁰ and 75 000 nonhatchlings in 2000.⁵¹ The recovery of the population has been characterized by a marked increase in the average size of the saltwater crocodile in the population.⁵¹ Whether the increased numbers of crocodiles and greater numbers of large crocodiles are implicated in the increased frequency of attacks is unclear. Andau et al⁵² concluded that the increased number of saltwater crocodile attacks in Sabah, Malaysia, were the result of increasing numbers of crocodiles. Glasgow⁵³ relates how increasing numbers of American alligators and an expanding human population in Louisiana in the 1970s resulted in increased interactions with alligators.

Table 2. Mean number of saltwater crocodile attacks per year in the Northern Territory and Australia

<i>Period</i>	<i>Fatal</i>	<i>Nonfatal</i>	<i>Total</i>
Northern Territory			
1971–1980	0.2	0.0	0.2
1981–1990	0.4	1.0	1.4
1991–2000	0.2	1.2	1.4
2001–2004	0.5	1.8	2.3
Australia			
1971–1980	0.4	0.1	0.5
1981–1990	0.8	1.2	2.0
1991–2000	0.3	1.9	2.2
2001–2004	0.5	3.3	3.8

The reasons why saltwater crocodile attack humans without any provocation are thought to be as follows:

1. Defense of territory: Saltwater crocodiles are highly territorial.^{8,54} Males and females establish territories^{55,56} and defend them against intruders, whether other crocodiles or humans.
2. Defense of nest and/or young: Most species of crocodilian exhibit some form of nest defense.⁵⁴ In the case of saltwater crocodiles, females vigorously defend their nest against intruders to deter potential predators of their eggs. Crocodilians will also react to distress calls of their young.^{1,57,58} There are 2 confirmed cases of female saltwater crocodiles attacking humans near their nests; one of these attacks resulted in the death of the victim.
3. Hunting for food: All crocodilians are opportunistic feeders, eating a wide range of prey. With increasing body size, crocodilians shift to larger prey,^{49,59} and humans are well within the size range of prey that can be taken by a large saltwater crocodile. Fifty-five attacks in our series (89%) were considered to be attempts by crocodiles to secure food, although the possibility of territorial defense cannot be ruled out in some cases.
4. Mistaken identity: It is possible that some attacks may be directed at dogs accompanying people, and the latter were bitten by mistake. There were 2 cases of people in our series being attacked while sitting near the water's edge with their pet dogs. In one of these attacks, the crocodile was relatively small (1.7 m) and is unlikely to have been attacking the much larger human. Dogs are commonly taken by crocodiles in northern Australia.⁶⁰
5. Self-defense: Attempts to catch crocodiles may result in the animal biting instinctively to protect itself.

Only one case in our series was considered a defensive reaction by a relatively small crocodile (1.8 m).

Most (81%) unprovoked saltwater crocodile attacks occurred with people in the water swimming or wading or at the water's edge (Table 3). All fatal attacks involved people in the water, either swimming (73%) or wading (27%). Five attacks (9%) involved people on land, with crocodiles coming completely out of the water. In 2 of these cases crocodiles actually entered tents and grabbed sleeping occupants. Data compiled by Conover and Dubow³² indicate that 89.7% of victims of 184 unprovoked American alligator attacks (1948 to 1995) were participating in activities where they were totally (39.1%) or partially (22.3%) immersed in water or standing at the water's edge (28.3%); 10.3% were on land (17 cases), on a boat or raft (2 cases), or not recorded (2 cases). In 12 of 16 fatal alligator attacks recorded by the Florida Fish and Wildlife Conservation Commission (unpublished data, 1928–2004), 10 involved victims in the water (swimming or wading) and 2 were on land. The circumstances of the other 4 attacks are not known. Fergusson⁶¹ reported 55.3% of Nile crocodile attack victims were swimming, bathing, or crossing a river with cattle, and 36.2% were collecting water, drinking, or fishing at the water's edge.

Attacks on people in boats and canoes are of particular interest. The first recorded attack in the Northern Territory, in 1870, involved the second mate of a schooner on the Roper River being taken as he slept with his legs hanging over the side of the boat. Since 1971, unsuccessful saltwater crocodile attacks have been directed at people pulling boats out of the water, but in each case the individuals were out of the boat and in the water or at the water's edge. Excluding one attack that may have been provoked (Bynoe Harbour, 1980), few attacks have been directed at people in boats. This consideration is significant because fishing is one of the common pastimes for locals and tourists in northern Australia.

Two specific instances of saltwater crocodiles deliberately attacking boats merit mention. A 5.1-m-long male saltwater crocodile (named Sweetheart) attacked the propellers of the outboard motors of a number of boats, overturning them and their occupants but never attacking the people in the water.⁶² It is thought that Sweetheart was probably reacting to the sound of the propellers, which he may have mistaken for another crocodile within his territory.⁸ Another large saltwater crocodile (5.1 m) began attacking the warm cowlings of outboard motors after the boats had been pulled up onto the bank. In this case, it is thought that this individual may have interpreted the warmth of the motor as a large mammal at the water's edge.⁸ Both of these cases appear

Table 3. Activities of people (62 attacks, 64 people) at the time of attack by saltwater crocodiles, 1971–2004

Activity	Nonfatal			Fatal		
	Day	Night	Un-known	Day	Night	Un-known
Water						
In shallow water (hunting, fishing, wading)	12	2	...	2	1	1
In water (skin-diving, spear-fishing)	4	...	...	...	...	...
In water (swimming)	6	3	...	5	6	...
At water's edge	5	1	...	...	...	...
Subtotal (<i>n</i> = 48; 81.4%)	27	6	...	7	7	1
Boats or canoes						
Leaning out of airboat into water	1	...	...	...	...	...
Getting into boat	1	...	...	...	...	...
Boat	2	...	1	...	...	...
Canoe	1	...	...	...	...	...
Subtotal (<i>n</i> = 6; 10.2%)	5	...	1	...	...	...
Land						
Asleep in tent	...	2	...	...	...	...
Asleep on beach	...	1	...	...	...	...
Asleep near water	...	1	...	...	...	...
Near crocodile nest	1	...	...	...	...	...
Subtotal (<i>n</i> = 5; 8.5%)	1	4	...	...	...	...
Unknown activity (<i>n</i> = 3)	...	...	2	...	...	1
Total No. (%)	33 (76.7)	10 (23.3)	3	7 (50.0)	7 (50.0)	2

to be unique and may not be representative of the usual behavior of saltwater crocodiles toward boats.

In the Northern Territory, crocodiles are an important tourist attraction, and crocodile feeding is undertaken by a number of tourist operators. Crocodiles may jump out of the water alongside a boat to take food being offered. More than half the body length of even large (>4 m) crocodiles may be out of the water during such jumps. One study examined the effect of these feeding activities on the behavior of the crocodiles involved and concluded that the crocodiles were attracted to tourist boats, either visually or by the sounds of the motors, and approached them closely. However, they would not approach smaller boats in the same way.⁶³

The situation with canoes and saltwater crocodiles is considered different from that with boats. There has been one serious attack on the occupant of a canoe in the East Alligator River in 1986, and several unsuccessful attacks are known.^{60,64} In northern Australia, canoeing is not a regular pastime in areas inhabited by saltwater crocodiles, but in other countries where the species occurs, canoes or similar types of watercraft are the main mode of transport. For example, many saltwater crocodile attacks have occurred on people in small perahu (sam-

pans) in the states of Sarawak and Sabah in Malaysia,^{10,65,66} but there have been no reports of such attacks on conventional boats of any size. Guggisberg²⁴ describes how a man in Sudan was taken by a Nile crocodile from a boat as he sat with his legs hanging in the water, but the boat was not the subject of the attack. However, Richardson and Livingstone⁶⁷ report an attack on a small boat. Nile crocodiles have been known to attack rubber boats and canoes and ignore the fleeing occupants.⁶⁸ Conover and Dubow³² reported 2 attacks by American alligators, one on someone "riding a sailboat" and the other on a person "lying on an inflatable raft," but the exact circumstances are not presented. Neill²⁹ reported 2 attacks by alligators on himself as he paddled a small pirogue. Why canoes are attacked more readily than other boats is unclear. However, the profile (silhouette) of a canoe viewed from underwater is very different from that of a boat and may resemble another crocodile or animal swimming in the water.

The fact that 70% of attacks in northern Australia occurred during the day is a reflection of people's activities (Table 3). Similarly, Fergusson⁶¹ reported that 86% of Nile crocodile attacks occurred during daylight hours, reflecting human activity patterns. Saltwater crocodile

Table 4. Months in which saltwater crocodile attacks have occurred in northern Australia, 1971–2004

<i>Month</i>	<i>No. (%) of attacks</i>		
	<i>Nonfatal</i>	<i>Fatal</i>	<i>Total</i>
January	1	...	1 (1.6)
February	5	1	6 (9.8)
March	1	2	3 (4.9)
April	3	1	4 (6.6)
May	3	1	4 (6.6)
June	3	1	4 (6.6)
July	3	1	4 (6.6)
August	2	1	3 (4.9)
September	6	1	7 (11.5)
October*	5	3	8 (13.1)
November	7	1	8 (13.1)
December†	6	4	10 (14.8)
Dry-cool season (May to July)			
Total	9	3	12 (19.4)
Attacks per month	3.0	1.0	4.0
Dry-warm season (August to October)			
Total	13	5	18 (29.0)
Attacks per month	4.3	1.7	6.0
Wet-warm season (November to April)			
Total	23	9	32 (51.6)
Attacks per month	3.8	1.5	5.3
All months	45	17	62

*Eight attacks involving 9 people.

†Ten attacks involving 11 people.

attacks have occurred in all months of the year (Table 4), including the cooler months (May to July) when crocodiles are generally less active. Pooley *et al*⁶⁸ indicated that 39 (91%) of 43 attacks by Nile crocodiles in northern Zululand and southern Mozambique occurred between November and early April, when weather conditions are warm, and coincided with the mating and breeding season. Fergusson⁶¹ reported similar results in attacks from Namibia and Kenya, where 78% of attacks occurred in November to May. In Florida, alligator attacks have occurred in all months of the year, but most (75%) took place in the warmer times of the year.³² In the states of Louisiana, South Carolina, and North Carolina, where winter temperatures are much lower than those in Florida, attacks have only been recorded in the warmer months (May to September)³² (R. Elsey, written communication, September 2004); alligators are generally inactive and/or aestivating in the cold winter months.

Tourist visitation to northern Australia is strongly seasonal, with 50% or more of visits occurring in a 3-month period (June to August). It is not surprising that the pat-

tern of attacks does not follow monthly trends in visitation, because almost all attacks (95%) have involved people who lived in the area or who visited northern Australia regularly and were aware of the potential danger. Only 2 fatal attacks involved overseas visitors (United States, Germany)⁶⁹ participating in tourist-related activities. The nesting season for saltwater crocodiles (October to May)⁸ coincides with the wet season, when outdoor activities such as camping and fishing are not undertaken as frequently as in the dry season. (In the Northern Territory, 87% of mean annual rainfall occurs between November and March.⁷⁰)

Fatal attacks have generally involved saltwater crocodiles longer than 4 m (Table 5) that have the strength and power required to overpower an adult human. Because females do not grow longer than approximately 3 m, all large crocodiles are males.⁸ Nonfatal attacks have usually involved smaller crocodiles (Table 5). Three of 5 nonfatal attacks by crocodiles longer than 4 m have involved victims that received assistance from other people to escape; the attacks would otherwise have resulted in death. The difference in bodyweight between the salt-

Table 5. Mean, minimum, and maximum estimated total lengths and sex of saltwater crocodiles involved in attacks in northern Australia, 1971–2004

Attack type	n*	Total length of crocodile, m			Fe- Male	Un- male known
		Mean	Mini- mum	Maxi- mum		
Fatal	14	4.3	2.7	5.1	12	1
Nonfatal	32	3.0	1.7	5.0	9	1
All	46	3.4	1.7	5.1	21	2

*Sample sizes on which means are based.

water crocodiles involved in nonfatal (3.0 m) and fatal (4.3 m) attacks is great: 100 kg compared with 350 kg.^{8,71} Nonfatal attacks by Nile crocodiles have also involved smaller (2.5 m) animals.⁶⁸ The mean size of American alligators involved in fatal attacks is 3.0 m³² (Florida Fish and Wildlife Conservation Commission, unpublished data, 1928–2004), with animals ranging in size from 1.8 to 3.7 m. The smallest alligator in the series killed a 2-year-old child, and it is unlikely that it would have been able to overpower an adult. Compared with the situation with saltwater crocodiles, relatively small (0.3 to 1.5 m) alligators have been involved in unprovoked, nonfatal attacks,³² which probably reflects the different levels of wariness between the 2 species.⁵⁴

Most attack victims in northern Australia have been males (75%), and the average age of all victims is 31.2 years (Table 6). A similar trend is apparent with American alligator attacks (1948 to 1995), where 84% of victims were male, and the average age of victims was 31.8 years.³² A lower proportion of males (59%) was reported for Nile crocodile attack victims.⁶¹

It is difficult to compare the frequency of crocodile attacks between species and/or countries, largely because of the lack of reporting in many countries, particularly in Africa. Since 1980 (24.4 years), 42 attacks (fatal and nonfatal) by saltwater crocodiles have occurred in Sarawak, Malaysia,⁷² compared with 56 attacks during the same period in northern Australia. Nile crocodiles kill many more people in Africa than do saltwater crocodiles throughout their range. For example, from January 2000 to March 2004 (4.25 years), 23 people were killed and 12 people were injured by Nile Crocodiles in Namibia,⁷³ and during 2.3 years (January 2002 to April 2004), 40 people were killed and 8 people were injured in Zambia.⁷⁴ A preliminary review of attacks by Nile crocodiles, with most records from Kenya and Namibia and for the period of 2000 to 2004, revealed 98 instances.⁶¹

The fatality rate in one American alligator series was

Table 6. Age and sex of saltwater crocodile attack victims in northern Australia, 1971–2004*

Age, y	Male	Female	All
1–10	1	3	4
11–20	4	2	6
21–30	11	3	14
31–40	12	3	15
41–50	3	1	4
51–60	1	3	4
61–70	...	...	...
71–80	1	...	1
Unknown	15	1	16
Total	48	16	64
Mean	31.8	29.9	31.2

*The 62 attacks involved 64 people.

5.8%⁷⁵; in another series of attacks that involved the same species (184 attacks; 1948 to 1995), 8 fatalities (4.3%) occurred.³² The Florida Fish and Wildlife Conservation Commission's records indicate a fatality rate of 6.6% (16 of 242) for unprovoked alligator attacks in Florida (1948 to mid-2004) but consider this an overestimate, because minor injuries that do not require medical attention are more likely to have been recorded in recent years than previously. These rates are lower than the 27.4% for our series of attacks by saltwater crocodiles in northern Australia (Table 1), the 50% mortality rate reported in Sarawak, Malaysia,¹¹ and the 36% reported in Sabah, Malaysia.⁷⁶ The relatively high fatality rate due to Nile crocodiles in Namibia (66%)⁷³ may be overestimated, because minor injuries from attacks, particularly in remote areas, tend not to be reported (P. Lindeque, written communication, September 2004). The same may apply to Zambia (83%),⁷⁴ with perhaps as many as 80% of minor, nonfatal attacks not being reported (G. Kampamba, oral communication, September 2004). As a result, the fatality rate (63%) reported by Fergusson⁶¹ for Nile crocodiles may also be overestimated.

Medical literature

The medical literature on crocodilian attacks remains scanty, limited to 2 larger series from northern Australia (16 patients)⁷⁷ and southern Malawi (60 patients)⁷⁸ and a number of case reports.^{79–88} Some additional series and case reports can be found in the herpetologic literature,^{19,26,86,88,89} and various accounts of attacks that describe injuries are in the general literature.^{10,24,29,54,76,90,91}

In the Australian series,⁷⁷ 16 cases are reported (13

men and 3 women) with 4 fatalities. Eight persons (all fatalities) were intoxicated; 10 attacks occurred in low light or at night; 11 occurred in the wet season; half occurred in remote areas, more than 150 km from the treating hospital; and more than half of the survivors developed significant wound infections.

In the Malawian series of 60 cases during a 4-year period, a similar male predominance is observed: 47 males, 10 females, and 3 children (sex not provided) were attacked.⁷⁸ The average age was 37 years, with a range of 9 to 70 years. Less than half of the individuals²⁸ arrived at the hospital within 24 hours of the injuries being sustained. Patients underwent an average of 4 surgical procedures each, and 40% of all discharged were left with “permanent deformities.”

The true number of global crocodilian attacks and the associated medical burden are difficult to quantify. Many attacks occur in remote areas and go unreported. Even in areas where attacks are common, the overall incidence of bites is difficult to assess; people with fatal injuries are rarely brought to the hospital. Assessment of fatalities can be even more problematic. Without autopsy, determining whether injuries on a cadaver were the cause of death or were inflicted following death may be impossible.³²

Animal behavior and crocodile attacks

An understanding of the motivation behind crocodile attacks on humans and the manner in which crocodiles attack humans allows better planning for treatment of injuries and preventive policy. Crocodilians are most likely to attack “out of the blue,” with a combination of “stealth, surprise, and a sudden final burst of speed.”⁴⁹ In a number of series, victims report having no idea of the presence of an alligator or a crocodile before the attack. Crocodilians use a variety of methods to take large prey. When prey is at the water’s edge, the crocodilian will typically lunge out the water at high speed and seize it with great force and considerable tenacity.^{24,39} Once the prey is grabbed, it may be unbalanced and dragged back into the water. Here, the crocodilian may roll its body over and over—the rather dramatically named *death roll*—which subdues prey through disorientation and hypoxia and also assists in breaking it up into more manageable pieces. Crocodiles will also lunge at large prey swimming in the water, and the attack is more likely to be successful, because the prey is already unbalanced and has no footing on which to gain purchase and resist the crocodilian. A sideways snap may also be used to grab prey.

Pathology of crocodilian attacks

MORTALITY

In the only reported Australian series to date,⁷⁷ cause of death was attributed to either decapitation or truncal transection (Figure 2). It should be assumed that massive blood loss⁹⁰ and drowning are the cause of death in a large number of crocodilian attacks. Assessing the actual cause of death can be complicated by the fact that bodies are sometimes not found, have been eaten, or are decomposed to an extent that makes cause of death difficult to ascertain. Mercifully, death appears to be swift, with little or no bruising seen on postmortem examination. If the initial attack is survived, a further risk of death from sepsis exists. In the Malawian series of 60, there was 1 death from sepsis; the authors attribute their success to early aggressive surgery and broad-spectrum antibiotics.⁷⁸

GROSS PATHOLOGY

The patterns of injuries inflicted by crocodilians occupy a wide spectrum in both nature and severity. The power and size of some animals are such that, if not lethal in the first instance, injuries can be as severe as those seen in major road trauma or in the military arena. Injury mechanisms are often a combination of penetrating, blunt, and shear forces, and this should be considered when evaluating wounds.

The most common injuries sustained in a crocodilian attack are serious soft tissue and bone injuries, most often of the extremities. Complex compound fractures and tissue loss are not uncommon in the more severe attacks. In the Malawian series, 40% of patients were left with permanent deformities, with the average patient undergoing 4 procedures during a 31-day hospital stay.⁷⁸ Crocodilian teeth are conical in shape and designed for penetration and holding,⁸ so most wounds are initially deep punctures. The interdigitating teeth of crocodiles in particular can inflict slash wounds. Most attacks occur in the water or at the water’s edge, and prolonged time underwater can result in drowning.

Although the most extensive injuries are frequently penetrating, consideration should be given to the added effect of the blunt force applied. This can devitalize large areas of tissue that surrounds penetrating injuries, rendering them even more susceptible to infection and delaying wound healing. Blunt injury can also be inflicted by the tail.

The anatomical area of the body affected by attacks appears to have a pattern of convenience—the animal will grasp whichever part of the person’s anatomy is presented. In the largest series of injuries inflicted by

Nile crocodiles that describes sites of injury, legs and arms accounted for more than 80% of soft tissue injuries.⁷⁸ In the largest series of alligator-inflicted injuries,³² this pattern of extremity injury is repeated, with 88% of injuries (where the site was described) affecting upper⁹¹ and lower ($n = 75$) limbs. Wounds of the torso and head or neck accounted for 8.4%¹⁶ and 4.2%,⁸ respectively. Injuries to upper and lower limbs, including amputation, are well described elsewhere,^{24,54,81,82,85,90} as are injuries to the chest,⁷⁷ head,^{77,81} and groin.⁸³

MICROBIOLOGICAL PATHOLOGY

In common with most carnivorous predators, bites from crocodilians must be assumed to be heavily soiled with a wide variety of bacteria. Compounding the problem of microbial load are the warm temperatures at which these wounds are inflicted, optimizing growth conditions. The first report⁴⁷ of oral flora of 2 captive alligators yielded *Clostridia*, enterococci, and *Citrobacter*, but these were not fully characterized. *Salmonella* has been reported in one series.⁸¹ Further case reports describe the frequency of *Aeromonas hydrophila* infection following alligator bites.^{86,87,92} One study of American alligators captured for the purpose of examining their oral flora also confirmed the presence of *A. hydrophila* in 9 of the 10 alligators assayed.⁸⁴ It is not clear whether similar microbial fauna contaminate the oral cavities of antipodean crocodilians, because similar studies have never been completed. In the only reported Australian series, similar microorganisms were isolated from wounds, but it is possible that these were environmental contaminants.⁷⁷ Whether the microorganisms isolated were from infected bite sites or clean wounds was not documented. Of note in this series, *Burkholderia pseudomallei* was also isolated from the wound site and blood of one case, the only such transmission of infection by this microorganism ever reported. In general, delayed wound healing and recurrent infections are the norm with crocodile bites.

The most prevalent species identified in the mouth and cloaca of captive and wild *C. porosus* and *C. johnstoni* were *A. hydrophila* and *Pseudomonas aeruginosa*, both found in 64% of crocodiles examined, followed by *Proteus vulgaris* (51%), *Proteus mirabilis* (38%), *Salmonella* spp. (36%), and *Proteus penneri* (33%).⁹³ Other gram-negative species identified included *Acinetobacter johnsonii*, *Bacillus* spp., *Budvicia aquatica*, and *Yersinia intermedia*.

The management of crocodilian injuries

Given the unusual nature of injuries sustained from crocodilian attacks, it is not surprising that the literature re-

garding their management is sparse. The management principles of crocodilian attacks can be compared with the management of shark attacks⁹⁴; the same problems of potentially massive injuries, sustained in remote areas, with subsequent virulent wound infection occur. Some shark attacks happen in areas frequented by surfers and bathers and therefore patrolled by lifeguards. They in turn are in a position to provide basic, and in some cases advanced, life support interventions. Crocodilian attacks, however, almost always occur in areas well away from such basic interventions.

PREHOSPITAL

The prehospital management of injuries inflicted by crocodilians can affect not only survival from the attack but also long-term morbidity. Initial resuscitation must be directed toward securing an airway and circulation management. In the prehospital phase, the patient should be rapidly removed to a place of safety well away from the water before treatment is commenced. Following a period of prolonged submersion, basic airway maneuvers, the clearance of inhaled or aspirated detritus from the upper airway, and even mouth-to-mouth ventilation may be required. Penetrating chest wounds should be bandaged with simple occlusive dressings taped on 3 sides, particularly if there is an air leak, to mitigate against the possibility of tension pneumothorax. Once the airway and breathing have been secured, hemostasis should be sought. Hemorrhage from vascular structures, where visible, should be controlled through direct pressure and, if required, wound packing combined with elastic bandage dressing.⁹⁵ Although the use of tourniquets in the military environment has recently been re-examined,⁹⁶ the evidence does not exist to either support or refute their use in the civilian environment, and the potential hazards are well described.⁹⁵ Considerable bleeding can occur from long bone and pelvic fractures. Long bone fractures should be reduced and splinted, and the pelvis should be strapped should a major fracture be suspected. This will not only minimize bleeding but also facilitate the transportation of patients to a point of definitive care. Evacuation can be problematic, because contacting emergency services with standard communication devices is often impossible due to the remote location of the attack. Emergency personal beacons have been used to good effect in remote outback Australia.⁹⁷

Prehospital care does not stop with addressing the airway, breathing, and circulation. Early methodical wound care, particularly (as is often the case with these injuries) if a delayed field extrication is anticipated, can help minimize later morbidity. Wounds should be irrigated with copious volumes of at least potable water—with soap or

disinfectant where available—and dressed with sterile dressings. The role of prehospital prophylactic antibiotics is unproven but may be considered if delay to extrication appears to be extending to days. Amoxicillin-clavulanate, azithromycin, and ciprofloxacin may all provide some protection from wound infection.

HOSPITAL

An attack by a fully grown crocodile or alligator usually results in serious injuries. Clinicians should be alert to the common pitfall of assuming that the most obvious and frequently massive injuries with which they are presented are the only ones present.

Once patients arrive in the hospital, unless they appear to have sustained minimal injuries and are cardiovascularly stable, management should be in the operating room. Plain radiographs should be taken of the injury sites to examine for fractures, periosteal stripping, or tooth fragments. Wounds associated with joints should be assumed to be intra-articular until local exploration proves otherwise. A strong argument can be advanced for obtaining a head computed tomographic scan on all patients who have sustained an injury to that region to rule out an intracranial injury. In remote hospitals where computed tomographic scanning is not available, there may still be some merit in obtaining skull radiographs.

All wounds should be considered heavily soiled and further compromised by the crushing forces generated by the bite, devitalizing tissue. In the hospital, exploration of all wounds should be encouraged, and surgical debridement of dead and threatened tissue should be undertaken in all patients. Topical antiseptics has been shown to be of some value in simple abrasions,⁹⁸ but in the deep puncture wounds generally created by crocodilians, their efficacy remains unproven.

The role of routine wound cultures and prophylactic antibiotics remains contentious. The routine culturing of wounds in general has limited value in predicting whether an infection will develop or not.⁹⁹ Some organisms that might be anticipated are fastidious, and a negative culture result might give a falsely reassuring result. Where there is a clinical suspicion of infection or in high-risk patients (such as those with diabetes), wound cultures might be of value. Similarly, there may be some role for simple quantitative culture of wound sites and debrided tissue. Wounds that have begun to show evidence of infection should be swabbed and sent for both aerobic and anaerobic culture. The microbiologists should be advised of the nature of the specimen in advance so that the appropriate selective media can be used. Prophylactic antibiotics have been recommended in certain high-risk situations for mammalian injuries,¹⁰⁰

and adopting at least these guidelines seems prudent. These situations include hand injuries, prolonged delays before definitive care, and crush injuries. The choice of antibiotics is at best empirical and will depend to a certain degree on local microbial flora. The authors of the Australian series recommend ceftazidime to cover the locally endemic *B pseudomallei* (and most *Aeromonas* spp.), penicillin for clostridial infections, and metronidazole for anaerobic infections.^{77,79} Flucloxacillin or an equivalent might be considered for skin commensals. Antibiotic choice should be altered according to culture sensitivities. If there is uncertainty about tetanus status, 250 to 500 U of human tetanus immunoglobulin and 0.5 mL of diphtheria tetanus toxoid should be administered in separate arms.

Given the grossly contaminated nature of all of these wounds, secondary closure should be considered in all cases. More than half of the cases where clinical details are recorded report wound infections. Neurovascular injury should be identified, and a number of surgical specialties (orthopedics, vascular) may need to be involved early in the person's care. Both the surgeon and the patient should anticipate the need for multiple surgical procedures.

REHABILITATION

The devastating nature of attacks caused by crocodilians usually results in a prolonged and often difficult period of rehabilitation. Regular physiotherapy for several months following injuries, punctuated by return to surgery for further debridement, is not uncommon. The psychological impact of such an event should similarly not be underestimated, and posttraumatic stress disorder symptoms should be anticipated and addressed.¹⁰¹ Management of the psychological impact of such large animal attacks is underreported and worthy of further study.

Prevention

The prevention of crocodile attacks can be considered as primary (avoiding an attack altogether) and secondary preventive techniques (minimizing the harm and complications after an attack has occurred). Primary prevention involves minimizing contact between humans and crocodilians. A wide variety of factors bring the 2 parties together, including the growing populations of both humans and crocodilians. In the developing world, circumstances can force humans into close proximity with crocodilians. In Tanzania in 1994, failure of the town water pump in the Korogwe district forced villagers to seek water from the crocodile-infested Pangani River, with a subsequent surge in crocodile-related injuries and

deaths.⁹² Movement of refugees in Africa into lands with which they are unfamiliar and pressure to reclaim marshland to grow cash crops have also been blamed for human encroachment on crocodile territory. In the developed world, the increased interest in outdoor adventure sports and so-called eco-tourism brings more people into contact with crocodiles, reducing the latter's natural apprehension for their only other predator.

Crocodiles are also increasingly encroaching on human territory. Since protective legislation was introduced in Australia and the United States in the 1970s, the numbers of crocodiles and alligators, respectively, has increased sharply, and sophisticated management programs are in place.^{102,103} The success in conservation has required the introduction of rational techniques in controlling populations and individual nuisance animals. In 1989, the Florida Fish and Wildlife Conservation Commission was receiving approximately 7000 nuisance alligator complaints per annum. In 2001, it received 16 749 complaints.⁶³ In the United States, trappers are typically employed to capture nuisance alligators, whereas in Australia, wildlife rangers are currently responsible for the capture and removal of problem saltwater crocodiles.^{51,104–106}

As is the case with many pathologic entities, secondary preventive interventions in mitigating the consequences of a crocodilian attack are far less satisfactory than the methods outlined herein. The unanimous advice for defending oneself against an attack appears to be to fight back. Survivors in Malawi and Australia all attribute their successful escapes to vigorously resisting the attack. Gouging the crocodilian's eyes appears to be an effective action.⁹⁰ It has been suggested that if your hand is trapped in the mouth of the crocodile, reaching in to displace the palatal valve and cause the crocodile to aspirate water is effective. This has resulted in success in at least one case reviewed.⁸⁰

A number of precautions can be taken to avoid adverse interactions with crocodiles.^{39,68,91,107} If venturing into areas that may contain crocodiles, it is advisable to contact the local wildlife authorities beforehand for relevant information about crocodiles in the area. Warning signs posted near waterways should be heeded.¹⁰⁴ If camping near bodies of water that contain crocodiles, camp should be set up some distance from the water's edge, and individuals should be particularly careful about venturing near the water. Water should be collected from a different spot each time, and no food scraps (eg, fish carcasses) that may attract crocodiles should be left behind. Swimming or wading should be avoided.

The fact that crocodiles cannot be seen in a particular body of water does not mean that they are not there, and caution should always be exercised. Unfortunately, the

effects of alcohol may affect people's behavior—at least 29% of the attacks in our series involved alcohol consumption.

Unless provoked, wild Australian freshwater crocodiles (*C johnstoni*) are generally considered harmless to humans and live in many areas visited by tourists and locals for recreational purposes. However, the long-term absence of saltwater crocodiles cannot always be guaranteed, even in habitats considered to be optimal for freshwater crocodiles.¹⁰⁸ For example, an intensive capture program for freshwater crocodiles in the McKinlay River area (Northern Territory) in 1978 to 1988 revealed no saltwater crocodiles in the river system. In 2001 to 2002, when the catch program was reinitiated, saltwater crocodiles (<4 m long) were recorded in various billabongs. Movement of saltwater crocodiles into these upstream habitats typically occurs during the wet season, when the isolated, dry season billabongs are joined as one waterway.

Conclusions

Crocodilians are opportunistic predators that are most dangerous in water and at the water-land interface,⁸ as confirmed by analysis of attacks by saltwater crocodiles, Nile crocodiles, and American alligators. Because of its highly territorial nature,⁵⁴ the saltwater crocodile is often described as the most dangerous of all crocodilians. Notwithstanding incomplete reporting of attacks, the Nile crocodile is responsible for more human fatalities than other crocodilians because of its wide distribution in Africa⁵ and the reliance by local communities on the same waterways inhabited by the species.

In northern Australia, the incidence of saltwater crocodile attacks has increased in recent years in part because of increasing populations of crocodiles in each state or territory.^{51,105,109} This situation is also apparent in other parts of the world, where successful conservation and management measures are leading to the recovery of crocodilian populations. Increases in human populations, development of habitat, and the increased popularity of water-based recreational activities are also cited as factors that lead to increased human-crocodilian interactions. When crocodilian populations are small and perhaps endangered, the community's view is generally positive toward their conservation and population recovery. However, once population recovery becomes apparent, the community's view may reverse, particularly if interactions between people (and livestock) increase and recreational activities such as swimming are restricted. At the 13th Conference of the Parties to CITES, a number of countries raised concerns regarding possible

loss of community support in the face of increasing crocodilian populations.¹¹⁰

Loss of community support has been recognized by the Crocodile Specialist Group of the Species Survival Commission of the IUCN-World Conservation Union, which established a Human-Crocodile Conflict Working Group in 2002. The aims of the Human-Crocodile Conflict Working Group are to develop guidelines on the prevention and management of human-crocodile conflicts for wildlife authorities, to develop a database on crocodile attacks based on formal reporting, and to develop a fact sheet that combines information from the guidelines and database to assist developing countries.¹¹¹

Outside the United States and Australia, detailed statistics on attacks are less reliable. Even in Australia, a more formal reporting format that attempts to link medical information to the circumstances and details of attacks would be useful. A crocodilian attack registry, similar to the International Shark Attack File, could provide invaluable herpetologic, ecologic, and clinical data regarding the best options for wound care, antibiotic choice, and other problems. Further studies are needed to elucidate the nature of the oral flora of Australian crocodiles, as have been completed for American alligators. Studies are also required to further delineate the likely organisms associated with crocodilian bite infections.

Acknowledgments

We thank Ruth Elsey and Allan Woodward for provision of data on alligator attacks and Mark Read for information on Queensland attacks that allowed data in the Crocodylus Park database to be verified.

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