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FORENSIC METHODS FOR CHARACTERIZING WATERCRAFT FROM WATERCRAFT-INDUCED WOUNDS ON THE FLORIDA MANATEE (*TRICHECHUS MANATUS LATIROSTRIS*)

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Abstract

Watercraft-related mortality represents 1,253 (24.9%) of 5,033 Florida manatee (*Trichechus manatus latirostris*) deaths recorded between 1 January 1979 and 31 December 2004. Wound patterns generated by collisions with watercraft are diagnostic. Sets of cuts and scrapes that are roughly equidistant and perpendicular to the direction of vessel travel are consistent with lacerations made by propeller blades. From these lesions, estimates of propeller diameter, pitch, rotation, and direction of travel may be obtained. Considerable overlap of propeller sizes and pitches on different size vessels, common use of counter rotation propellers, and numerous other complicating factors may confound efforts to accurately predict vessel size and type from propeller wounds. Of the more than one million watercraft registered in Florida, 98% are ≤12.2 m (40 ft), yet watercraft 5.3–36.6 m (17.5–120 ft) are known to have killed manatees. Analysis of a 5-yr subset of mortality data suggests that a disproportionate number of propeller-caused watercraft-related mortalities could be attributed to propeller diameters ≥43.2 cm (17 in.), inferring that these were caused by watercraft ≥12.2 m (40 ft).

Key words: forensic methods, watercraft-induced wounds, Florida manatee, *Trichechus manatus latirostris*, propeller wounds, trauma.

Introduction

Responsibility for the manatee carcass salvage program was assumed by the State of Florida in July of 1985. The Florida Fish and Wildlife Conservation Commission's Marine Mammal Pathobiology Lab (MMPL) operates the program. The MMPL currently collects and necropsies between 300 and 400 manatee carcasses annually.

The most common anthropogenic cause of death, and the focus of this report, is watercraft-related death, which accounted for 1,253 (24.9%) of the 5,033 manatee deaths between 1 January 1979 and 31 December 2004. Because of the endangered status of manatees and the ever-increasing numbers of power boats in Florida waters, reaching a better understanding of the types of boats involved in collisions with manatees is very important.

The methods described here are used to characterize watercraft-related wounds from which estimates of watercraft size can be inferred. This work addresses Objective 1.5.1 of the Florida Manatee Recovery Plan (U.S. Fish and Wildlife Service 2001), the goal of which is to find ways to reduce manatee deaths related to very large vessels. This report also addresses Objective 2.4.2, the goal of which is to improve the evaluation and understanding of injuries and deaths caused by watercraft.

Manatees killed by boats, barges, ships, tugboats, or any other type of watercraft are placed in the watercraft-related mortality category. These deaths may result from propeller wounds, propulsion machinery or hull impacts, crushing, or any combination of the three (Lightsey *et al.* 2006). The objectives of this paper are to describe the forensic analysis methodology used at the MMPL to characterize the vessel and if possible suggest a range in size of the responsible watercraft; and to apply the methodology to a historical data set in order to determine a measure of watercraft-related mortalities that were caused by very large (≥76.2 cm [30 in.] diameter) propellers of vessels typically ≥19.8 m (65 ft).

Characteristics of Watercraft-Related Trauma

Watercraft can inflict both sharp- and blunt-force trauma. Sharp-force trauma involves injuries from sharp skegs, fins, and propeller blades (Fig. 1A–G). Blunt-force

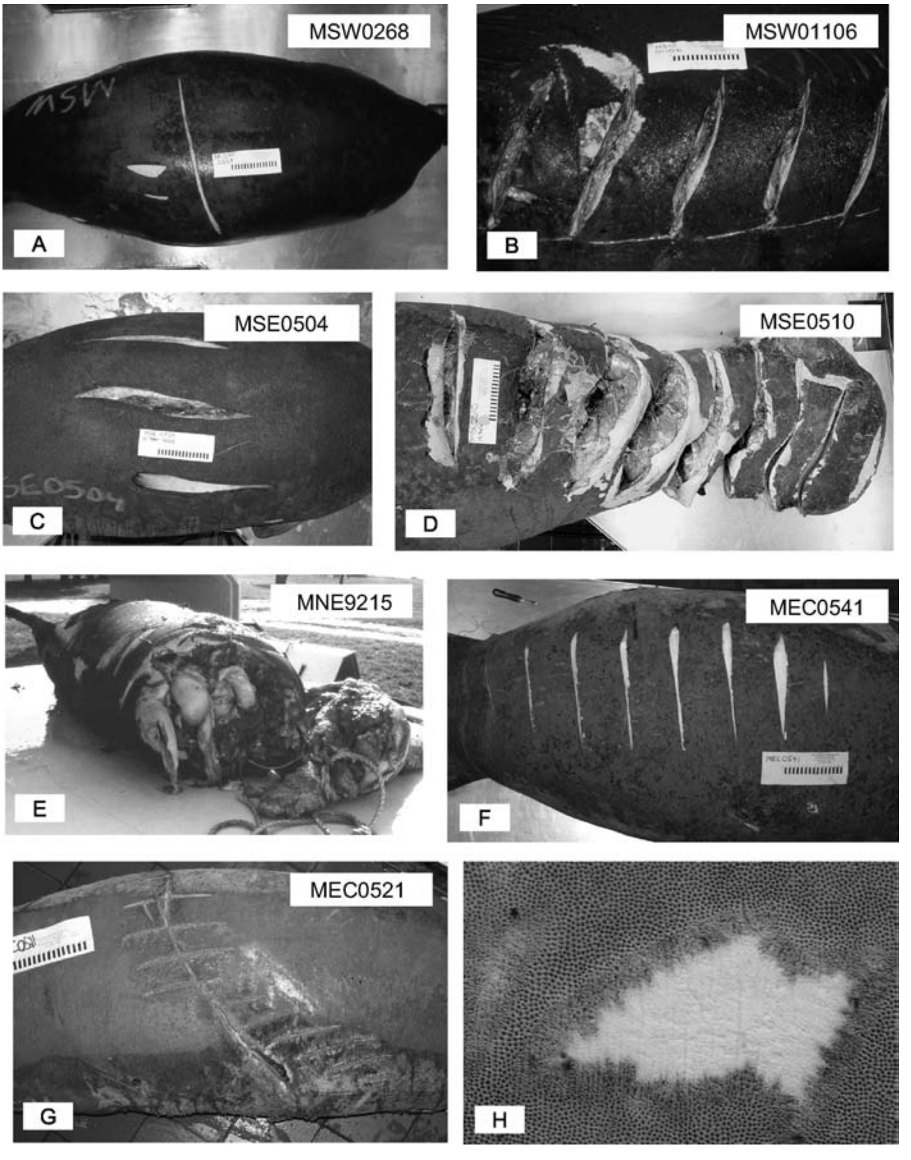

Figure 1. Photographs illustrating externally visible watercraft-caused ante-mortem trauma on manatee carcasses; 15 cm scale. (A) A long superficial linear wound and two smaller superficial cresentic propeller wounds. (B) Five propeller wounds each of which penetrated the skin (epidermis & dermis) and some of the underlying tissues. (C) Three propeller wounds, the middle one of which penetrated the skin and underlying tissues, the others of which only penetrated the epidermis. (D) Deeply penetrating propeller wounds some of which partially transected the peduncle and fluke. (E) Adult carcass transected by a very large propeller (carcass diameter at cut, approximately 70 cm [27.6 in.]). (F) Eight superficial propeller wounds, which only penetrated the epidermis. (G) Resolving propeller wounds and associated linear lesion. (H) Healed scar (note the smooth texture of the scar in contrast to the dimpled appearance of the adjacent epidermis).

trauma involves injuries from hulls, keels, blunt skegs and propellers, boat strakes, anti-ventilation plates, trim tabs, propeller shafts, struts, rudders, propulsion system torpedoes, or speedometer pickups (Fig. 2). In part because the dermis is so tough, slightly more than half of the lethal trauma inflicted on manatees by watercraft is blunt-force trauma (Lightsey *et al*. 2006).

Linear cuts or scrapes (Fig. 1A, 3A) roughly parallel to the direction of vessel travel are caused by watercraft projections (Fig. 2) that are dragged across the manatee. Interestingly, speedometer pickups and twin engine rudders are typically positioned off center, whereas keels and single engine skegs are commonly on center. Twin drive configurations have twin skegs that are off center. Propeller-driven watercraft may be configured with outboard engines (Fig. 2A), sterndrives (Fig. 2B), or fixed propeller shaft inboard engines (Fig. 2C). Each configuration has a propulsion system that varies in design and size (Snyder 1992).

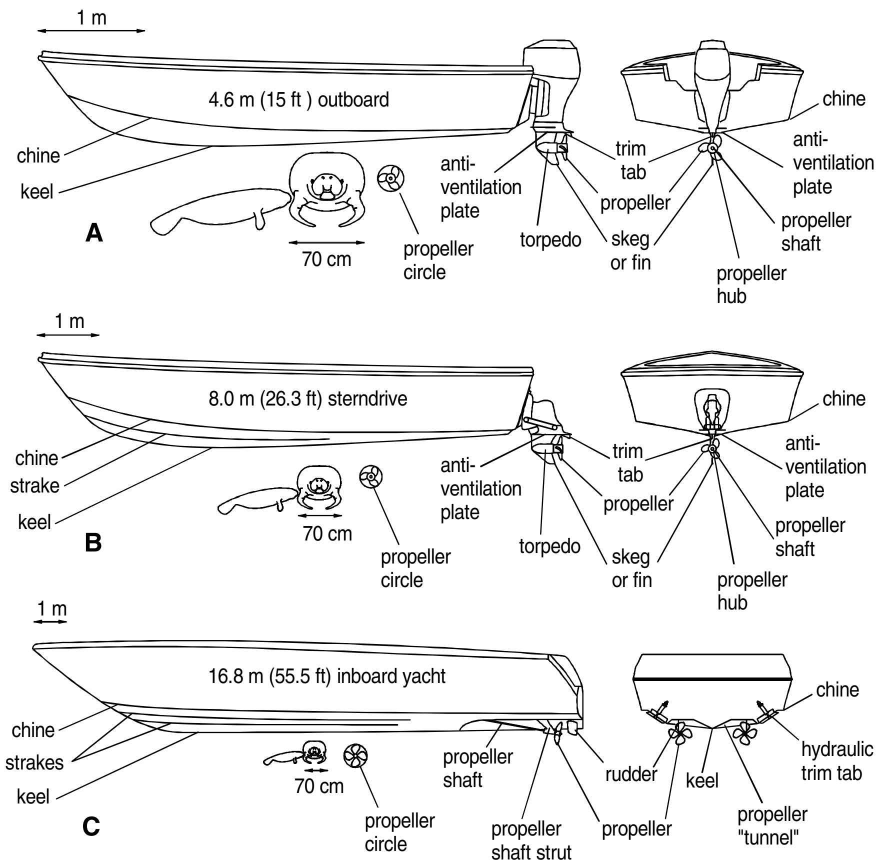

Figure 2. Watercraft hulls, propulsion units, and structures extending from them that can inflict wounds on manatees. A, B, and C watercraft with lengths of 4.6 m (15 ft), 8 m (26.3 ft), and 16.8 m (55.5 ft), respectively. An adult manatee (70 cm [27.6 in.] in diameter) with a nursing calf (130 cm [51.2 in.] in length) are illustrated in each drawing to provide scale for each of the watercraft and propellers shown.

Materials and Methods

A propeller wound or scar pattern (Beck *et al.* 1982, Bonde *et al.* 1983) may be composed of relatively parallel, approximately equidistant, and typically curved (at least on wounds from smaller propellers) lesions (Pitchford *et al.* 2001, 2002), all assumed to be related to the same event (Fig. 1, 3, 4). Gross appearance of a wound changes dramatically in a short period of time. Thus, patterns generated at different times vary in color, texture, pigmentation, granulation, and soforth. At necropsy, distinct wound and scar patterns are identified, and the total number of patterns is noted in the narrative report.

Definitions

Wounds—Each lesion suspected to be involved with the proximate cause of death is numbered. If there is a sequence of parallel lesions, such as those made by a single propeller pattern, each lesion is numbered consecutively (Fig. 4 D, E). The numerical sequence in which the wounds are labeled represents the order in which they were measured, not the order in which the wounds occurred. In some cases, the skin is removed from the carcass and manipulated on flat and curved surfaces in order to further analyze the pattern (Fig. 3D, G).

Wound axis—If there are two or more propeller cuts, a wound axis may be determined (Fig. 4D). The wound axis is a line passing through roughly the center of each cut in the series and is an estimate of the travel path of the watercraft and its propeller. If a substantial percentage of the length of the propeller blade is involved, then the entry point of each cut—essentially a compressive event—may have different characteristics from the exit point—essentially a tensile event.

Length—Using calipers, the length of each cut is measured in a straight line. This measurement provides a projection of the wound and is a better representation of the device that caused the wound than is a curvilinear measurement.[5]

Width—Width is the widest part of each lesion. It is measured roughly parallel to the wound axis and is a measure of wound gape and of differences in distortion in the wound pattern.

Depth—Depth is the maximum depth of a cut. A lesion penetrating into the body cavity or through an extremity is recorded as "through."

Distance or cut span—Distance or cut span is the distance, along the wound axis, between successive cuts in a single pattern and is measured from leading edge to leading edge or from trailing edge to trailing edge.

The accuracy of these measurements is degraded by postmortem distortion of the carcass. The values for each measurement may vary considerably within a single pattern because of body curvature, relative speed and direction with respect to the boat, changes in the operational characteristics of the propeller or boat during the event, or movement of the manatee during impact.

[5] In a May 2005 workshop on watercraft-related propeller wounds held at FWC, Fish Wildlife Research Institute, additional measurements were suggested. The MMPL is now using new data sheets to collect additional information from each propeller wound in an effort to better determine watercraft characteristics. These measurements include angle between wound axis and propeller cut, depth below chord as well as cut depth, and penetration angle as affected by propeller blade rake, propeller shaft angle, and boat attitude angle. Wound length has been renamed to chord length.

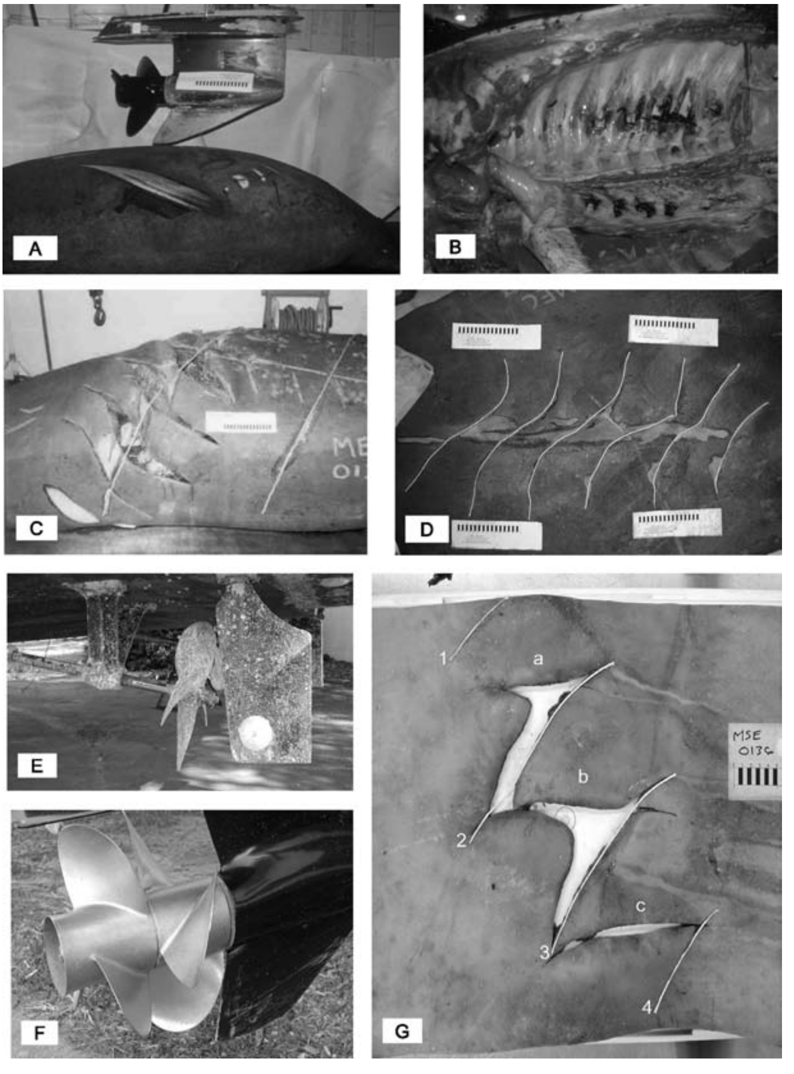

Figure 3. Analysis of skeg and propeller wounds. (A) Photograph of the surface scrapes found on carcass MSW0079. The vessel that struck this manatee was a 6.7-m (22 ft) sterndrive, traveling at 11.2 m/s (25 mph) in 3 m (10 ft) of water. A lower unit similar to that causing the wounds is suspended above the carcass. (B) Photograph of some of the internal injuries (broken ribs, lacerated lung, lacerated parietal pleura, blood clots, hemorrhage) associated with the apparently superficial wounds (the head is to the left, the damaged lung is reflected to the opposite side). (C) Photograph of a series of fresh propeller wounds made in manatee carcass MEC0127. (D) Photograph of the skin (placed on a flat surface) from the carcass in C. (Note that the skin may darken when it dries.) Strings were placed on the lesions to make them more visible. (E) One of a pair of large-diameter propellers with rudder, an example of a drive system consistent with the wounds illustrated in C & D. (F) A photograph of counter rotating propellers on a single shaft; a configuration similar to this caused the wounds illustrated in G. (G) The skin from the wound region of MSE0136 arranged on a flat surface to help analyze the wound pattern. The letters and numbers represent two sets of cuts, which were made during the same event.

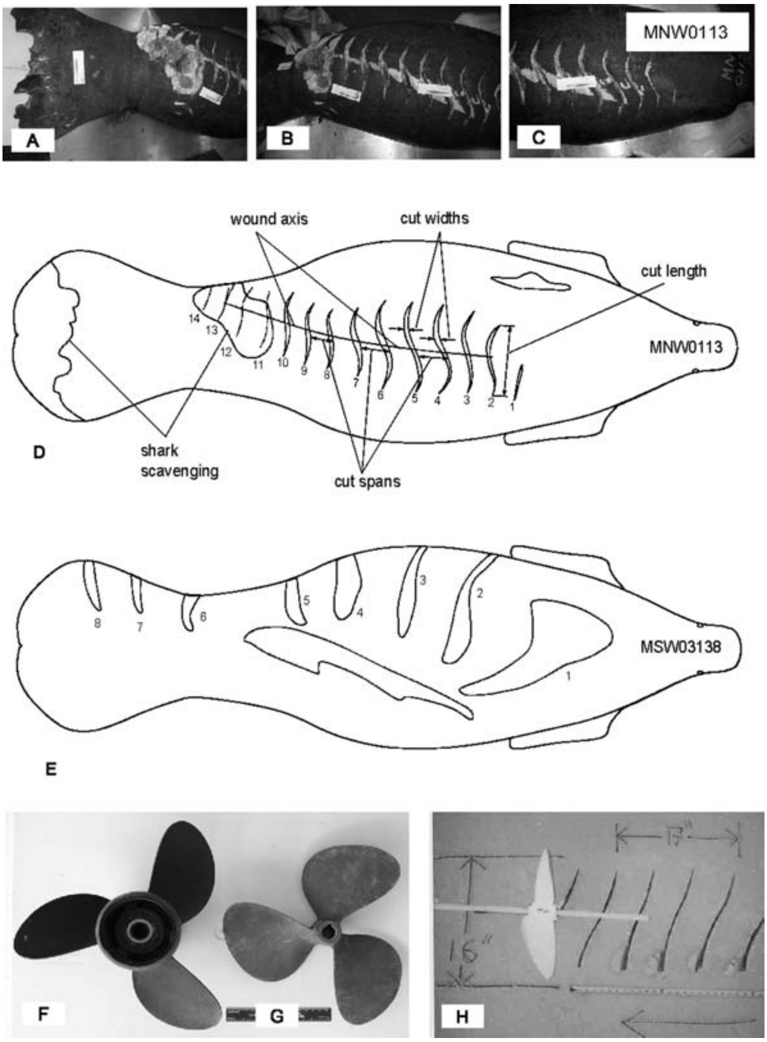

Figure 4. Propeller cut patterns and propellers. (A–C) Photographs of a watercraft-related wound (MNW0113) pattern consisting of, roughly equidistant lesions and a single linear lesion. In addition, sharks have scavenged the fluke and parts of the wound. (D) Wound sketch of MNW0113 drawn during necropsy. (E) Wound sketch of carcass MSW03138 illustrating that successive propeller cuts can have different spacing and orientation. Propeller blade shape and dimensions vary; even propellers of roughly the same diameter can have different shapes, depending on the application as illustrated in the next photographs. (F) Photograph of a fast, right-handed, exhaust-through propeller from an outboard engine. The engine exhaust exits in the region between the shaft and the outer hub (base of the blades). (G) Photograph of a slow, left-handed propeller from a sail boat. Because of the large diameter of the hub, the propeller on the left will have a smaller percentage of the overall diameter in blade length than the propeller on the right. (H) Photograph of impressions in sand made by a right-handed propeller, illustrating how rotation and pitch influence propeller patterns. The three-bladed propeller with diameter 16 in (40.6 cm), pitch 17 in (43.2 cm), has moved from the right to the left. Note that each entry cut (top of pattern) is cleaner than the exit cut (bottom of pattern).

Table 1. Tabulated information on vessel characteristics collected from vessel operators who reported the incidents. Inboard? may mean either sterndrive or straight shaft inboard propulsion system. Outboard? may include true outboards or sterndrives.

Field ID	Year	W/C cause	Vessel type	Vessel size (ft)	Propulsion type	Speed (kts)	Longest cut (cm)
M7834	1978	—	Planing	46	Inboard	18	—
M155	1979	Propeller	Displacement	40	Inboard	—	60
MSW081	1986	Both?	Planing	24	Outboard	—	—
SWFTM8656	1986	Propeller	—	43	Inboard?	—	Yes
MSW180	1988	Propeller	Planing	36	Outboard?	—	18
MSW214	1989	Impact	Planing	18	Outboard	35	None
MNW9017	1990	Impact	—	41	Inboard	22	None
MSW9113	1991	Impact	Planing	20	Outboard	20	None
MSE9219	1992	Propeller	Planing	40	—	25+	112
MSW9431	1994	Impact	Planing	17.5	Outboard	On plane	None
MEC9547	1995	Impact	Barge	120	—	—	None
SWFTM9905	1999	Propeller	Planing	45	Inboard	18	50
MNW9929	1999	Impact	Planing	18	Outboard	30–35	None
MSW0079	2000	Impact	Planing	22	Outboard?	25	None
MSE0009	2000	Both	Planing	25	Outboard	20–25	16
MEC0143	2001	Propeller	Planing	56	Inboard	23	61.9
MEC0220	2002	Impact	Planing	18–20	—	35–40	None
MEC0244	2002	Propeller	Planing	21	Outboard	Onto plane	22.6

Scars—Scars (as used here) are grossly visible dermal lesions that are in the process of healing or are healed (Fig. 1G, H), and which are unlikely to be associated with the proximate cause of death. However, in chronic cases, the original incident is defined as the cause of death.

Healing scars may have rough or granular margins and a pink, white, or yellow color. Most healing scars repigment unless the wound was initially very deep or very wide. Older scars can be recognized by their texture and striated appearance (Fig. 1H).

Propeller Characterization

Verification via known vessel—To date there have been eighteen watercraft-related mortalities in which the offending vessel was reported and identified (Table 1). These vessels range from 5.3 m to 36.6 m (17.5–120 ft). There is limited information about propeller size in these cases.

Very large vessels versus *very large propellers*—Propeller characteristics vary considerably with respect to vessel size and engine configuration; by inference we can estimate vessel size or type from our observations of wound morphology.

Manatees are not large enough to completely characterize most of the properties of very large propellers. For this study, very large propellers are defined as those large enough to either transect the thoracoabdomen of an adult or subadult carcass or produce wound lengths approaching the diameter[6] of the carcass itself (Fig. 1E). Almost 99% of the more than one million watercraft that are registered in Florida

[6] A typical adult manatee can be 300 cm (9.8 ft) long and have a maximum diameter of approximately 70 cm (27.6 in.). Extremities may be transected by smaller propellers.

are <19.8 m (65 ft). These vessels typically have propeller diameters ≤ 71.1 cm (28 in.). Watercraft with propeller diameters ≥76.2 cm (30 in.) are typically mega yachts, ships, and tug boats.

Theoretical considerations— To produce forward motion, propellers rotate clockwise or counterclockwise on their shafts (Avallone and Baumeister 1996, Snyder 1992). When viewed from the back of a boat, a right-handed propeller screw advances when turned clockwise (Fig. 4F) and a left-handed screw when turned counterclockwise (Fig. 4G). The wound pattern inflicted by a right-handed propeller always has a pattern opposite that of a left-handed propeller (Fig. 5, 6). Most of the propellers used in the United States on single-engine vessels are right-handed.

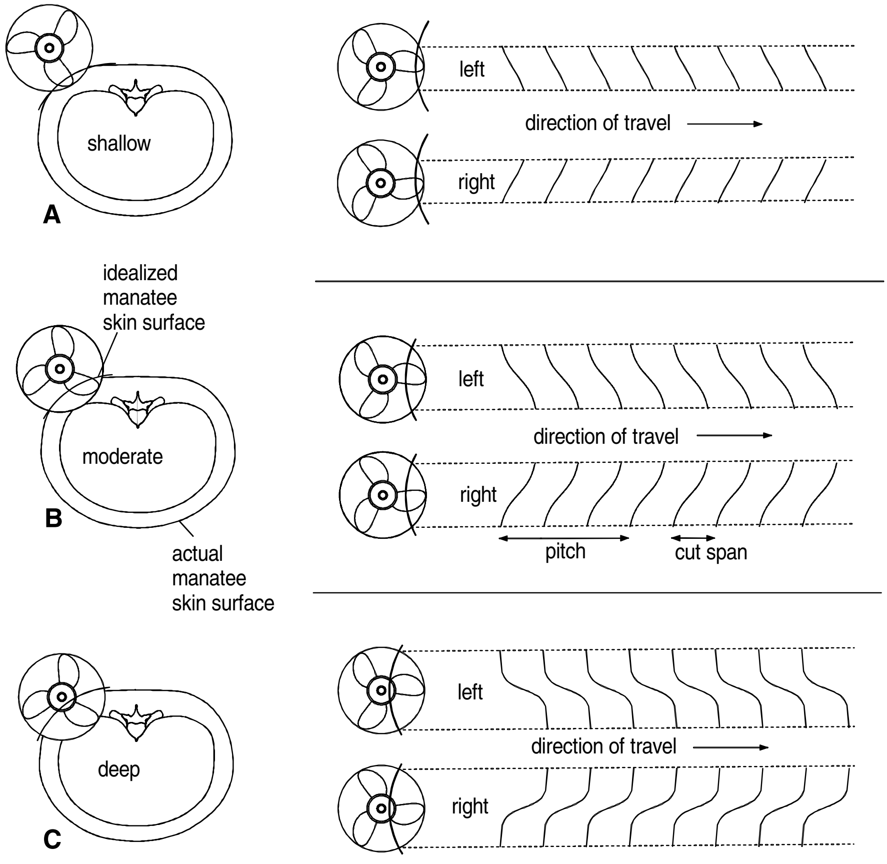

Figure 5. Schematic illustrations generated using projective geometry of the trajectories made by propeller cuts with different depths of penetration. The shape of the cuts made by a propeller will be proportional to the depth of penetration. (**A**) Shallow (10%); (**B**) Moderate (20%); and (**C**) Deep penetration (40%); the percentages were computed from the depths of blade penetration divided by the diameter of the propeller. Shallow penetration produces relatively straight lines. Deeper penetration produces more sigmoid cuts. The patterns are of a propeller diameter that is half the diameter of the manatee. Patterns produced by right- and left-handed rotations are illustrated. These patterns were generated for a manatee that is circular in cross-section; noncircular regions will have slightly different patterns.

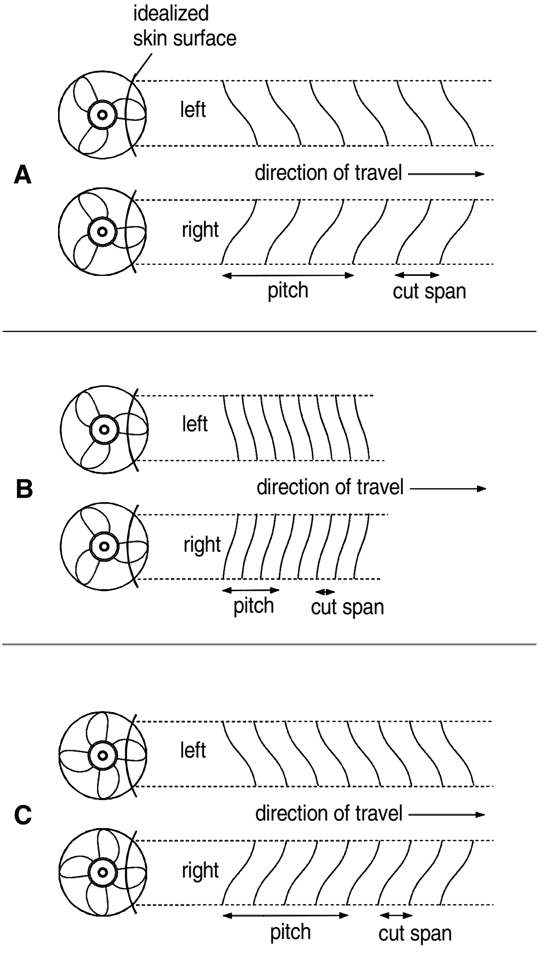

Figure 6. Schematic illustration, generated using projective geometry and assuming zero slip, of the influence of pitch and blade number on wound spacing (cut span). The depth of penetration, 10% of propeller diameter, is depicted on the left side of the illustration; on the right side of the illustration is the idealized pattern for two complete revolutions of the propeller. Left-handed rotation is labeled left, right-handed rotation is labeled right. (A) Three-bladed 35.6 cm (14 in.)-diameter, 53.3-cm (21 in.)-pitch propeller. (B) Three-bladed 35.6-cm (14 in.)-diameter, 21.6-cm (9 in.)-pitch propeller. (C) Four-bladed 35.6-cm (14 in.)-diameter, 53.3-cm (21 in.)-pitch propeller.

Propeller wounds on manatees can be complex. If manatee tissues reacted like a soft solid such as sand (Fig. 4H), then the resulting wound pattern would be relatively simple. The experimental work to describe the amount of slip (see below) that occurs when a propeller cuts into a manatee's hide has not been conducted. In addition, the manatee is (at least at the moment of impact) a moving, complexly shaped, and responsive creature. Features of the wound pattern may result from release of mechanical tension inherent in the collagen structure of manatee skin (Kipps *et al*. 2002). This tension could account for some of the observed differences between successive cuts both at the center of each wound and at its margins (Fig. 1 B, D). Many carcasses have considerable variation in cut spans within a single pattern (Fig. 4A–E), and wound patterns can vary considerably depending on depth of propeller penetration (Fig. 5) and propeller characteristics (Fig. 6). Other complicating factors are muscle contraction, body curvature, and differences in penetration and orientation of projecting elements of the watercraft in the water at the moment of collision (Fig. 1C, D). Compression of the manatee's hide and underlying tissues by a torpedo, propeller shaft (Fig. 3C, D), or propeller blade could potentially increase the wound length.

The cut spans will reflect normal propeller slip if the lacerations are relatively superficial. The deeper a propeller cuts into the manatee, the more there is a tendency to slow down the propeller; this is similar to when a propeller strikes a soft bottom such as mud or sand. When a propeller cuts deeply, there should be a sudden brief reduction in propeller RPM due to the added resistance. This can result in a momentary increase in cut span because there may not be a matching reduction in boat speed. Operational changes in speed or direction of the boat at the time of impact also affect slip. Acceleration may produce progressively decreasing cut spans, and deceleration may generate progressively increasing cut spans.

Propeller size is generally related to engine horsepower and propeller-shaft RPM and not necessarily to vessel size (Avallone and Baumeister 1996, Snyder 1992). Individual blades do not represent the entire propeller radius because the central hub can occupy a significant percentage of the inner diameter (Fig. 4F, G), especially on outboards and sterndrives. The measurements collected at the MMPL use the metric system, but propeller diameter and pitch are stamped in inches on most outboard and sterndrive propellers; we therefore provide this information in both metric and U.S. units.

A propeller can produce wounds of different shapes depending on the depth and angle of penetration (Fig. 5). The radius of curvature of the animal will influence the wound depth distribution (Fig. 4D, E); however, propeller circle templates can be fitted into wounds to overcome this problem (Fig. 7).

One can approximate, assuming little deformation of the manatee's hide, the propeller diameter using both the length and depth of an individual propeller cut (Fig. 8). In this graph, length is used as the chord of the propeller circle and the depth as the maximum distance between the chord and the circle perimeter. If the cut length used is chord length (Fig. 8) and the cut depth used is chord depth, then the principle can be applied to curved or flat regions[7] of the manatee. It is therefore more appropriate to always use chord length and chord depth. Large-diameter propellers produce relatively shallow cuts for their lengths, whereas small-diameter propellers produce deeper cuts for the same lengths. Cuts made by the same propeller that have similar cut lengths will be deeper in smaller-diameter manatees than in larger-diameter manatees or in body regions of smaller radii of curvature. The safest and most accurate method currently employed at MMPL uses propeller-circle templates[8] that can

[7] At small depths, there is relatively larger potential error when interpreting the graph in Figure 8 due to deformation of the skin (skin thickness is between 2 and 3 cm on the dorsum) and measurement error, thus we have found that a minimum penetration of 1.4 cm (0.6 in.) is required for chord-depth measurements.

[8] Note that if the manatee were curved in the location of this particular measurement, the diameter of the propeller might be underestimated if cut depth were measured from the manatee skin surface instead of from the chord-width line, and over estimated if curvilinear cut length were recorded instead of chord length. Assuming no distortion of the carcass, errors that increase cut depth will decrease the "computed" propeller diameter. Assuming no distortion of the carcass, errors that increase the chord-length overestimate the "computed" propeller diameter.

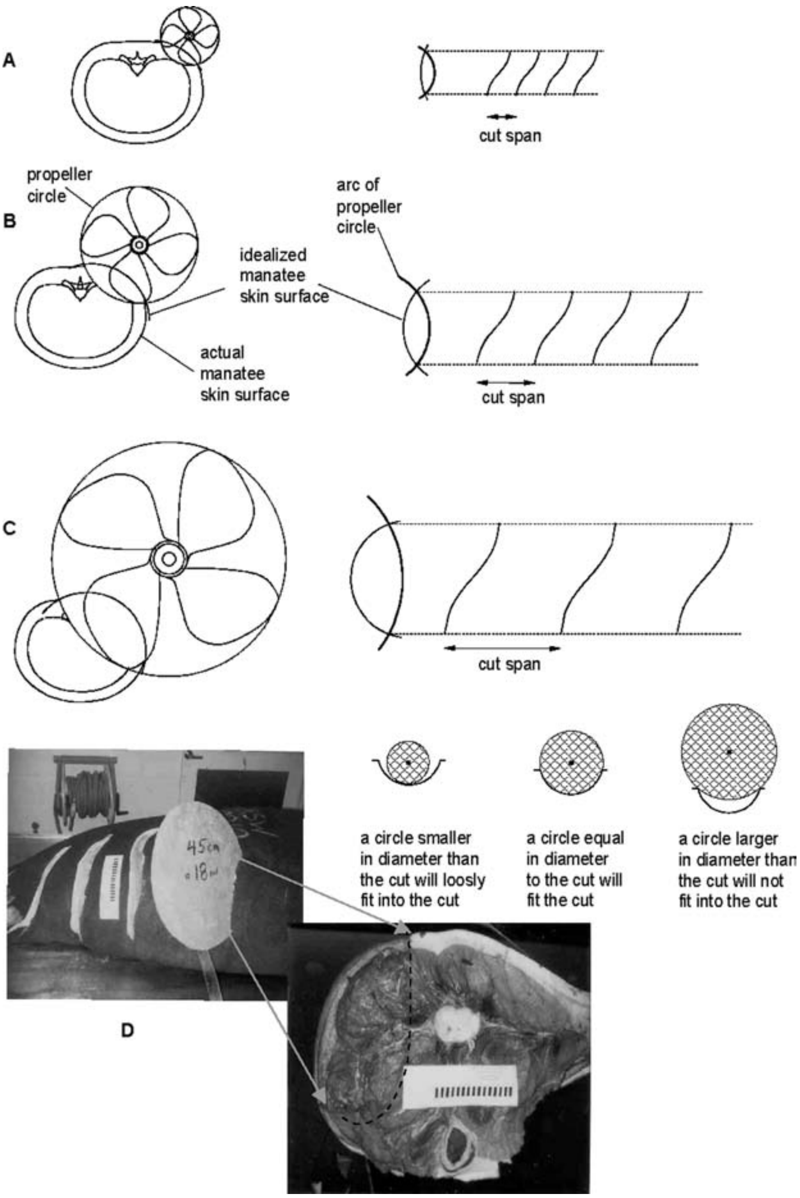

Figure 7. Together, wound depth and length can help determine propeller size. Schematic illustration, generated using projective geometry, of the influence of propeller diameter, relative to manatee diameter on wound shape and size. The examples illustrate different propeller sizes for the same diameter manatee and depth of penetration. (A) Propeller diameter equal to half of manatee diameter. (B) Propeller diameter equal to manatee diameter. (C) Propeller diameter equal to twice that of manatee. (D) Disks or arcs of a circle inserted into a wound can represent the margins of a cut made by a rotating propeller. Photographs illustrating the fit of a 45-cm (17.7 in.)-diameter disk in a manatee lesion created by a propeller approximately 18 in. (45.7 cm) in diameter.

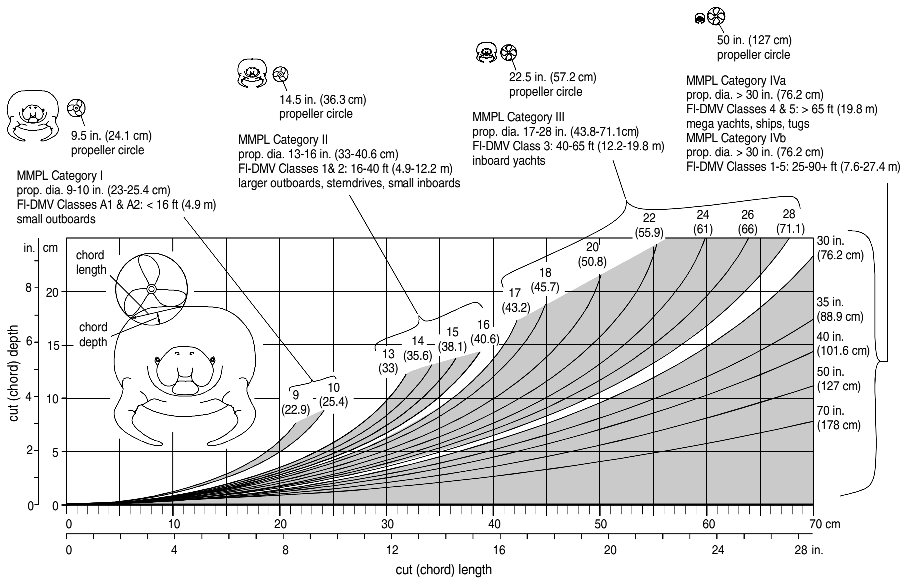

Figure 8. Marine Mammal Pathobiology Lab (MMPL) propeller size categories based on commonly used propellers and the FL-DMV resident watercraft registration classes. Cut-length *vs.* cut-depth curves computed for propeller diameters 22.9–178 cm (9–70 in.). With these curves, propeller diameter can be approximated (assuming little deformation of the manatee's body) using both the cut-length and cut-depth of an individual propeller lesion. Category I = small outboards; Category II = larger outboards, sterndrives, small inboards; Category III = medium to large inboards; Category IV = very large inboards (mega yachts, ships, and tugs). All these categories contain recreational and commercial use vessels. The numerical values along the margins of each curve are propeller diameters in inches/centimeters.

be fitted to the wound (Fig. 7D). Flexible (plastic and thin sheet metal) templates facilitate fitting in wounds that are not straight. The MMPL has a number of circle templates representing different propeller diameters. These templates can be used without chord length and chord depth of a cut to approximate propeller diameter by finding the best circular fit.

Pitch and slip—Propeller *pitch* is the distance that a propeller (or screw) travels through a soft solid during one complete revolution (Avallone and Baumeister 1996; Fig. 4H). Much like a screw through wood, the distance traveled per revolution by a propeller screw in a soft solid is independent of the speed at which the propeller is turned. This is because pitch, not propeller RPM or vessel speed, most determines the spacing between successive penetrating propeller wounds (cut span; Fig. 4D).

If the propeller is moving through a deformable fluid rather than a soft solid, then the additional phenomenon of slip[9] must be considered (Snyder 1992, Gerr 2001). Slip is calculated as:

[9] We have described slip, pitch, and other propeller characteristics in a simplistic manner that is adequate for the forensic analysis at hand. A more detailed but very readable description of these concepts can be found in Gerr (2001).

Slip (%)

$$= 1 - (\text{distance actually traveled by the propeller per revolution/propeller pitch})$$

and is different for different propeller designs and for the same propeller under different loads.[10]

Changes in speed will affect the amount of slip. Slip remains fairly constant at planing speeds but changes significantly with throttle changes. When the boat accelerates, slip increases and cut span decreases. In contrast, when the boat decelerates, slip decreases (and in some cases becomes negative) thereby increasing cut span. No experimental data are available to determine how much slip occurs when propellers cut manatees. We know that a screw moving through a soft solid advances without slip. Spacing of propeller wounds (cut span) will differ under conditions with minimal slip *versus* conditions with substantial slip. Deeper penetrating wounds may therefore reflect a reduction in slip and subsequent increase in cut span. Measurements of cut spans in manatees killed by known boats are limited (Table 1). Although some of these watercraft-related mortalities have distinct propeller cuts, none are deep enough to potentially reduce the slip significantly.

Based on engineering experience from years of operating boats on the water, we must assume that slip does not reduce to zero. Thus, something has to give. That something is probably the manatee itself. This strongly suggests that during impact, deformation of the manatee will occur, thereby reducing the value of cut span as a tool in characterizing the propeller involved.

Pitch determination for very large propellers is more complicated than for smaller propellers. This is because, at least for pleasure craft with a given engine power and gear ratio, pitch decreases and slip may increase as vessel size and propeller diameter increase. Thus, larger propellers can create cut spans smaller than those of much smaller (lighter, faster) watercraft.

Blade number—The most common propellers typically have three blades (Snyder 1992), but four- and five-bladed propellers are becoming more popular. For a given pitch, the distance a propeller travels per revolution is not affected by the number of blades on the propeller. However, the number of blades will determine the number of cuts per revolution and therefore cut span for a given pitch (Fig. 6). Although one cannot usually determine blade number from a wound pattern, when there is a distinct notch or other imperfection on a blade, it is possible to determine blade number from lesions associated with repetition of that imperfection.

Other features—We have not yet determined what separates superficial from deep in terms of blade penetration and its effects on the shape of a propeller cut. Propeller blade tip shape and sharpness vary considerably and can influence wound shape. If the blade is dull or has a thicker edge, the skin will deform more. A sharp propeller blade will more readily penetrate the hide and leave a wound more similar to those predicted from projective geometry. Rake (slant back or forward; Snyder 1992) of the blade will contribute to the crescent shape of the wound.

[10] With propellers correctly selected for the operating conditions, slip would be as follows: high performance hulls 10 to 15%; planing runabouts 12 to 25%; planing cruisers 15 to 35%; displacement cruisers 30 to 40%; sailing auxiliaries 35 to 40%; work boats 40 to 80%.

Some General Considerations about Propellers and Watercraft Sizes

Propeller size categories are not absolute and are therefore used only as a guide for forensic analysis. The MMPL propeller categories (Table 2; Fig. 8) described below are based on the vessel registration classes used by the Florida Department of Motor Vehicles[11] (FL-DMV) and the most common propeller sizes found on watercraft in U.S. waters.

MMPL category I—MMPL category I includes commercial and pleasure vessels <4.9 m (16 ft). This group combines FL-DMV-registered vessel classes A1 (<3.7 m; 11 ft 11in.) and A2 (3.7–4.9 m; 12–15 ft 11 in.) and represents approximately 39.5% of all watercraft registered in Florida. These vessels have small propellers found on open fishing boats powered by hand-tilled ≤30 hp (commonly 10–15) outboards (Fig. 2A). They typically have right-handed, three-bladed propellers with diameters 22.9–25.4 cm (9–10 in.) and pitches ≤33 cm (13 in.). Assuming no deformation of the manatee, these propellers could produce wounds with cut lengths 20.3–22.9 cm (8–9 in.) and cut depths 7.6–8.9 cm (3–3.5 in.). Cut spans would commonly be 6.4–8.9 cm (2.5–3.5 in.) under normal operating conditions. This group includes personal watercraft (jet skis). Although personal watercraft do not have propellers and do not protrude below the water surface more than a few centimeters, they can kill manatees (Mignucci-Giannoni *et al*. 2000).

MMPL category II—MMPL category II includes commercial and pleasure vessels 4.9–12.2 m (16–39 ft 11 in.). This group combines FL-DMV–registered vessel class 1 (4.9–7.9 m; 16–25 ft 11 in.) and class 2 (7.9–12.2 m; 26–39 ft 11 in.), which represent approximately 58.9% of all watercraft registered in Florida. These vessels have mid sized propellers typically mounted on larger outboards, sterndrives, small inboard yachts, and ski boats (Fig. 2B, C). They normally have right-handed, three-bladed propellers with diameters 33–40.6 cm (13–16 in.) and pitch 27.9–58.4 cm (11–23 in.); some propellers have up to 88.9 cm (35 in.) pitch. Dual (or more) propulsion units have become common and characteristically use counter rotating propellers (on separate shafts). In addition, counter rotating propellers on a single shaft centerline are employed by some sterndrives and outboards (Fig. 3F).

Assuming no deformation of the manatee, typical maximum cut lengths will be 30.5–38.1 cm (12–15 in.) and maximum cut depths 11.4–14 cm (4.5–5.5 in.), in part due to the 10.2–12.7 cm (4–5 in.) diameter of the propeller hub (Fig. 4F) and torpedo (Fig. 2A, B). Assuming typical slip and three blades, cut spans will be 10.2–17.3 cm (4–6.8 in.). Three-bladed configurations are most common, but four- and five-bladed propellers are gaining popularity. With the same pitch, four-bladed propellers would have cut spans 75% and five-bladed propellers 60% of the three-bladed cut span.

The 15° blade rake of most propellers in this category is rather unique. Most propellers in the other vessel categories have considerably less rake (or even negative rake) due to different performance demands.

MMPL category III—MMPL category III includes commercial and pleasure vessels 12.2–19.8 m (40–64 ft 11 in.). This group corresponds to FL-DMV-registered vessel class 3 and represents approximately 1.5% of all watercraft registered in Florida. These vessels have large propellers found on straight-shaft inboard yachts (Fig. 2 C). They typically have right- and left-handed, four-bladed propellers with diameters 43.2–71.1 cm (17–28 in.), pitches 43.2–96.5 cm (17–38 in.), and rake 0–8°. These

[11] The Florida Department of Motor Vehicles has a Website for this information: http://www.hsmv.state.fl.us/html/revpub/revpub2004.pdf; see pages 134–135.

Table 2. Summary of some propeller and watercraft characteristics used in the MMPL propeller size categories. Manufacturers of most of the watercraft in Florida waters use U.S. units. Maximum cut length assumes no distortion of the manatee and accounts for hub size preventing cut length to be the full diameter of the propeller.

MMPL category	Max prop cut length	Propeller diameter/Pitch	Vessel size	Comments
I	20.3–22.9 cm (8–9 in.)	22.9–25.4 cm (9–10 in.) / ≤33 cm (13 in.)	<4.9 m (16 ft) Fl-DMV Class A1, A2	≤30 hp, hand tilled outboard, three blades
II	30.5–38.1 cm (12–15 in.)	33–40.6 cm (13–16 in.) / 27.9–88.9 cm (11–35 in.)	4.9–12.2 m (16–40 ft) Fl- DMV Classes 1, 2	Larger outboard, sterndrive, inboard ski boat, small inboard yacht, 3–5 blades
III	40.6–68.6 cm (16–27 in.)	43.2–71.1 cm (17–28 in.) / 43.2–96.5 cm (17–38 in.)	12.2–19.8 m (40–65 ft) Fl-DMV Class 3	Inboard yacht, four blades
IVa	≥80 cm (31.5 in.)	≥76.2 cm (30 in.) / ≥76.2 cm (30 in.)	>19.8 m (65 ft) Fl-DMV Classes 4, 5	Propellers transecting adult manatee or much larger than category I-III, ships and mega yachts, 3–5+ blades
IVb	≥80 cm (31.5 in.)	≥61 cm (24 in.)/ ≥50.8 cm (20 in.)	7.6–27.4 m (25–90+ ft) Fl-DMV Classes 1–5	Tugs, extreme range of slip, 4+ blades

propellers do not have exhaust-through hubs (Fig. 4G) and have a solid hub design with smaller diameters 7.6–10.2 cm (3–4 in.). These propellers produce maximum cut lengths 40.6–68.6 cm (16–27 in.) with depths 17.8–33 cm (7–13 in.). These propellers may operate with 15–35% slip if the vessels are planing cruisers and 30–40% slip if they are displacement cruisers (see footnote no. 6). Their cut spans will vary considerably assuming that normal operational slip persists during the cut.

MMPL category IVa—MMPL category IVa includes commercial and pleasure vessels ≥19.8 m (65 ft). This group corresponds to FL-DMV–registered vessel class 4 (19.8–33.5 m; 65–110 ft) and class 5 (>33.5 m; 110 ft) and represents (with MMPL category IVb) approximately 0.1% of all watercraft registered in Florida. Notably, there are numerous watercraft in Florida waters that fit this propeller size category but that are not registered in Florida. No official numbers of these vessels are on record.

MMPL category IVa includes very large propellers found on ships and mega yachts, which are large enough to either transect a juvenile/adult carcass (Fig. 1E) or create cut lengths and/or spans significantly larger than those produced by watercraft in MMPL category III. They typically have right- and left-handed, 3–5+ bladed propellers with diameters ≥ 76.2 cm (30 in.) and a wide range of pitch. Pitch of very large propellers is often given in terms of a dimensionless ratio, P/D (pitch divided by diameter); P/D ratios range from 0.5 to 1.4 (Avallone and Baumeister 1996). Using a nominal P/D = 0.9, we compute a pitch of 144 cm (56.7 in.) for a 160 cm (63 in.) diameter propeller. A three-bladed propeller with this pitch would have a zero-slip cut span of 48 cm (18.9 in.); a four-bladed propeller would have a zero-slip cut span of 36 cm (14.2 in.). Assuming typical slip and three blades, cut spans will be 10.2–17.3 cm (4–6.8 in.). Because ship propellers may have five or more blades with varying pitch, the cut spans may be significantly smaller, particularly if slip is high.

MMPL category IVb—MMPL category IVb includes very large propellers found on tugs and work boats. Tug boats are typically 7.6–27.4+ m (25–90+ ft) and have propeller diameters 61–221 cm (24–87 in.). Their very large propellers are driven by relatively low RPM diesel engines with large gear reduction ratios. Slip varies dramatically depending on whether the propellers are under load or not.

For example, a 6:1 gear reduction and slow turning diesel engine designed for maximizing thrust at speeds ≤ 2.2 m/s (5 mph) might employ a four-bladed propeller with 163 cm (64 in.) diameter, 127 cm (50 in.) pitch, and a low rake angle. Cut length could be as great as 152.4 cm (60 in.), with a depth of 73.7 cm (29 in.). When pushing a load at 2.2 m/s (5 mph), the slip of a tug boat propeller can be as high as 62% with a resulting cut span of only 9.6–12.7 cm (4.5–5 in.). Without a load, the same tug can reach 4.5 m/s (10 mph) at the same rpm, such that slip would drop to 24% and the cut span would increase to 24.1 cm (9.5 in.). Range of cut spans in this category—probably more so than other categories—is related to activity of the watercraft.

Size of Watercraft Versus *Characteristics of Watercraft-Related Wounds*

A wide range of propeller sizes is used on similarly sized recreational and commercial vessels. Conversely, various vessel sizes have similar propeller characteristics. In order to estimate the number of watercraft-related mortalities due to various sized propellers, the principles illustrated in Figure 8 were used to analyze data from 2000 to 2004 by plotting propeller lesion length-depth data collected during necropsy from propeller-caused watercraft-related mortalities. In some cases where depths were listed as through the body wall or penetrating into a body cavity, some maximum and minimum cut depths could be estimated from known relationships between body wall thicknesses and body length. If there was a minimum propeller penetration of 1.4 cm, then minimal distortion was assumed and some relatively small propeller diameters could be excluded using maximum cut lengths. Obvious outliers were rejected only if the other computed propeller diameters were definitive and as such could exclude the outlying value. We chose 80 cm (31.5 in.) to be a cut length beyond the maximum cut caused by MMPL Cat III propellers assuming minimal distortion of the carcass during impact. In a few cases, where propeller wounds were nonpenetrating, it was possible to assume some carcass deformation to a maximum of 1/2 the circumference of the propeller and to calculate the corresponding range of propeller diameters; these diameter estimates would likely bias the results, because only large and very large diameter propellers can be differentiated using this method.

Results

Applying Cut Dimensions to a Subset of the Historical Database

Of the 396 watercraft-related deaths (Table 3) examined from the 2000 to 2004 interval, 227 had at least one recognizable propeller cut or scrape. Of these 396 watercraft-related mortalities, 138 were caused by trauma only from propellers, 89 were caused by trauma from both propellers and nonpropeller components, and 107 were caused by trauma only from nonpropeller components of watercraft. In addition, there were 62 carcasses that were deformed, decomposed, or had missing data so that propeller and/or nonpropeller damage could not be differentiated. Only 115 of the 227 propeller related mortalities had sufficient information to apply the principles illustrated in Figure 8. Of these, twenty-four resulted in more than two MMPL propeller size categories (Table 3).

Fifty-eight of the 115 were determined to fit the large and very large propeller categories. Regardless of wound appearance, this number includes adult and subadult manatees that were either transected or nearly transected ($n = 3$). Twenty-seven of the 115 were determined to fit in the small and medium propeller categories. Six of the 115 fell between the two groups.

Example of an Incident in Which the Watercraft was Known

The vessel that struck manatee MSW0079 (Fig. 3A) was 6.7 m (22 ft) with twin sterndrives (Table 1). During the collision it was traveling at 11.2 m/s (25 mph) in 2.7 m (9 ft) of water. In Figure 3B, note the five fractured ribs and corresponding lacerations of the lung; this damage was deep to the superficial scrape.

Additional Cases

MSW03138 is an example of a complex wound pattern. The sketch (Fig. 4E) of the wound pattern on this carcass illustrates an incident in which the propeller superficially scraped the animal at the front of the body and cut the animal at the tail. Note that spacing between individual propeller cuts is different in different

Table 3. Estimates of propeller size from wound dimensions. Of the 396 watercraft-related deaths of Florida manatees from 2000–2004, 227 had at least one recognizable propeller cut or scrape. Of these 227, there were 115 propeller-caused watercraft-related mortalities that had wounds to which the relationships described in Figure 8 were employed to determine that 91 mortalities fell in one or two of the MMPL propeller size categories (MMPL Cat I&II, propeller diameters $\geq$40.6 cm (16 in.), $n = 27$; MMPL Cats III&IV, propeller diameters $\geq$43.2 cm (17 in.), $n = 58$; MMPL Cat-II/III, $n = 6$). In addition, 24 mortalities fell in more than two MMPL categories (the three columns on the far right). YR = year, #W/C = number of watercraft mortalities for that year; lethal prop lesions = number of watercraft-related mortalities that had one or more recognizable propeller cuts or scrapes associated with cause of death.

		Lethal prop	MMPL propeller size categories									
YR	#W/C	Lesions	I	I/II	II	II/III	III	III/IV	IV	I/III	II/IV	I/IV
2000	79	47	5	4	1	3	1	10	3	1	0	2
2001	81	48	0	2	1	2	4	8	6	0	3	2
2002	95	54	3	1	3	0	3	6	2	0	9	1
2003	73	35	2	1	0	0	3	3	2	0	0	2
2004	69	43	0	2	2	1	5	2	0	1	2	1
Totals	396	227	10	10	7	6	16	29	13	2	14	8
Summaries			Cats I & II = 27				Cats III & IV = 58			>2 Cats = 24		

parts of the pattern. The cut spans between successive lacerations of the pattern are inconsistent except in the tail where the propeller blades entered the flesh. These cuts (labeled 6–8 in Fig. 4E) through the tissues of the tail are evenly spaced and reflect the pitch (and some unknown amount of slip) of the propeller. In front of these cuts are five other wounds (labeled 1–5 in Fig. 4E) that are progressively farther apart (because of the narrowing of the body there is a "missing" cut—not numbered—between 5 and 6). Direction of propeller travel can be inferred from the manner in which the epidermis was scraped from the underlying dermis at the wound margins. The wound labeled #1 in Figure 4E occurred first and wound labeled #8 occurred last. The animal may have rotated on its axis and flexed its body as part of its reaction to the watercraft strike, thus contributing to pattern complexity.

Manatee MEC0127 (Fig. 3C, D) provides an example of a complex wound pattern, including propeller cuts, rudder scrapes, and an offset keel scrape. The skinned section (Fig. 3D) highlights the shape of the propeller wounds. In this example, a right-handed propeller made the cuts (see Fig. 5C). The linear wound bisecting the cuts is consistent with a keel or ski boat turning fin (modern power boats rarely have sharp keels), propeller hub or shaft, or centered rudder. The linear lesion (indicated by string in Fig. 3C) offset to the right of the lethal part of the pattern is consistent with a keel, turning fin, or rudder. This lesion occurred at the same time as the pattern on the left, but because the head was deeper than the tail, the second propeller of the vessel did not touch the carcass.

In case MSE0136, the unique X-shaped cuts consist of four cuts from a left-hand-rotating propeller (Fig. 3G, labeled 1–4) and three cuts from a right-handed propeller (Fig. 3G, labeled a–c). The combination of wounds is consistent with counter rotating on the same shaft (Fig. 3F). The front propeller is slightly larger in diameter and left handed; the propeller in back has a slightly smaller diameter and is right handed.

Discussion

Using physics, projective geometry, and observations from known-boat manatee mortalities, it is possible to accurately interpret some watercraft propeller wounds. Nonetheless, the wide range of watercraft configurations and the number of possible distortions from the posture and behavioral reaction of the manatee to the watercraft reduce the utility of this methodology.

The wound feature that best describes the propeller that caused the injury is propeller diameter, which can help determine some vessel characteristics, especially when combined with other features such as pitch, rotation, and rake. Cut depth and length can be used to estimate propeller diameter.

Deformation of manatee tissues significantly obscures wound analysis. Skin toughness and angles of impact influence the way propellers cut the manatee and thus add to the overall wound complexity. Propeller pitch is important in determining the spacing between deep cuts (Pitchford *et al*. 2001, 2002). If constant, the speed at which the propeller turns should not directly affect the spacing between individual cuts (Fig. 4D, E) of a pattern (Avallone and Baumeister 1996).

Perhaps most important is the recognition that none of these values and calculations hold steadfast in light of changes to sea state, vessel direction, vessel speed, and other factors. Sharp turns without throttle changes increase slip. In such situations, the increase in slip is dependant on the sharpness of the turn and size and weight of the vessel. Boaters might increase slip by turning sharply to avoid a manatee. Acceleration and deceleration also affect slip dramatically. Slip can increase to over 50% during acceleration, especially when accelerating from a nonplaning state. Conversely, during deceleration slip values can drop to zero or below, thereby increasing the cut span. Deceleration effects on pitch may be quite common if boaters see the manatee before impact and try to slow down. A manatee traveling parallel to a vessel and matching its speed may result in a near-zero cut span, but a manatee moving toward a watercraft should result in an increased cut span. These complications can lead to underestimation of a large-pitch propeller and overestimation of a small-pitch propeller.

Some manatees have propeller scars and wounds on their lateral aspects, suggesting that the sides of the propeller can contact the animal. If shaft rotation axis is not horizontal, then the effective pitch angle on the right and left sides of the propeller will be different from the pitch angle at the top and bottom and between left and right sides. For fixed shaft inboards, shaft angle is commonly -7°. For a right-handed propeller with its shaft rotation axis at -7°, the wound angle will decrease by 7° at the center of the upswing (left side of propeller circle) and it will increase by 7° at the center of the down swing (right side of the propeller circle). Thus, a shaft tilt of 7° will introduce a potential difference of 14° in the cut angles made on a manatee, depending on which side of the propeller cuts the manatee. Because of the inevitable bow-up attitude of a boat, particularly when on plane, or even more so when going through the transition of getting on or coming off plane, shaft angle can increase by an additional 3–15°. A planing boat operates most efficiently when its bottom is moving across the water at a 4–5° bow-up angle. The additive combination of both the fixed, negative shaft angle and the varying boat attitude can increase the effective shaft angle to 10–20°. With most sterndrive and larger outboard propulsion systems, the operator may adjust (trim) the angle of the propeller shaft rotation axis in the vertical plane. The standard tilt range is 20° (6° in, 14° out) although an operator will generally trim the prop shaft to be near horizontal for best boat performance and efficiency. For example, if the operator trims an outboard out 5° and the boat is running at an efficient 5° bow-up attitude, the result will be a prop shaft running perfectly horizontal. Thus, a cut pattern generated by this propeller will be the same, no matter where on the propeller contact is made.

Table 3 illustrates the distribution of propeller sizes for 115 propeller-caused watercraft-related mortalities from a recent 5-yr interval. All MMPL propeller size categories can be found in these propeller-caused watercraft-related injuries. Unfortunately, a significant number of the 115 ($n = 24$) range over two or more MMPL categories. With the exclusion of these twenty-four cases and the six that are between MMPL categories II and III, we can compare small and medium propeller-caused mortalities with large and very large propeller-caused mortalities. The number of propeller-caused deaths in MMPL categories I and II ($n = 27$) is considerably smaller than the number of propeller-caused deaths in MMPL categories III and IV ($n = 58$). This difference implies that—for propeller-caused watercraft-related manatee mortalities—larger watercraft may be disproportionately more lethal than smaller watercraft. Interestingly, large and very large watercraft represent a very small percentage ($<2\%$) of the watercraft registered in Florida.

It is important to note that injuries resulting from chronic propeller wounds cannot usually be evaluated using cut length and depth. Therefore, if smaller propellers are responsible for more of the chronic deaths, our methods have limited value in accounting for them. In addition, any tearing of wound margins or expansion of nearby tissues from decompositional gas—as is common in moderately and badly decomposed carcasses—have a tendency to overestimate propeller size by increasing the length and/or decreasing the depth of a wound. It therefore becomes apparent that any wound length to depth analyses using historical wound measurement data should use caution when attempting to draw any conclusive results—unless measurements in only fresh carcasses are used and the accuracy of those measurements is relatively certain.

All of the known watercraft-related mortalities (Table 1) occurred before the utility of Figure 8 was established. In the few cases where propeller cuts penetrated sufficiently to apply these curves, the cuts were either through or depths were not collected. In only one case were the propeller cuts usefully analyzed using Figure 8. This carcass had two cuts that were deep enough to attempt estimating propeller diameter, but the protocol at that time used maximum depth and width rather than chord depth and chord length. In addition, the propeller circle templates in use at that time were too rigid to bend and fit the cuts. Thus the measurements of depth and width from MEC0244 underestimated the propeller category displacing it from MMPL category III to MMPL category I. This suggests that the numbers in each computed MMPL category could be an underestimation of the deaths caused by larger propellers.

Commercial Versus *Recreational Watercraft*

It has been suggested that commercial watercraft kill more manatees than recreational watercraft.[12] This is very unlikely because the numbers of watercraft registered

[12] Jacksonville Waterways Commission, March 3, 2005, 9:00 AM: "Dr. Gerstein said that he was struck by the considerable amount of commercial traffic that he encountered in Jacksonville's waterways and suggested that most of the manatee fatalities in the region were probably linked to commercial vessels."

in Florida indicate that only a small percentage of all but the largest classes are commercial watercraft. There are large numbers of watercraft, registered outside Florida, that visit Florida waters each year. The exact numbers of these visitors are not known. In addition, most watercraft-related mortalities, excluding those attributed to very large propellers, are not concentrated around shipping ports. Consequently, regions of Florida that have no large commercial traffic often have dense concentrations of watercraft-related mortalities.

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