The chelonian shell is composed of at least 67 bony plates of dermal origin and covered by epidermal keratin scutes. The shell is divided into the upper carapace and lower plastron, which are connected laterally by bridges formed by the fusion of lateral extensions of carapacial and plastral bones. This unique configuration separates the chelonian anatomy from other reptiles, with the shell providing support and protection. The extent of shell protection varies by species, with snapping turtles (Chelydra serpentina) and soft-shell turtles (Apalone spinifera) having much smaller plastrons relative to other common North American freshwater turtles like painted turtles (Chrysemys picta) or red-eared sliders (Trachemys scripta elegans).

Human-induced trauma is the most common reason for free-ranging freshwater turtle species to present to wildlife centers in North America, with automobile collisions being the prevailing primary cause. Damage to the shell is often fatal but can be medically or surgically repaired depending on the severity of the injury. With respect to wildlife rehabilitation, surgical intervention should only be attempted if it is likely to result in an outcome that allows for the release of a fully functional turtle.

Numerous shell repair techniques have been described and recommended in the literature. Less invasive (no shell penetration) stabilization techniques, including epoxy resin alone or epoxy resin used to attach plastic cable ties, metal bridges, or metal fabric hooks and eyes to the shell, have been suggested to be effective in several species. However, open fractures can be difficult to manage with...
these techniques due to purposeful or accidental sealing of the fracture site with epoxy resin or insufficient fracture site stabilization and apposition. Therefore, shell repair using metal hardware, specifically surgical plates, screws, and wire, is recommended for displaced or open shell fractures. Some disadvantages of plate coaptation include the cost of surgical-grade steel implants and management of screw holes postremoval. Custom plates made from stainless steel or aluminum obtained from home improvement stores have been used successfully by the authors for the past 7 years and avoid the high costs of surgical-grade bone plates.

Shell fracture healing in freshwater turtles is expected by 4 to 8 weeks, similar to bone in other species. In a report, the fracture healing time was 3 to 6 months when using a dental acrylic and lock/release ratchet mechanism for repair. A similar healing time of 3 months was reported for shell fracture repair in aquatic turtle species using adhesive glue and bandaging.

No systematic evaluation of the outcome of shell fractures in turtles repaired using screws and wire or plates has been reported. The objectives of this study were to evaluate the effectiveness and treatment outcome of custom plate stabilization plus screws and wire repair on shell fractures in wild freshwater chelonians presenting to a wildlife rehabilitation facility and to establish the prevalence of shell fractures in wild freshwater turtles admitted to a wildlife center in Wisconsin.

Materials and Methods

Case selection
The medical records database of Dane County Humane Society's Wildlife Center was searched for freshwater turtles admitted and treated for carapace, plastron, and bridge fractures between 2014 and 2019. Turtles with shell fractures that were surgically stabilized with plates, screws and wire, or both were included in the study. Still, only animals that survived > 4 weeks after surgery (reported minimum duration for shell fracture healing) or were euthanized as a direct result of hardware complication were used to assess fracture healing and treatment outcome. Turtles with shell fractures that were euthanized before or at the time of the initial physical examination or were managed by a method other than plates or screws and wire were reported in the number of admissions for each species but excluded from the evaluation of hardware repair success and patient outcome. Turtles with shell fractures that were repaired with surgical hardware but did not survive > 4 weeks postoperatively were reported in the patient outcome but excluded from hardware repair success outcome.

Medical records review
Information extracted from the medical records included species, age, sex, year of admission, location of the shell fracture(s) (carapace, plastron, or bridge), concomitant problems, and therapeutic approach, including type of hardware used for repair, dry-docking duration, time to hardware removal, postremoval care, and treatment outcome. A successful outcome was defined as complete fracture healing that was stable on manual palpation and provided adequate cover for protection. An unsuccessful outcome was defined as incomplete fracture healing that led to the decision to euthanize the turtle. The outcome was determined subjectively by the attending veterinarians. Hardware failure was defined as breaking of any screw, wire, or plate, regardless of clinical significance.

Application of plates and screws and wire
For each turtle, shell fractures were repaired with one of the following methods: plates and screws, screws and wire, or the application of both techniques in the same patient. All fracture repair methods were performed under general anesthesia by a board-certified zoological medicine specialist or zoological medicine resident. The repair method used was selected based on the attending veterinarian's preference. The fractured shell was aseptically prepared with chlorhexidine or povidone-iodine prior to repair. Fracture edges and wounds were debrided until fresh bleeding or fresh tissue was observed. For turtles treated with the screws-and-wire technique, pilot holes were drilled parallel through the dermal bone of the shell at least 0.5 cm from the fracture edge. The size and length of the screws used varied with the size of the turtle being treated. Stainless steel screws (drive pan head type No. 4-24 X 3/16 inch or type No. 2-32 X 1/4 inch; Phillips) were most commonly used. Sterile screws were inserted into pilot holes and advanced partially into the bone by hand with a screwdriver. Screws were then connected using 20- to 22-gauge surgical cerclage wire wrapped in a figure-of-eight fashion to maintain rigid fracture reduction (Figure 1).

For turtles treated with the plate technique, custom metal plates were created using 1/16-inch aluminum strips with holes drilled every 1/4 inch using a drill press. Pilot holes for screws were created in the shell as previously described. Plates were positioned to allow placement of a minimum of 1 screw, preferably at least 2 screws, on each side of the fracture (Figures 1 and 2). Screws were placed through the plate and advanced into a pilot hole by hand using a screwdriver. If necessary, a short section of a plate containing a single hole was used as a washer to reduce screw penetration depth and avoid coelomic penetration.

Following surgery, turtles were maintained in a controlled, heated environment with access to UV lighting during dry-docking and transferred to an outdoor holding area for either intermittent periods of full water immersion or constant access to water once deemed appropriate by the veterinary staff. Turtles had access to natural sunlight during outdoor periods. The frequency and duration of dry-docking were dependent on the fracture type and severity. Subcutaneous administration of parenteral balanced...
electrolyte solutions (20 mL/kg, every other day) and wound treatment, including flushing of fracture lines and topical application of silver-containing antimicrobials, were provided for the duration of dry-docking. Topical treatments were applied every 3 to 7 days after implementing full water access. Honey, silver-containing hydrogels, or granulated sugar was used every 1 to 3 days when bandaging was indicated. Analgesics, meloxicam (0.2 to 0.4 mg/kg, SC, q 24 h), and tramadol (10 mg/kg, SC, q 72 h) were administered for a minimum of 5 days based on the perceived pain level. Antimicrobials, specifically ceftazidime (20 to 30 mg/kg, SC, q 72 h), were administered for a minimum of 2 to 3 weeks after surgical fixation. Choice of antimicrobial was altered as necessary based on patient response to treatment and results of bacterial culture and antimicrobial susceptibility testing, when available.

Turtles were examined weekly by the attending veterinarians. Staging and removal of plates and screws and wire were initiated when the fractures showed signs of sufficient stabilization by palpation. Following hardware removal, screw holes were cleaned daily to weekly with dilute chlorhexidine or saline flush and in some cases packed with silver-containing, antimicrobial, topical medication until deemed completely healed. In other cases, no topical treatment of the screw holes was performed. Additional doses of injectable antibiotics were administered after hardware removal in some cases based on clinician discretion.

### Results

#### Turtles

Of the 381 live freshwater turtles admitted to the wildlife center during the study period, 245 (64%) were admitted for shell fractures (Table 1). This equated to a median of 39 (range, 27 to 55) turtles with shell fractures examined each year. Painted turtles (n = 144 [59%]) and common snapping turtles (85 [35%]) constituted the majority of turtles with shell fractures. There were 111 (45%) males, 101 (41%) females, and 33 (14%) turtles of indeterminate sex. Suspected vehicular trauma (n = 218 [59%]) was the most frequent cause of fractures, with other causes of trauma reported in 27 (11%) turtles.

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**Figure 1**—Photographs showing surgical repair techniques for traumatic shell fractures in freshwater turtles. A—Screws and custom-made aluminum plates as well as screws and cerclage wire were used for multiple cranial carapacial shell fractures in a western painted turtle (Chrysemys picta bellii). B—Plates and screws were used to stabilize a left bridge fracture in the same turtle. C—Three custom-made aluminum plates in addition to a cuttable stainless steel surgical plate were used for stabilization of a cranial plastron fracture in a Blanding’s turtle (Emydoidea blandingii). D—Surgical stabilization of a caudal carapacial fracture was performed in a western painted turtle. To reduce the penetration depth of the stainless steel screws and reduce the risk of coelomic penetration, custom-made washers, consisting of single-hole sections of the aluminum plates, were used.

**Figure 2**—Photographs of a Blanding’s turtle (Emydoidea blandingii) with a comminuted cranial carapacial fracture. A—Appearance of the fracture prior to surgical repair. B—Use of stainless steel screws and custom-made aluminum plates for stabilization of the fracture. C—Appearance of the fracture site and screw holes after final hardware removal, 49 days after fracture repair. Staged hardware removal was performed 42 days after surgery, and therefore most screw holes appear shallow. The 2 holes in the center contained the screws, which were removed on day 49 and were therefore deeper. This turtle was released 81 days after initial admission and surgical fracture repair.
Table 1—Species distribution of all freshwater turtles admitted to a Wisconsin wildlife center from 2014 to 2019.

<table>
<thead>
<tr>
<th>Species</th>
<th>No. of turtles presented</th>
<th>No. (%) of turtles with shell fractures</th>
<th>No. (%) of fractured turtles euthanized</th>
<th>No. (%) of turtles selected for hardware repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>Painted turtle (Chrysemys picta spp)</td>
<td>198</td>
<td>144 (73)</td>
<td>88 (61)</td>
<td>32 (22)</td>
</tr>
<tr>
<td>Common snapping turtle (Chelydra serpentina)</td>
<td>154</td>
<td>85 (55)</td>
<td>47 (35)</td>
<td>11 (13)</td>
</tr>
<tr>
<td>Blanding’s turtle (Emydoidea blandingii)</td>
<td>9</td>
<td>5 (35)</td>
<td>2 (40)</td>
<td>3 (60)</td>
</tr>
<tr>
<td>Common map turtle (Graptemys geographica)</td>
<td>7</td>
<td>5 (71)</td>
<td>2 (40)</td>
<td>3 (60)</td>
</tr>
<tr>
<td>Eastern spiny soft-shell turtle (Apalone spinifera)</td>
<td>6</td>
<td>4 (67)</td>
<td>1 (25)</td>
<td>2 (50)</td>
</tr>
<tr>
<td>Common musk turtle (Sternotherus odoratus)</td>
<td>4</td>
<td>1 (25)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Ornate box turtle (Terrapene ornate ornate)</td>
<td>2</td>
<td>1 (50)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Ouachita map turtle (Graptemys ouachitensis)</td>
<td>1</td>
<td>0 (0)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>381</strong></td>
<td><strong>245 (64)</strong></td>
<td><strong>140 (57)</strong></td>
<td><strong>51 (21)</strong></td>
</tr>
</tbody>
</table>

— = Not applicable.

Of the 245 turtles with shell fractures, 194 (79%) were excluded from the outcome portion of this study. One hundred forty (57%) turtles were euthanized before or during initial veterinary examination, 19 (8%) were found dead before veterinary examination, 2 (0.8%) had incomplete records, and 33 (13%) were stabilized by second intention or a method other than plate or screws and wire. The nonsurgical treatments included second-intention healing without any treatments (n = 12 [8%]), bandages (8 [3%]), silver-containing topical ointment only (5 [2%]), tape for fragment stabilization (3 [1%]), removal of mobile fragments (3 [1%]), and epoxy alone or with plastic (2 [0.8%]).

Ultimately, 51 turtles that underwent surgical fixation using plate and screws and wire hardware were included in the study. This group included 32 (63%) painted turtles, 11 (22%) common snapping turtles, 3 (6%) common map turtles (Graptemys geographica), 3 (6%) Blanding’s turtles (Emydoidea blandingii), and 2 (4%) spiny soft-shell turtles. There were 21 (41%) adult females, 27 (53%) adult males, 2 (4%) sex-undetermined adults, and 1 (2%) sex-undetermined juvenile. Body weight at the time of examination ranged from 0.08 to 11 kg (median, 0.6 kg).

Shell fracture repair outcome

Of the 51 turtles, single shell fractures were reported in 25 (49%) turtles and multiple fractures in 26 (51%) turtles (Table 2). Most turtles had at least 1 fracture affecting the carapace (43/51 [84%]), followed by fractures of the bridge (20/51 [39%]) and plastron (15/51 [29%]). At least 1 fracture communicated with the coelom in 26 of 51 (51%) turtles, none of the fractures communicated with the coelom in 10 (20%) turtles, and presence or absence of communication with the coelom was not documented in 15 (29%) turtles. The shells of most turtles were surgically repaired with plates alone (n = 38 [75%]), followed by a combination of plate and screws and wire technique (8 [16%]) and screws and wire only (5 [10%]). Of 51 turtles, 13 (25%) did not survive > 4 weeks following hardware repair. As a result, 38 turtles were available for shell fracture outcome determination.

Patient outcome

Of the 38 turtles, complete shell fracture healing occurred in 36 turtles (95%) and incomplete frac-

Table 2—Shell fracture type, repair method and outcome for 51 freshwater turtles treated by surgical fixation using plates, screws and wire, or both.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total No. of turtles</th>
<th>No. (%) of turtles with successful fracture healing</th>
<th>No. (%) of turtles released</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number fractures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single fracture</td>
<td>25</td>
<td>21 (84)</td>
<td>19 (76)</td>
</tr>
<tr>
<td>Multiple fractures</td>
<td>26</td>
<td>15 (58)</td>
<td>14 (14)</td>
</tr>
<tr>
<td>Fracture type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open to coelom</td>
<td>26</td>
<td>17 (65)</td>
<td>15 (58)</td>
</tr>
<tr>
<td>Closed to coelom</td>
<td>10</td>
<td>7 (70)</td>
<td>6 (60)</td>
</tr>
<tr>
<td>Not reported</td>
<td>15</td>
<td>10 (67)</td>
<td>10 (100)</td>
</tr>
<tr>
<td>Fracture location</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carapace only</td>
<td>22</td>
<td>17 (77)</td>
<td>16 (72)</td>
</tr>
<tr>
<td>Plastron only</td>
<td>5</td>
<td>3 (60)</td>
<td>2 (40)</td>
</tr>
<tr>
<td>Bridge only</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Multiple locations</td>
<td>24</td>
<td>15 (63)</td>
<td>14 (58)</td>
</tr>
<tr>
<td>Patient outcome</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All turtles surgically repaired</td>
<td>51</td>
<td>36 (71)</td>
<td>33 (65)</td>
</tr>
<tr>
<td>Survived &gt; 4 wk after repair</td>
<td>38</td>
<td>36 (95)</td>
<td>33 (87)</td>
</tr>
</tbody>
</table>

— = Not applicable.

ture healing occurred in 2 (5%). The median time to start staged hardware removal was 42 days (range, 35 to 49 days). After initial hardware placement, the median time to fracture stability and removal of all hardware was 56 days (range, 26 to 77 days). The median duration of topical screw hole treatment following hardware removal was 14 days (range, 7 to 49 days). The median duration of systemic antimicrobial administration after initial hardware placement was 39 days (range, 13 to 216 days) and of analgesics was 10 days (range, 5 to 44 days).

Complications associated with surgical hardware placement were reported in 6 of 38 (16%) turtles (Table 2). The most common complication was screw hole infection (n = 4 [11%]), followed by fracture necrosis (1 [3%]) and deep screw hole penetration (1 [3%]). Most complications were associated with successful outcomes (5/6 [83%]) and eventual release of the affected turtle (4/6 [67%]). Complications associated with an unsuccessful outcome occurred in a single turtle (1/6 [17%]) secondary to implant-induced fracture necrosis in a spiny soft-shell turtle.

Fracture stability was not achieved by 4 weeks after surgical repair in 10 of 38 (26%) turtles, resulting in
premature removal of hardware. Premature removal of hardware was most frequently associated with fracture necrosis (n = 8), followed by fistula formation (1) and nonunion fracture (1). Most premature removals were associated with successful outcome and eventual release of the affected turtle (8/10). Hardware failure did not occur in any of the turtles.

Overall, the outcome was considered successful (ie, complete shell fracture healing) in 36 of 51 (71%) turtles, and 33 (65%) turtles were eventually released back into the wild. One animal was placed in a zoological institution due to hind limb paresis unrelated to shell fracture repair. For the remaining 2 turtles with successful fracture healing, one turtle was found dead 21 days after complete shell fracture healing and the other turtle was euthanized due to chronic aural abscessation.

Of the 2 (4%) turtles classified as having had an unsuccessful outcome (ie, euthanized due to incomplete fracture healing), both were euthanized due to extensive fracture necrosis resulting in premature plate removal on the plastron of a spiny soft-shell turtle and on the carapace of a common snapping turtle. The remaining 13 of 51 (25%) turtles did not survive > 4 weeks following hardware repair due to incomplete recovery from anesthesia (7 [14%]), a sudden decline in mentation (4 [8%]), and euthanasia due to hindlimb paresis (2 [4%]).

Discussion

Multiple surgical and external coaptation methods have been described in chelonians, with the method chosen for each fracture being dependent on the location and severity of the fracture and preference of the clinician. 6,8,16–21 The goal of this retrospective study was to evaluate the outcome of shell fractures after plate stabilization, screws and wire stabilization, or both in wild freshwater turtles. Most literature sources describing the management of shell fractures using plates and screws and wire are case reports involving a single animal or review articles describing the authors’ anecdotal experience. 6,8,16–21 Our results indicate that 71% of all turtles with shell fractures repaired with plates, screws and wire, or both resulted in acceptable healing and fracture stability for release.

Shell fracture immobilization aims to achieve a normal anatomic position for a sufficient time to allow bone healing while permitting visual assessment of healing. 5,7 While epoxy resin and fiberglass repair methods can be effective, these methods have fallen out of favor for traumatic shell fractures due to the risk of sealing in infection and the inability to manage open wounds. 7,8,17,22 Bridging methods utilizing metal bridges, fabric hooks and eyes, and cable ties have also been described but do not provide the same degree of stabilization as orthopedic repair. 5,10,11,22,23 Compared with other repair methods, plate and screw and wire repair techniques provide improved ability to reduce complex fractures and increased fracture stabilization. 8,11 Additional benefits include the ease of application without the need for specialized equipment or specialized training.

A major reported drawback of plate or screw and wire stabilization is the potential introduction of infection into the coelom through shell penetration by screws. 7,12,22 However, our results demonstrated an overall low (11%) occurrence of screw hole infections secondary to plate and screw and wire repair, and all turtles with screw hole infections were eventually released. Another reported disadvantage with plate and screws and wire techniques is the potential for implant failure. 12 While no incidences of hardware failure occurred in this study, fracture instability prompting premature hardware removal did occur in several turtles (26%). Fracture necrosis was associated with both premature hardware removals, indicating that the chronicity and severity of the fracture is more a contributing factor to fracture instability than the hardware itself. When hardware had to be prematurely removed, the fractures typically continued to heal. Both the size and weight of turtles can be limiting factors with plate or screws and wire application, with smaller turtles having a limited area for proper plate placement. While most turtles in this study were adults, our results suggested that plate application can be successfully performed in juvenile turtles as small as 81 g.

Complications occurred in 16% of cases in the present study. The most common complication was screw hole infection. Most complications were minor and improved with time, resulting in acceptable fracture healing for release (83%). This high number of successful outcomes suggests fracture healing was not hindered by shell penetration from screws.

An unsuccessful outcome occurred in 4% of turtles in this study. This failure rate is likely an indication of the difficulties in treating chronically infected shell fractures in freshwater turtles rather than failures of surgical fixation techniques. The 2 cases in which fractures failed to heal were associated with multiple chronic fractures of the carapace of a common snapping turtle and of the plastron of a spiny soft-shell turtle. Increased chronicity of shell fractures has been described to be correlated with a higher risk of contamination and a more guarded prognosis compared with fresh (< 6 hours old) fractures. 9 The suspected chronicity of these fractures could explain the lack of healing in the fractures of these turtles compared with the other turtles in this study. Another potential factor affecting fracture healing is the difference between the thick, leathery skin of the spiny soft-shell turtle compared with the other turtle species with keratinized shells in this study. 2 The pliable skin and poorly mineralized bone may provide a less stable anchor for screws and lead to increased mobilization of the hardware compared with a keratinized shell.

The median time to shell fracture healing with surgical hardware repair was 8 weeks in this study. While no studies have evaluated time to fracture healing with surgical hardware in freshwater turtles, a few case reports 9,13,14 have evaluated fracture healing time for some coaptation methods. In 4 Caspian turtles (Mauremys caspica) and 3 spur-thighed tortoises (Testudo graeca), the reported fracture healing time was 3 to 6 months. 9 A similar healing time
of 6 to 7 months was reported using hooks and cable ties in a spur-thighed tortoise and an African spurred tortoise (Geochelone sulcata).\textsuperscript{13} In aquatic turtle species, a healing time of 3 months was achieved using adhesive glue and bandaging.\textsuperscript{14} Compared with these methods, wound and fracture healing was rapid with surgical hardware repair and corresponded with the expected shell fracture healing time of 4 to 8 weeks.\textsuperscript{8} This rapid healing time can permit gravid turtles to be released earlier to lay eggs and can help reduce the burden on rehabilitator resources associated with overwintering turtles when release is delayed.

Chelonians with open fractures involving the coelom are reported to have a fair to guarded prognosis and can be difficult to treat successfully.\textsuperscript{6,8} However, our results do not support this statement. Shell fractures with coelomic communication successfully healed in 65\% of affected turtles, and 58\% were successfully released.

The high prevalence of motor vehicle impact injuries seen in this study was consistent with previous studies\textsuperscript{5,4} evaluating causes of reptile morbidity and mortality. This was expected given the tendency of freshwater turtles to migrate across roadways in search of suitable aquatic and breeding habitats. The turtle species presented for shell fractures in this study is consistent with previous studies\textsuperscript{6,5} in the Midwest region of the US, where the most common species noted were painted turtles followed by common snapping turtles.

Limitations of the present study, aside from its retrospective nature, included the lack of a control group, small sample size, incomplete records, and dependence on subjective evaluations from multiple clinicians. Despite these limitations, our results indicated that plate and screws and wire techniques are effective treatment options for shell fractures in freshwater turtles. Further clinical experience is needed to compare the effectiveness of the plate and screw and wire techniques with other shell repair methods and to evaluate their potential usefulness in wildlife and general practice settings.

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