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ARTICLE

Tensile strength and knot security of five suture materials exposed to natural summer conditions of a temperate lake

Connor H. Reid | **Steven J. Cooke**

Fish Ecology and Conservation Physiology Lab, Department of Biology, Carleton University, Ottawa, Ontario K1S 5B6, Canada

Correspondence
Connor H. Reid
Email: connorreid@cmail.carleton.ca

Abstract

Objective: Wild fish and other aquatic ectotherms are often subjected to procedures during field research that require wound closure using sutures. A variety of absorbable sutures are available for such purposes, yet degradation processes are highly dependent on temperature, and the environments in which wild ectotherms are released are almost always colder than the conditions for which absorbable sutures are typically designed (i.e., ~37°C). We therefore studied the degradation of various suture materials under a set of biologically relevant conditions for temperate freshwater fish.

Methods: Using a force gauge, we tested the tensile strengths and knot securities of loops tied with five different absorbable suture materials (PDS-II, dyed coated Vicryl, undyed coated Vicryl, plain gut, and chromic gut) prior to and during submersion in a temperate lake over an 8-week period.

Result: The naturally derived collagen-based suture materials (i.e., plain gut and chromic gut) exhibited major decreases in tensile strength within 2 weeks of submersion but maintained relatively high knot security throughout the study period. The synthetic suture loops had poorer initial knot securities that increased following submersion and showed little to no evidence of degradation after 8 weeks.

Conclusion: Variable rates of absorbable suture degradation, or lack thereof, were observed. We discuss the implications of these trends for fish welfare considerations such as suture retention, wound healing, inflammation, and infection under natural conditions.

KEYWORDS

equipment, fish, surgery, tagging, tools, welfare

INTRODUCTION

As with human medicine, veterinary practices, laboratory research, and field research may all entail procedures on animals that require closure of wounds. Whether a wound is being treated or an incision is made as part of a surgical procedure, sutures or surgical staples are often used to reappose tissues and facilitate healing, ideally aiding with the prevention of further damage or novel infections. For research on wild fish and aquatic ectotherms, sutures are generally preferred over surgical staples as staples, though quicker to administer, are definitively nonabsorbable as well as being more prone to dislodging, loss, and inconsistent healing success (Wagner et al. 2011; Reese Robillard et al. 2015). Although they could technically be removed, the reality is that most fish tagged in field situations are released into the wild and may never be captured again. A large array of suture materials is available for human and animal use, comprising varieties of both natural and synthetic origins. Many suture materials are absorbable, being degraded at variable rates depending on factors such as the type of tissue and fluid(s) surrounding the suture (e.g., stomach acid, bile, etc.; Tian et al. 1994). Since absorbable sutures are intended to break down over time and not be removed manually, they are desirable for use on wild animals that are to be released without the possibility or intention of recapture.

The extents to which absorbable sutures are degraded, and the rates at which degradation occurs, depend largely on temperature. The dissolution of absorbable sutures has historically been primarily targeted and tested under conditions physiologically relevant to humans, (e.g., test temperatures of ~37°C; Frazza and Schmitt 1971; Okada et al. 1992). The internal body temperatures of aquatic ectotherms, such as fish and amphibians, are controlled by ambient water temperatures far below the body temperatures of humans and most other mammals, which usually fall within ~36–40°C (Jensen 2012). The expected retention periods of absorbable sutures can therefore be much higher in organisms with lower body temperatures. Examples of prolonged absorbable suture retention to various extents have been observed in Chinook Salmon *Oncorhynchus tshawytscha* held for 98 d at 12°C (Panther et al. 2011), Chinook Salmon held for ≥100 days at ~9–13°C (Ammann et al. 2011), European Eel *Anguilla anguilla* held for 6 months at 4–12°C (Thorstad et al. 2013a), and hybrid Striped Bass (Striped Bass *Morone saxatilis* × White Bass *M. chrysops*) held for 120 days at 12–18°C (Walsh et al. 2000). Such long timeframes may be exacerbated for aquatic ectotherms if the suture degradation period overlaps with large environmental temperature decreases, such as seasonal cooling. Conversely, since the rates of wound healing and other biological processes also tend to slow with decreasing temperature, protracted suture retention may be advantageous if the sutures do not pull or tear through the skin before wound healing is complete (e.g., Byrd et al. 2019). Other factors that may or may not be influenced by temperature can affect suture degradation rates, depending on the material and degradation mechanisms. For example, synthetic sutures are degraded by nonenzymatic hydrolysis, while sutures of natural origin (e.g., gut) are primarily degraded by proteolytic enzymes such as collagenase at the suture site (Singhal et al. 1988). Bacteria that may be linked with infections have also been shown to variably affect suture degradation rates in mammalian tissues (Williams 1980). Thus, the question of which suture material is best used to close wounds or incisions in aquatic ectotherms being released into the wild is complex, with implications for postrelease wound healing and suture retention in cooler environments.

The tensile or breaking strength of a suture is the force required for a suture to break, divided by the cross-sectional area of the suture (Moy et al. 1992). Different suture materials and knot types affect the overall strength of a knot that, under physical loads, may either slip or come undone (knot failure) or remain intact while the suture itself breaks (Marturello et al. 2013). The capacity for a knot to resist failure under load is referred to as knot security. Suture tensile strengths and knot securities are often tested as a means of determining what materials and techniques produce optimal results in human and veterinary applications (e.g., maintaining incision or wound closure, withstanding forces generated by necessary movements; Rosin and Robinson 1989; Gnandt et al. 2016). Absorbable sutures should be degraded via their intended mechanisms (enzymatic or nonenzymatic hydrolysis) and not before the initial healing stages are complete, rather than coming undone prematurely due to poor knot security. In general, increasing the number of throws in a knot will increase knot security to a point, yet eventually the addition of extra throws will serve only to enlarge the knot, rendering the site more prone to physical irritation and infection (Wagner et al. 2011; Marturello et al. 2013). Positive associations have been found between surgeon experience and knot security, with more experienced surgeons capable of achieving optimal suture retention using simpler knots than less experienced surgeons (e.g., Deters et al. 2012; Marturello et al. 2013).

Impact statement

Incisions in fish are often closed with sutures that dissolve easily in humans, yet these sutures may not dissolve well in fish since they live in waters cooler than the human body. We studied how well five suture materials dissolved in a temperate lake over late summer/early autumn.

Suture degradation rates have been studied in vivo in fish, usually under aquaculture or laboratory conditions (Gilliland 1994; Chapmna and Park 2005; Thorstad et al. 2013a). However, observations under such conditions are typically limited to qualitative descriptors of degradation (e.g., suture presence/absence, intact/loose/fragile) rather than quantitative measures of tensile strength and knot security, which are difficult if not impossible to conduct on sutures implanted in living tissues. Field studies on wild fish are rarer but also highlight the possibility of prolonged suture retention; 3 out of 17 Largemouth Bass *Micropterus salmoides* captured and tagged in a small Ontario lake were found to have retained at least one absorbable (PDS II) suture after 1 year postrelease (Caputo et al. 2009). In another experiment, recaptured Walleye *Sander vitreus* from Lake Erie and Lake Huron had an estimated 50% probability of retaining at least one absorbable (PDS II) suture by 673 d posttagging (Schoonyan et al. 2017). We are only aware of suture degradation being quantitatively studied at environmentally relevant temperatures under laboratory conditions with tap water (Cannizzo et al. 2016) rather than in natural waterbodies with fluctuating temperatures, variable water chemistries, microbiota, and other potentially relevant parameters. This experiment was therefore conducted in order to quantify suture degradation under ambient conditions in a temperate lake over an 8-week period. We tested tensile strength, knot security, and breaking patterns before and over the course of the submersion period in suture loops tied with five different commercially available suture materials.

METHODS

Experimental protocol

This experiment was conducted at Queen's University Biological Station on Lake Opinicon, Elgin, Ontario (44.565585°N, −76.323234°W). We did not collect water chemistry data; however, 2019 data from this lake reported by Balasubramanian et al. (2022) included a pH of 8.2, silica levels of 1.69 mg/L, and total nitrogen and phosphorus values of 406 and 11.3 µg/L, respectively. We obtained size 3–0 sutures (Ethicon) made of five different material types that are considered to be absorbable in mammalian contexts: PDS-II (polydioxanone, a synthetic monofilament suture), undyed braided coated Vicryl (polyglactin 910; synthetic), violet-dyed braided coated Vicryl, plain gut, and chromic gut. All sutures were purchased within 2 months of the experiment, and thus were not expired. Sutures were tied into loops around a section of 0.75-in (19.05-mm) chlorinated PVC tube (loop circumference ≈ outer diameter of chlorinated PVC tube ≈ 1 in or ~25.4 mm). Each knot consisted of a double throw, followed by a single throw, followed by another double throw (i.e., a surgeon's knot with an extra double throw; Wagner et al. 2011). A total of 50 knots were made for PDS-II and plain gut sutures, while 51 were made for dyed coated Vicryl and chromic gut sutures due to a counting error. The undyed coated Vicryl sutures were shorter and only provided enough material for 38 loops. All loops were tied by one author (C.H.R.) wearing nonsterile latex gloves, with a needle driver manipulating the needle end of the suture and gloved fingers handling the opposite end. To measure suture integrity over time, we used a digital force gauge (50 N max; Mxmoonfree) to record the break force of sutures prior to immersion in water and following 2, 4, 6, or 8 weeks of immersion. The number of loops tested at each time point is given in Table 1.

Throughout, we use the term tensile strength to refer simply to the force required for sutures to break since all sutures were the same diameter. To test tensile strength, loops were placed around a nail hammered straight into a wooden plank that was laid down on a table (Figure 1A). The force gauge was hooked onto the loop and set to "peak" mode to record the force (N) required for a loop to break. The model of force gauge we used had a safe maximum force of 50 N but could withstand up to 60 N, a value that was not surpassed over the course of this study. Each loop was positioned such that the knot was on one of the stretched sides of the loop, halfway between the nail and force gauge hook (Figure 1B). Once positioned, force was applied to the suture by pulling the force gauge away from the nail at a rate of ~3–4 mm/s until the loop broke or failed. A ruler was placed on the wooden plank parallel to the direction in which loops were pulled to help gauge the pulling rate. We recorded the measured break force and whether the knot itself came undone, but only began recording whether the suture broke at the knot for each loop partway through testing at week 2 due to an oversight. For each material, loops were divided as evenly as possible across sampling times; for each combination of material and sampling time, suture loops were grouped on a loop of braided fishing line (similar to keys on a keyring).

TABLE 1 Number of suture loops tested at each point in time over the course of this experiment for each material type. Week 0 refers to testing after tying with no immersion in water. Weeks 2–8 denote the time that loops had been left in lake water under ambient conditions in Lake Opinicon prior to testing. All sutures tested were size 3–0.

Suture material	Week 0	Week 2	Week 4	Week 6	Week 8
PDS-II (polydioxanone)	10	10	10	10	10
Coated Vicryl (910 polyglactin), dyed	10	10	11	10	10
Coated Vicryl, undyed	8	8	7	7	8
Plain gut	10	10	10	10	10
Chromic gut	10	10	11	10	10

FIGURE 1 Panel (A) shows an image of the suture loop tensile strength testing setup, with force meter and suture contained within a plastic bag to minimize posttesting suture flight. The suture was looped onto a nail in the board (visible above the force meter), and the meter was pulled down the board away from the nail to put tension on the suture loop. A plastic ruler, also shown, was used to gauge approximate pulling rates. Panel (B) shows a close-up of how sutures were positioned on the setup, looped around both the nail and the hook on the force meter. The knot was positioned halfway between the nail and hook such that the applied force put tension on the two strands leading to the knot at 180°. Panel (C) shows the weighted wooden board holding all suture loops as well as the temperature logger (vertical yellow cylinder near the board's center), prior to being covered with several layers of black window screening to reduce photodegradation. The anchor is not shown.

The first trials, "week 0," were conducted after the loops were tied with no time spent in water.

The fishing line rings holding the remaining loops were tied to metal hooks on a wooden board that was left submerged ~65 cm below the surface of Lake Opinicon off one of the docks at Queen's University Biological Station (Figure 1C). The wooden board was tied to a cleat on the dock and weighed down with an anchor. Three to four layers of black window screening were wrapped around the board to shade the sutures without entirely blocking light, reducing the risk of excessive photodegradation by mimicking the relatively dark ventral sides of a fish where sutures are often required after electronic tag implantation surgeries. A temperature logger (RBRsolo^3 T; RBR Global) was suspended at the same depth as the wooden board and programmed to record temperature every 15 min over the course of the experiment. The sutures were pulled out of the water every 2 weeks for a total 8 weeks, and one group of loops from each material was removed each time for tensile strength testing. Testing took place in the manner described above at each point in time, with suture material testing order randomized each time. Only one suture loop, a chromic gut loop tested at week 8, broke with too little force to register on the meter, thus the break force for this loop was recorded as the minimum measurable value on the device (0.01 N) to provide a realistic but conservative estimate. Data were also downloaded from the temperature loggers every 2 weeks at the same time as testing, with any values recorded out of the water deleted from the dataset. Temperature data were exported and logger programming set and verified using Ruskin version 2.19.1 (RBR, Ltd.).

Statistical analyses

All data analyses were performed in RStudio (version 2022.07.0 + 548, RStudio Team 2022; R version 4.1.3, R Core Team 2022). Figures were generated using "ggplot2" (Wickham 2016). A generalized linear model was fitted for break force, with a Gaussian error distribution and suture material, testing time point, and the interaction of material and time as predictor variables. Similar generalized linear models but with binomial error distributions were also fitted for whether the knots failed during testing and whether loops broke at the knot. Post hoc comparisons were performed using "emmeans" (Lenth 2022), with Bonferroni corrections applied to account for the high number of simultaneous pairwise comparisons.

RESULTS

General trends

Water temperatures throughout the 8-week submersion period ranged from 27.6°C to 19.8°C (Figure 2). The tensile strengths of suture loops changed with time ($F_{4,\ 213} = 55.85$, $p < 0.0001$) and differed between materials ($F_{4,\ 213} = 9.60$, $p < 0.0001$), with highly differential patterns observed across combinations of materials and time (interaction $F_{16,\ 213} = 33.25$, $p < 0.0001$). Overall, the force required for loops to break or fail was least different across materials during initial testing on loops that had not been submerged in water, and the synthetic material loops that were submerged for 2–8 weeks showed increased break strengths relative to the initial measurements, while loops derived from natural sources rapidly lost structural integrity over the same time period (Figure 3). Whether loop knots failed was dependent on material (likelihood ratio [LR] $\chi^2 = 32.39$, df = 4, $p < 0.0001$) rather than time (LR $\chi^2 = 6.79$, df = 4, $p = 0.148$), though a somewhat consistent interaction trend was observed (interaction LR $\chi^2 = 26.22$, df = 16, $p = 0.051$). Precise statistical comparisons of knot failure rates, where knots came undone during testing before the loop could break, was precluded by many combinations of material and testing time having no failures (i.e., no variance in the data for 13 out of 25 material–time combinations; Figure 4). No chromic gut knots failed during the experiment and only two plain gut knots failed at week 2, while knot failure rates were higher for synthetic suture loops. As mentioned, we began recording whether loops broke at the knot or elsewhere partway through the study; therefore, we have no such data for all materials at week 0 or for chromic gut loops at week 2. Nonetheless, the probability of loops breaking at the

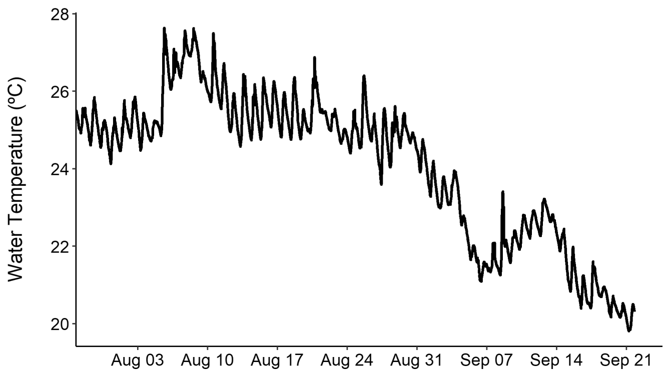

FIGURE 2 Temperature data for the submersion period in this experiment (July 27 to September 21, 2022) at ~65 cm below the surface, where the sutures remained while submerged.

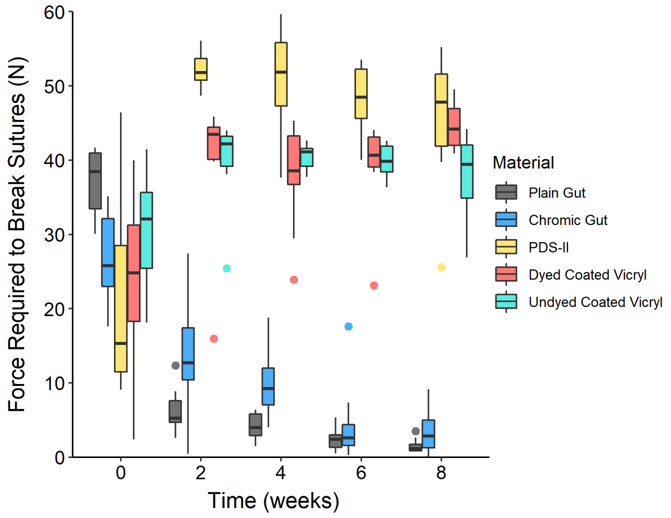

FIGURE 3 Tensile strength distributions of suture materials tested prior to submersion (week 0) and every 2 weeks until 8 weeks after submersion. The bars in the boxes show the median, the box dimensions show the 25th to 75th percentile range, the whiskers run to the furthest points falling within 1.5× the interquartile range, and dots are outliers falling beyond the whiskers' maximum range.

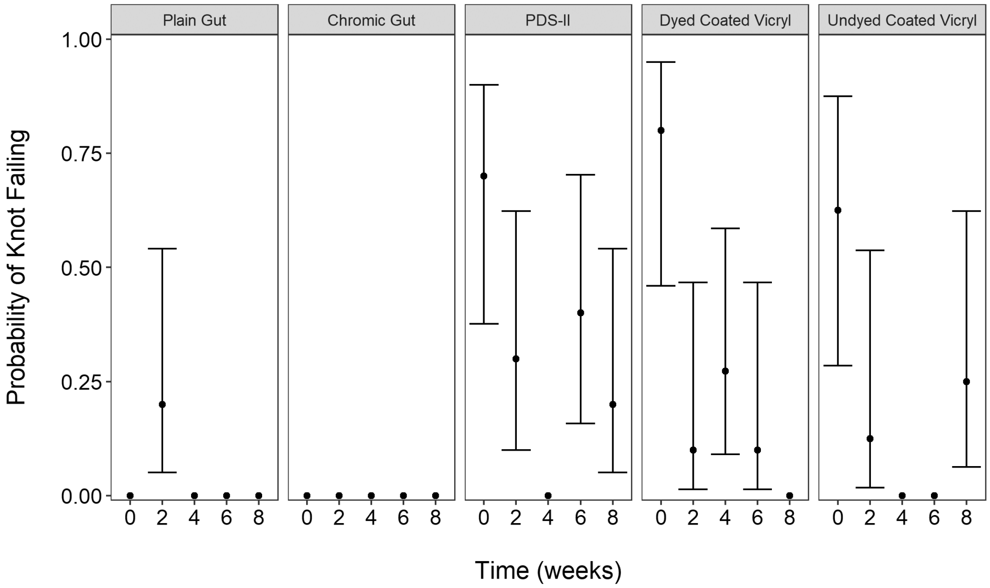

FIGURE 4 Mean probabilities of suture knots failing (coming undone) rather than loops breaking for each material and testing time, with asymptotic 95% confidence intervals. No confidence intervals are present for material and time point combinations that had 0% knot failure rates.

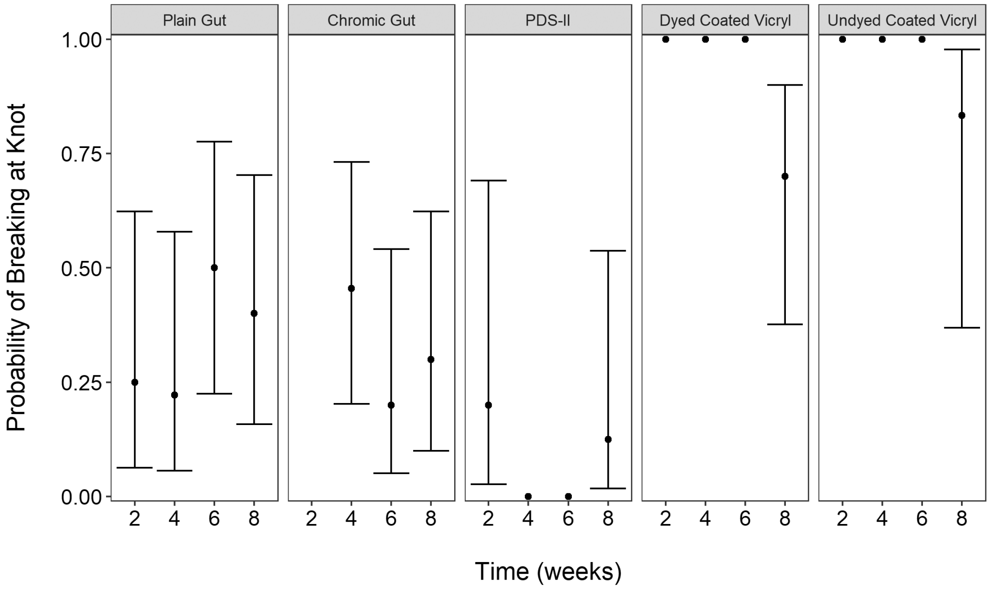

FIGURE 5 Mean probabilities of suture loops breaking at the knot versus elsewhere on the loop for each material and testing time, with asymptotic 95% confidence intervals. No confidence intervals are present for material and time point combinations that had 0% or 100% probabilities of breaking at the knot.

knots was different across material types (LR $\chi^2 = 86.58$, df = 4, $p < 0.0001$) regardless of the time of testing (LR $\chi^2 = 1.26$, df = 3, $p = 0.739$). We did not observe any notable interaction effects between material and time on where the loops broke (interaction LR $\chi^2 = 17.24$, df = 11, $p = 0.101$). As with knot failure rates, post hoc comparisons of where sutures broke were confounded by 8 of the 19 available material–time combinations having either 100% or 0% probabilities of breaking at the knot (Figure 5). Both dyed and undyed coated Vicryl loops broke at the knot 100% of the time at weeks 2, 4, and 6 and at week 8 broke at the knot 70% and 83% of the time, respectively. At all tested times, plain gut and chromic gut loops broke at the knot 20–50% of the time. The

PDS-II loops had the lowest rates of breaking at the knot, with 20% of loops at week 2, 0% at weeks 4 and 6, and 12.5% of loops at week 8.

Changes in tensile strength over time

At initial testing (week 0), plain gut suture loops had a higher mean tensile strength (37.17 N) than those made of chromic gut (26.69 N), PDS-II (21.66 N), and dyed coated Vicryl (22.96 N; all $p \leq 0.0032$) but not undyed coated Vicryl (30.77 N; $p = 0.359$). None of the knots failed during initial testing of plain or chromic gut loops, while high rates of knot failure were observed for PDS-II and both dyed and undyed coated Vicryl loops (mean probabilities of failure = 62.5–80%; Figure 4). Synthetic suture materials, particularly PDS-II and dyed coated Vicryl, displayed particularly high variation in initial tensile strength.

After 2 weeks of submersion in the lake, large differences were observed in both the mean values and variation observed in tensile strengths. Relative to week 0, mean tensile strengths were higher by 31.51 N for PDS-II (52.17 N; $p < 0.0001$), 17.21 N for dyed coated Vicryl (40.17 N; $p < 0.0001$), and 9.01 N for undyed coated Vicryl (39.77 N; $p < 0.053$). Conversely, mean tensile strengths had decreased by 31.01 N for plain gut (6.16 N; $p < 0.0001$) and by 13.06 N for chromic gut (13.64 N; $p = 0.0001$). Both plain and chromic gut loops required far less mean force to break than any of the synthetic materials (all $p < 0.0001$) but did not differ greatly from each other ($p = 0.096$), apart from higher observed variance in the chromic gut loops. On average, PDS-II suture loops had the highest tensile strengths, requiring more force to break than dyed coated Vicryl ($p = 0.0006$) and undyed coated Vicryl ($p = 0.0006$).

Over weeks 2–8, dyed and undyed coated Vicryl suture loops exhibited no major changes in tensile strengths at each subsequent testing period (all $p \geq 0.195$) or relative to each other at a given time (all $p \geq 0.211$). Changes in average tensile strengths of PDS-II loops every 2 weeks were minimal (all $p = 1.00$), with a total decrease of only 6.47 N from week 2 to week 8 ($p = 0.250$), concomitant with greater variances observed from week 4 onwards. Similarly, minimal changes were observed in mean tensile strengths for plain gut loops from weeks 2 to 8, decreasing by no more than 2.08 N with every subsequent test (all $p = 1.00$), for a total decrease of 4.64 N from week 2 to 8 ($p = 1.00$). Greater changes in mean tensile strengths occurred for chromic gut loops; although these did not differ by more than 5.71 N during consecutive test periods (all $p \geq 0.422$), the overall decrease from week 2 to week 8 was 9.99 N ($p = 0.0059$).

DISCUSSION

Tensile strength performance and knot security over time

Suture materials of synthetic versus natural origin displayed highly differential trends in tensile strength over the 8-week submersion period in the lake. Plain and chromic gut sutures lost 83% and 50% of their tensile strengths, respectively, within the first 2 weeks of submersion during which water temperatures were ~24–28°C. Synthetic sutures showed no net loss of tensile strength over the 8-week period and, if anything, became somewhat stronger during the first 2 weeks. Cannizzo et al. (2016) tested two synthetic suture materials and noted similar increases in tensile strength after 2 weeks in water at 25°C that contrast with other reports of tensile strength only decreasing with time (e.g., Capperauld 1989; Freudenberg et al. 2004). Despite submerging suture loops under different chemical conditions, our results replicate the observation of Cannizzo et al. (2016) that 2 weeks (or less) of submersion in water appears to increase the tensile strength of at least some synthetic sutures and also corroborate their proposed explanation that this trend would be influenced by higher knot failure rates in the initial test group. Our experiment does not necessarily support the hypothesis that submersion-induced increases in tensile strength may also be due to whether initial strength testing was performed on wet or dry loops as Cannizzo et al. (2016) also suggested, as our baseline loops had been tested dry while their baseline loops had been submerged for 5 h.

In humans, gut sutures and synthetic absorbable sutures are primarily broken down by different mechanisms. Gut sutures, which consist mainly of collagen fibers, are degraded by collagenases, while synthetic sutures are primarily broken down by nonenzymatic hydrolysis, though some enzymatic processes may contribute to synthetic polymer degradation as well (Singhal et al. 1988; Okada et al. 1992). The sutures in this experiment would have been exposed to both nonenzymatic hydrolysis from the lake itself and enzymatic hydrolysis from microbiota such as bacteria, many species of which are capable of producing various types of collagenases (reviewed in Duarte et al. 2014). We did not quantify collagenase activity on the loops, and we do not know how the observed degradation rates of plain and chromic gut sutures would compare to those that would be observed for gut sutures implanted in a fish, where most of the collagenase would likely come from surrounding tissue, with less expected colonization of exposed suture material by bacteria and algae due to swimming-induced friction. Anecdotally, we observed considerable build-up of algae and microbes on all of the suture loops over time; physical removal of this build-up to limit microbial degradation was not possible as this would risk damaging the sutures and confounding our results. For this reason, we also did not collect data on what microbial taxa were present on the loops at the time of testing. However, we recommend that future research on suture dissolution in natural waters include data on both the general microbial community assemblages present in the water as well as which of these taxa were specifically observed growing on suture materials. Such data may help elucidate candidate species that may be capable of colonizing sutures implanted in live fish in the system of interest. If overall collagenase activity were to be lower in fish, then perhaps the retention of plain or chromic gut sutures may be longer than the values reported here. In one experiment on Largemouth Bass maintained at 18°C, average absorption times for plain and chromic gut sutures were 3 and 5 weeks, respectively (Gilliland 1994), though the influence of temperature differences between that experiment and ours (along with other presumed differences in water chemistry) cannot be ignored.

The ambient conditions in the lake fell between ~9–17°C cooler than the healthy internal body temperature of humans (~37°C). Degradation of synthetic sutures by abiotic hydrolysis was therefore slower in the lake, and in fact we have little evidence that much dissolution took place at all given the relative consistency in tensile strengths of PDS-II and both forms of coated Vicryl suture loops over time (Figure 3). In sutures (as well as other strings, ropes, etc.), the weakest points of a loop or tied segment tend to be the knots themselves or places adjacent to the knots, where the material is highly curved and under increased load relative to sections farther away from the knot (Tera and Aberg 1976; Pieranski et al. 2001; Greenberg and Clark 2009). That both dyed and undyed coated Vicryl loops started to begin breaking away from the knot at week 8 may be indicative of some degree of dissolution that was not detected in tensile strength testing. An alternative explanation could be increases in knot security, but this is unlikely as the trends in knot failure rates for Vicryl loops suggest that knot security would only have increased within the first 2 weeks of submersion. The PDS-II knot failure rates exhibited a similar trend but loops largely broke away from the knots, which is surprising given the reputation of PDS-II for relatively poor knot security (Rosin and Robinson 1989; LaBagnara 1995).

Implications for use on wild fish

Wound healing in fish is a complex process that can demand days, weeks, or even months to complete, depending on the type and size of wound, the wound's location on the body, the species of fish in question, infection occurrences, suture type and retention, and environmental temperatures (Jepsen et al. 2002; Caputo et al. 2009; Ceballos-Francisco et al. 2017; Schoonyan et al. 2017; Sveen et al. 2020; Yun et al. 2021). We echo concerns previously raised by others (e.g., Gilliland 1994; Jepsen et al. 2002) that gut sutures may be inappropriate in situations where the suture is likely to be absorbed or shed before wound healing is complete. Furthermore, for fish that have been surgically implanted with intracoelomic transmitters or loggers, premature suture degradation can lead to implant loss through openings at the surgical site (Deters et al. 2012; Wagner et al. 2011). Chromic gut sutures are designed to have slower degradation rates than plain gut sutures in human medicine (Moy et al. 1992); however, under our experimental conditions our results suggest that chromic gut sutures yield little to no practical benefit over plain gut in terms of tensile strength changes over time. When long wound healing periods are anticipated and premature suture loss and wound dehiscence are likely, synthetic materials appear to be the more reliable choice. Moreover, higher rates of tissue reactivity are often reported for plain and chromic gut sutures compared with synthetic sutures in human and mammalian literature (e.g., Benicewicz and Hopper 1990; Moy et al. 1992; LaBagnara 1995). This trend is also generally, but not universally, reported in fishes (e.g., Gilliland 1994; Hurty et al. 2002).

In the short term, synthetic monofilament sutures tend to elicit less inflammation than Vicryl or other braided sutures such as silk (Gilliland 1994; Wagner et al. 2000). Increases in inflammation severity may be pertinent to tag retention, with wounds that heal more poorly being more susceptible to tag loss (Ivasauskas et al. 2012), further supporting the use of synthetic monofilament sutures for electronic tag implantation surgeries. However, once a wound is healed, sutures that fail to degrade in a timely manner may increase the risk of subsequent irritation and infections (Caputo et al. 2009). In the long term, PDS-II can become brittle and break into potentially irritating fragments in fish months after administration, while Vicryl may be more readily absorbed (Chapmna and Park 2005). The odds of recapturing wild fish to remove sutures after a wound has healed are very often low to virtually impossible, and so it is worth considering the eventual fate of sutures and fish welfare beyond the scope of wound healing. The only reliable means for nonrecaptured wild fish to lose sutures are to either absorb them and/or shed them over time through decreasing suture strength and sufficient physical forces (e.g., water drag or biting if fish can reach the sutured area; Thorstad et al. 2013a, 2013b). Yet, differences in wound inflammation and healing at an incision site do not necessarily translate to biologically relevant effects on other metrics of fish health and welfare, such as behavior, growth, and survival (Miller et al. 2013; Wagner and Stevens 2000). With considerable variation in study species, environmental conditions, and research aims, future work involving suturing and releasing wild fish should consider how to limit suture retention past the point of wound healing and keep the potential negative consequences of suture retention to the minimum necessary (or unavoidable) extent on a case-by-case basis. The board on which our suture loops were placed also remained stationary in the water, whereas sutures placed in fish would be exposed to additional forces from the natural movement of fish, depending on the fish and position of the suture. These forces may affect both suture retention (for materials that may be more prone to breakage) or infection (for materials that are resistant to degradation and continue to irritate tissues). Moreover, although we attempted to bring more realism to our research by holding sutures in a lake, the reality is that there is a need to consider how conditions across different water bodies (e.g., water chemistry, hydraulics, temperature, microbiota) influence suture performance. Quite simply, more research is needed to better inform suture choice when working on wild aquatic ectotherms in the field. Other factors that were not explored here were knot type and suture diameter, which could potentially be manipulated to obtain the optimal trade-off that allows for healing followed by rapid loss of sutures.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data and statistical analysis code are available from the cooresponding author upon request.

ETHICS STATEMENT

This research used no animal models and no ethical guidelines were applicable to this study.

ORCID

Connor H. Reid https://orcid.org/0000-0001-9431-9044

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