Bleeding associated with surgery is a potentially serious complication, and hemostasis is vital for a successful outcome. Secure ligation of vasculature is essential in surgery, including commonly performed procedures such as ovariohysterectomy, ovarioectomy, orchietectomy, splenectomy, nephrectomy, liver and lung biopsy and lobectomy, and limb amputation. Although several vessel ligation modalities, including stapling equipment, electrocautery vessel sealing devices, harmonic scalpels, resorbable polydioxanone cable ties, and vascular ligation clips, have been evaluated, ligation with suture remains a cornerstone for hemostasis for many veterinary surgeons.

Although postoperative complications following ovariohysterectomy are relatively uncommon and intraoperative bleeding during this procedure rarely results in life-threatening postoperative hemorrhage, it remains the most common cause of postoperative death in dogs. In studies that evaluated complications observed during and after ovariohysterectomy and ovarioectomy performed by veterinary students, hemorrhage from an ovarian pedicle occurred in 4% to 9% of dogs. In 1 study, intraoperative hemorrhage was observed in 69 of 87 (79%) large-breed dogs (> 22.7 kg [50 lb]), most commonly resulting from loss of control of a vascular pedicle prior to ligation completion or ligature failure secondary to insufficient knot-tying technique. Regardless of a surgeon's degree of experience, large amounts of intra-abdominal fat can make pedicle ligation difficult. Fat coating the surface of suture has also been shown to decrease knot security of monofilament absorbable sutures. It is vital to maintain a tight first throw on a ligature because it prevents slippage or unwanted loosening until subsequent locking throws are placed. If the first throw accidentally loosens before the second throw is formed, the knot can be locked in a loose fashion, and the vascular pedicle may not be securely ligated. Adding extra throws can enhance security of a tight first throw, but this changes the knot profile and increases its bulk.

Vessel ligation is commonly and successfully performed with suture in veterinary surgery; however, we have observed (during surgical training of veterinary students with live patients and in clinical surgery cases from other veterinary hospitals) that many knots are commonly tied improperly or used inappropriately. The surgeon’s throw has previously

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**In vitro holding security of six friction knots used as a first throw in the creation of a vascular ligation**

Kurtis M. Hazenfield, DVM, and Daniel D. Smeak, DVM

**Objective**—To compare in vitro security of 6 friction knots used as a first throw in the creation of a vascular ligation.

**Design**—Experimental study.

**Sample**—20 constructs of 6 friction knots created with 2-0 polyglyconate suture.

**Procedures**—Security of the surgeon’s throw, Miller’s knot, Ashley modification of the Miller’s knot, constrictor knot, and strangler knot was evaluated. Each knot configuration was constructed around each of 2 balloon dilation catheters used as small- and large-diameter vascular pedicle models and pressure tested to failure (bleed-off) 10 times. Results were compared by means of ANOVA and Student t tests.

**Results**—Mean leakage pressure for the surgeon’s throw was significantly lower than that of all other knots tested in both pedicle models. The Miller’s knot, constrictor knot, and strangler knot had mean leakage pressures > 360 mm Hg regardless of model diameter, whereas the surgeon’s throw, Ashley modification of the Miller’s knot, and modified Miller’s hand tie consistently leaked at pressures at or below those found in arteries under normal physiologic conditions (pressures of 90 to 140 mm Hg).

**Conclusions and Clinical Relevance**—Security of the Miller’s knot, constrictor knot, and strangler knot was considered excellent. In vitro results suggested that, when constructed correctly, these friction knots may be preferable first-throw constructs during vascular pedicle ligation and should be further evaluated for clinical use. The surgeon’s throw was less reliable as a first throw for vascular pedicle ligation in the model tested. (J Am Vet Med Assoc 2014;245:571–577)

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Covidien donated 2-0 polyglyconate suture material.

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been shown to help appose tissue edges held under tension until additional throws are placed. However, in the case of vascular ligation, tension must be released from the suture ends during creation of a second throw to prevent conversion of the first throw into an insecure half hitch. During this brief period, the first throw of a knot may loosen because of pressure and radial expansile force within the encircled vessel or pedicle, causing the entire ligature, regardless of the number of additional throws placed, to be loose and allow bleeding or even to slip from the pedicle. Many veterinarians advocate use of the surgeon’s throw as the first throw of a vascular ligation; however, the authors’ clinical impression is that this knot is likely a poor choice for this purpose.

To our knowledge, there is no information available that establishes the holding power of the first throw (ie, friction knot) of an encircling ligature. Current information on friction knots is often inconsistent or difficult to visualize and interpret from illustrations. The purpose of the study reported here was to compare in vitro security of 6 friction knots used as a first throw in the creation of a ligation. Our first hypothesis was that all other friction knots tested would have greater leakage pressure than that of the surgeon's throw. Our second hypothesis was that use of a pedicle model with greater diameter would have a negative effect on knot security, compared with a smaller-diameter model.

**Materials and Methods**

**Model and study design**—Open-ended esophageal balloon dilation catheters of 2 diameters (6 and 12 mm) were used as a vascular pedicle model in an in vitro experimental study. The inner diameter of the 6-mm balloon dilation catheter was 0.51 mm. A piece of silicone rubber tubing was used to create an inner diameter of 6.35 mm within the 12-mm balloon dilation catheter to represent a thick segment of tissue within a large pedicle (Figure 1). All knot constructs were tied and tensioned as described in the next section by 1 investigator (KMH). Each configuration was evaluated with increasing (within-catheter) pressure application 10 times on each of the small and large-diameter balloon dilation catheters (n = 10 trials/knot type/pedicule model). Each set of 10 trials for each knot configuration was performed in sequence.

**Knot construction**—Six types of friction knots (the Ashley modification of the Miller’s knot, the constrictor knot, the Miller’s knot, the modified Miller’s knot hand-tie, the strangle knot, and the surgeon’s throw) were
each constructed with a 15-cm length of monofilament absorbable suture (2-0 polyglyconate; Figure 2). Prior to construction and testing of a friction knot, an overhand loop knot17 was tied at each end of each strand in preparation for securing the suture ends during tensioning. To mimic the effect of perivascular adipose tissue on knot security, cadaveric falciform fat (at room temperature [approx 21°C]) was applied to the surface of each suture strand by running the suture through the center of the fat sample 3 times and to the balloon dilation catheter by topical application before each throw was constructed. The balloon dilation catheter was filled to capacity with saline (0.9% NaCl) solution to eliminate redundancy within the balloon prior to suture placement; no pressure was created within the balloon during this step. Following construction, each throw was tightened with equal tension on opposite sides, with the pretied end loops attached to a custom, fixed, bench-mounted base and a digital hand scale, to a force of 19.61 N (2.0-kg force). Tension was maintained for 10 seconds prior to release and pressure testing. No locking throws were placed to ensure the test was only evaluating friction knot holding strength.

Pressure testing—Following friction knot construction and tensioning, system pressure was calibrated at 0 mm Hg, and saline solution was infused into the balloon dilation catheter at a constant rate of 3.0 mL/min with a digital syringe infusion pump. The closed system was instrumented with a micropipet transducer, and pressures were monitored continuously with a commercially available software program. leakage pressure (mm Hg; used as a measure of friction knot security) was defined as the point at which a plateau or drop in the pressure curve (defined as a 0.2% offset) occurred. To ensure that testing only evaluated first-throw holding strength, no locking throws were used.

Table 1—Mean ± SD first-throw leakage pressures and 95% confidence intervals for 6 types of surgical knots constructed with 2-0 polyglyconate around 6- and 12-mm-diameter pedicle models (n = 10 trials/knot type for each model size).

<table>
<thead>
<tr>
<th>Knot type</th>
<th>6 mm Pressure (mm Hg)</th>
<th>95% CI (mm Hg)</th>
<th>12 mm Pressure (mm Hg)</th>
<th>95% CI (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashley modification of the Miller’s knot</td>
<td>105.87 ± 19.52</td>
<td>91.90–119.84</td>
<td>82.39 ± 44.93</td>
<td>50.25–114.54</td>
</tr>
<tr>
<td>Constrictor knot</td>
<td>389.27 ± 3.08</td>
<td>386.06–392.47</td>
<td>365.74 ± 2.55</td>
<td>363.91–367.56</td>
</tr>
<tr>
<td>Miller’s knot</td>
<td>388.19 ± 5.49</td>
<td>384.27–392.12</td>
<td>375.68 ± 3.41</td>
<td>372.25–383.08</td>
</tr>
<tr>
<td>Modified Miller’s hand-tie</td>
<td>280.83 ± 6.87</td>
<td>234.42–327.24</td>
<td>31.93 ± 2.21</td>
<td>30.33–33.49</td>
</tr>
<tr>
<td>Strangle knot</td>
<td>280.43 ± 5.06</td>
<td>280.81–384.05</td>
<td>360.11 ± 3.58</td>
<td>357.55–362.67</td>
</tr>
<tr>
<td>Surgeon’s throw</td>
<td>44.73 ± 5.96</td>
<td>40.47–49.00</td>
<td>32.79 ± 9.05</td>
<td>26.39–39.27</td>
</tr>
</tbody>
</table>

Leakage pressure was used as a measure of throw security and was defined as the point at which a plateau or drop in the pressure curve (defined as 0.2% offset) occurred. To ensure that testing only evaluated first-throw holding strength, no locking throws were used.

*Value is significantly (P < 0.05) lower than that for the same knot in the 6-mm pedicle model.

CI = Confidence interval.

Values with different superscript lowercase letters are significantly (P < 0.05) different among knot types for a given model size.
when there was evidence of leakage from the catheter distal to the knot.

Statistical analysis—Descriptive and comparative statistics were computed with commercially available software. Leakage pressure measurements were evaluated via the Shapiro-Wilk test and found to normally distributed for all groups. Leakage pressure measurements were summarized as the mean ± SD and 95% confidence intervals. One-way ANOVA was used for comparison of mean leakage pressure among all groups, and a Student t test was used to compare values between groups. Mean knot leakage pressure for the small- and large-diameter trial groups was compared by means of ANOVA, and a least squares mean differences Student t test was used to compare results for identical knots between groups. Values of P < 0.05 were considered significant.

Results

Mean ± SD leakage pressure differed significantly (P < 0.001) among the 6 knot types in trials where the small-diameter pedicle model was used (Table 1; Figure 3). The surgeon’s throw and the Ashley modification of the Miller’s knot leaked at pressures at or below those that would normally be encountered in arterial vessels under physiologic conditions (systolic arterial pressure, 90 to 140 mm Hg). All other knot constructs leaked at supraphysiologic pressures, with the constrictor knot having the highest mean leakage pressure. There was no significant difference in mean leakage pressure among the constrictor knot, Miller’s knot, and strangle knot.

In trials where the large-diameter model was used, mean pressure at which leakage occurred was also significantly (P < 0.001) different among knots (Table 1; Figure 3). The surgeon’s throw, Ashley modification of the Miller’s knot, and modified Miller’s hand-tie leaked at or below pressures expected in arterial vessels under physiologic conditions. There was no significant difference in leakage pressure between the surgeon’s throw and modified Miller’s hand-tie or between those of the constrictor knot, Miller’s knot, and strangle knot.

Increase in vascular pedicle model diameter resulted in a significant (P < 0.001) decrease in knot security (as determined by decreased leakage pressure) for all knot types except the surgeon’s knot and Ashley modification of the Miller’s knot; the largest significant (P < 0.001) difference associated with increased pedicle model diameter was found for the modified Miller’s hand-tie, for which mean leakage pressure decreased from 280.83 ± 64.87 mm Hg to 31.93 ± 2.21 mm Hg. The constrictor knot, Miller’s knot, and strangle knot all had leakage pressures > 360 mm Hg, although mean leakage pressure was significantly decreased from values for the same constructs with the small-diameter model (Table 1).
Vascular pedicle ligation with suture remains a standard means of achieving hemostasis in most veterinary surgeries. Several studies have shown that ligatures with suture achieve higher bursting pressures than newer bipolar sealing devices and may be used more effectively when ligating large-diameter vessels (>5 mm). Security of the first throw of a surgical knot is of paramount importance during vessel ligation because tension must be released from the suture ends following the first throw to create a second locking square throw. The first throw can be loosened by intravascular or tissue pressure during this short period, and if this occurs, additional locking throws may prevent further loosening but may not tighten the initial throw, resulting in the entire ligature being insecure and the possibility of slippage from the pedicle. Bleeding may not be observed immediately following vessel transection because of vascular wall spasm or hypotension secondary to anesthetic drug administration. However, these phenomena are typically corrected or subside in the postoperative period, and latent hemorrhage may occur in the event of insecure ligature placement.

In our study, the surgeon’s throw was found to be significantly less secure (ie, had significantly lower mean leakage pressure values) than that of all other knot types in both small- and large-diameter pedicle models. Increase in pedicle model diameter significantly decreased knot security for all constructs evaluated, and the modified Miller’s hand tie had the greatest difference in mean leakage pressures between the small- and large-diameter models.

Knot security of the Miller’s knot, constrictor knot, and strangle knot was considered excellent, with leakage detected only at pressures 2 to 3 times that of physiologic arterial blood pressure (systolic arterial blood pressure, 90 to 140 mm Hg) in small- and large-diameter pedicle model trials. This degree of security was achieved even with fat coating of the suture and pedicle model surfaces. The result could be attributable to the presence of an overriding turn (a section of suture that passes on top of another section of suture, often perpendicular or at an angle to the underlying section), which maintains tension by providing compression on the underlying turns of suture within these constructs (Figure 4). It was observed during this study that these knots could not be untied once constructed and tensioned unless the overriding turn was cut and released. These knots have inherently larger bulk than do encircling ligatures with a single turn (a wrap of suture around a pedicle that leaves the working end [end of a suture that is used to construct the knot] and standing end [part of the suture that remains static and is not used in knot construction] facing in opposite directions). However, on the basis of our in vitro model results, the slight increase in suture bulk is likely inconsequential when the improved friction knot security is taken into account. In our experience, construction of the strangle knot is easier to teach and faster to perform than the Miller’s knot or constrictor knot, whether done with an instrument or as a hand-tie. A step-by-step description with illustration for construction and tensioning of the strangle knot is provided (Figure 5). During construction of the Miller’s knot, constrictor knot, and strangle knot, the orientation of the subsequent turns remains crossed on the front side of the pedicle and parallel on the back side of the pedicle to maintain knot integrity.

In the present study, the modified Miller’s hand-tie was considered to have excellent security when used with the small-diameter pedicle model but substantially poorer security when used with the large-diameter model. The modified Miller’s hand-tie and strangle knot are very similar in construction, the difference being that the modified Miller’s hand-tie has 2 parallel turns beneath an overriding turn and the strangle knot, like the constrictor knot, has 2 crossed turns in an overhand knot configuration beneath the overriding turn. When the small-diameter model was used, it appeared that the modified Miller’s hand-tie could be constricted down on itself and tension could be maintained. However, with the large-diameter model, the parallel orientation of the underlying turns prevented the adjacent suture strands from locking on one another as seen with the constrictor knot and strangle knot.

There are 2 likely explanations for our observation that the surgeon’s throw was the least secure of all friction knots tested. First, the surgeon’s throw is constructed of 2 successive turns of the suture on itself with no overriding turn, therefore minimizing friction between the adjacent turns and limiting ability of the knot to maintain tension. Throw slippage was likely responsible for poor knot security in trials with the large-diameter pedicle model. Second, the surgeon’s throw cannot be tightened completely because as it is tensioned, the ends of the completed throw twist and capsize on its center, preventing further tightening (Figure 6). This phenom-
Surgical and postsurgical hemorrhage secondary to ligature failure observed during ovariohysterectomy or ovariohysterectomy procedures performed by veterinary students represents a lack of experience with appropriate use of friction knots for creation of secure ligatures. The effects of suture size and type on these friction knots should also be evaluated because there is likely to be a difference, compared with the results of the present study, in which only 2-0 polyglyconate was used. Construction and tensioning of a knot around an inflated catheter would seem more representative of a clinical scenario. However, during pilot testing, it was observed that all knots generated the same high pressures (> 360 mm Hg) with no difference in pressure curve or evidence of leakage if the balloon was left intact. An open-ended system was required to observe leakage; all knots had to be constructed and tensioned around an uninflated balloon that was subsequently inflated. An ex vivo extension of this study would be a more preferable method to evaluate knot security under conditions that better correspond to a clinical scenario. The Miller's hand tie had excellent knot security in the small-diameter model, imparting that it should be further evaluated for a critical diameter over which this construct should not be used. Our findings that the strangle knot, constrictor knot, and Miller's knot consistently remained secure in vitro at pressures far greater than those expected in arterial vessels under physiologic conditions suggest that these should be evaluated further for use in clinical conditions.

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