In vitro holding security of four friction knots of monofilament or multifilament suture used as a first throw for vascular ligation

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OBJECTIVE
To evaluate holding security of 4 friction knots created with various monofilament and multifilament sutures in a vascular ligation model.

SAMPLE
280 friction knot constructs.

PROCEDURES
10 friction knots of 4 types (surgeon's throw, Miller knot, Ashley modification of the Miller knot, and strangle knot) created with 2-0 monofilament (polyglyconate, polydioxanone, poliglecaprone-25, and glycomer-631) and braided multifilament (silk, lactomer, and polyglactin-910) sutures were separately tied on a mock pedicle and pressure tested to the point of leakage. Linear regression analysis was performed to compare leakage pressures among suture materials (within friction knot type) and among knot types (within suture material).

RESULTS
Mean leakage pressure of surgeon's throws was significantly lower than that of all other knots tested, regardless of the suture material used. All the other knots had mean leakage pressures considered supraphysiological. Significant differences in mean leakage pressure were detected between various friction knots tied with the same type of suture and various suture types used to create a given knot. Variability in leakage pressure among knots other than the surgeon's throw was greatest for poliglecaprone-25 and lowest for polydioxanone.

CONCLUSIONS AND CLINICAL RELEVANCE
Most differences in knot security, although statistically significant, may not have been clinically relevant. However, results of these in vitro tests suggested the surgeon's throw should be avoided as a first throw for pedicle ligation and that poliglecaprone-25 may be more prone to friction knot slippage than the other suture materials evaluated. (*Am J Vet Res* 2020;81:821–826)

Secure vascular pedicle ligation is a fundamental skill required for surgeons to safely perform a vast number of invasive procedures.[1] Despite the increasing availability of vessel-sealing devices able to consistently achieve hemostasis for surgeries such as ovariectomy,[2] castration, and splenectomy,[3] the importance of being able to properly secure hemostatic knots cannot be understated. Currently, vascular pedicle ligation remains the most commonly performed hemostatic technique used in a general practice setting where, because of cost limitations, vessel-sealing devices may not be practical.[4] Hemorrhage has been reported as a cause of death in dogs undergoing ovariohysterectomy,[5] splenectomy,[6] liver lobectomy,[7] and limb amputation.[8] The reported incidence of intraoperative bleeding following ovariohysterectomy at various teaching hospitals ranges from 4% to 9%,[9–11] but an incident rate as high as 79% has been reported for dogs weighing > 22.7 kg.[10] A greater frequency of intraoperative bleeding in this subset of dogs could be explained by latent bleeding attributable to a lack of securing and maintaining a tight first throw as subsequent square knot overthrows are placed.[1,4] After large pedicles are compressed with the first throw, expansion of the crushed tissue can unintentionally loosen the first throw before the second throw of a square knot locks the first throw in place.[1] This can produce a loose pedicle ligature that can allow substantial postoperative hemorrhage. It is imperative that the first throw remains tight when ligating a pedicle until subsequent throws are placed to secure the knot. In recent in vitro studies[1,4] of knots tied with monofilament and multifilament suture material on a variety of vascular pedicle models, it was shown that a single surgeon's throw is not reliable as a first throw on large vascular pedicles. Compared with other friction knots, the first throws of surgeon's knots have

ABBREVIATIONS

AMK	Ashley modification of the Miller knot

been shown to loosen and readily leak at pressures well below physiologic arterial pressure.[1,4]

In the human and veterinary medical literature,[12–16] there is no consensus on which type of suture material is best used for pedicle ligation. Some investigators have found that monofilament suture may perform better than multifilament suture,[12] whereas others have reported the opposite result.[13,14] The use of various types of suture material has theoretical advantages and disadvantages, with multifilament suture having greater pliability but also more tissue drag and higher capillarity that may lead to an increased risk of bacterial colonization of the suture.[15] On the other hand, because of their greater memory and lower coefficient of friction, monofilament sutures may compromise knot security, especially when a large gauge is chosen.[16]

The purpose of the study reported here was to compare the in vitro security of 4 different friction knots used as a first throw in the creation of a ligature with a variety of monofilament and multifilament suture types. We hypothesized that there would be a significant difference in knot security achieved with the 4 friction knots, but that knot security would not differ among suture types for each knot investigated.

Materials and Methods

Model design

A 12-mm-diameter, open-ended esophageal balloon dilation catheter[a] was used to mimic a vascular pedicle in the prospective experimental study as previously described.[4] Briefly, the mock pedicle was created by removing the distal end (approx 1 cm) of the plastic balloon portion of the catheter. A piece of silicone tubing[b] was advanced over the guidewire present in the central part of the balloon dilation catheter, but within the confines of the balloon, to create a pedicle with a diameter of 6.35 mm. This size of tubing was chosen to reproduce the test design from a previous study,[4] thereby allowing comparison of results between studies. The silicone tubing was secured to the metallic guidewire of the balloon dilation catheter with 3 strangle knots created with 2-0 polyglyconate[c] and cyanoacrylate glue. This step was performed to occlude the hollow portion of the tubing and avoid leakage of fluid during testing. Test samples were positioned proximal to the cut edge of the plastic portion of the balloon, in the approximate center of the remaining part of the balloon. The length of the tubing used was less than the remaining balloon length (approx 2/3 the length of the balloon present on the dilation catheter; **Figure 1**).

Knot construction

All knots were constructed and tensioned by 1 investigator (GT). Four friction knots were created with each of 7 different suture types commonly used in small animal surgery. The friction knots tested were the surgeon's throw, Miller knot, AMK, and strangle knot **(Figure 2)**. The materials used to create knots were 2-0 monofilament (polyglyconate,[c] polydioxanone,[d] poliglecaprone-25,[e] and glycomer-631[f]) and 2-0 braided multifilament (silk,[g] lactomer,[h] and polyglactin 910[i]) sutures.

Ten knots for each knot construct and suture type were created. All 10 samples created with different sutures were tested in an arbitrary order for each knot type. Each knot was constructed with a 20-cm-long suture strand. The testing setting was reproduced from a previously published study.[4] Before the construction and testing of a friction knot, an overhand loop knot was tied at the end of each strand to allow the suture ends to be secured during tensioning. To mimic the effect of greasy perivascular adipose tissue on knot security, fresh cadaveric falciform fat was applied to the surface of each suture strand by passing the suture through the center of the fat sample 3 times before it was used. The fat was collected with owner consent from dogs undergoing necropsy for reasons unrelated to the study and was maintained at room temperature (approx 21°C) before use. The balloon dilation catheter was filled with saline (0.9% NaCl) solution before suture placement; no pressure was created within the balloon during this step. Following construction, each friction knot was tightened with equal tension to a force of 19.61 ± 2.94 N (2.0 ± 0.3 kg) with the previously created end loops attached to a custom-made, fixed bench-

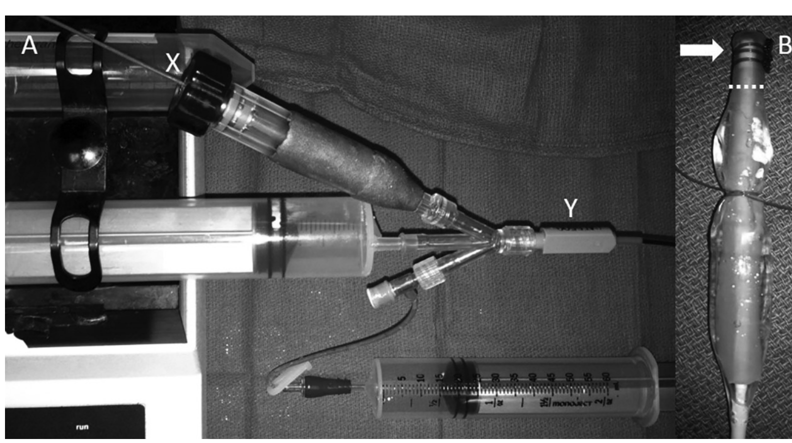

Figure 1—Photographs depicting the testing setup to evaluate leakage pressure in a study to determine knot security of 4 friction knots created with various monofilament and multifilament sutures and used for ligation of a mock pedicle in a vascular ligation model. No locking throws were placed after the friction knot to be tested was created. A—The pressure transducer with pressure transducer chamber (X) and connector of the balloon dilation catheter (Y) are indicated. B—Location of test ligature placement on the modified balloon dilation catheter (mock pedicle). The dotted line shows the level where the tip of the balloon catheter was cut. The arrow indicates where the silicone tubing was secured to the metallic guidewire present in the central part of the balloon dilation catheter.

mounted base and a digital hand scale.[j] Tension was maintained for 10 seconds before release and pressure testing. No locking throws were placed to ensure the test only evaluated the resistance of the first-throw friction knot to loosening during incremental balloon dilation.

Pressure testing

After knot tensioning, the balloon dilation catheter was inflated with saline solution at a rate of 3 mL/min by use of an infusion pump.[k] The balloon was distended to expand the first-throw friction knot to failure. The tip of a pressure transducer catheter[l] was positioned immediately before the balloon dilation catheter connector. Pressure was monitored continuously with commercially available software.[m] The test was discontinued if leakage was visibly noted between the outer surface of the tubing and the inner portion of the balloon catheter. Leakage pressure (measured in millimeters of mercury) was defined as the point on the pressure curve when the pressure decreased or reached a plateau. For purposes of comparison, a pressure > 160 mm Hg (the upper systolic arterial blood pressure measurement for normotensive dogs[17]) was considered a supraphysiological measurement for arterial blood pressure.

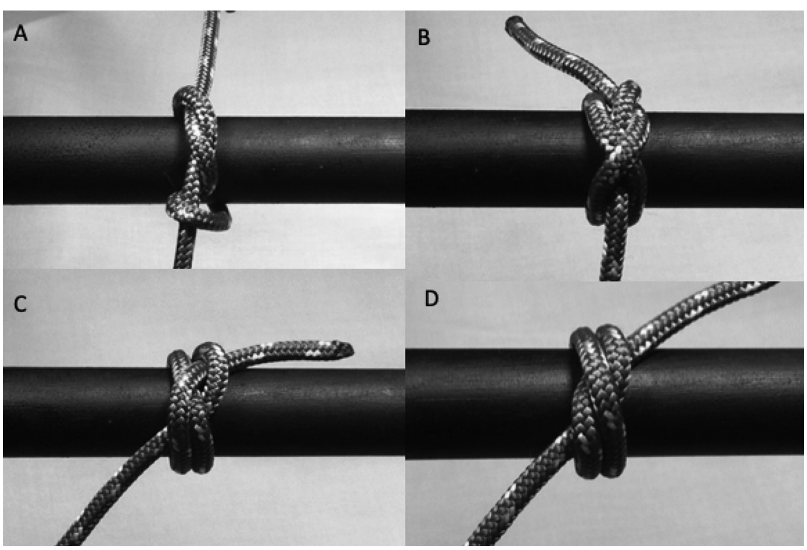

Figure 2—Photographs depicting examples of the 4 different friction knots created and tested in the study. A—Surgeon's throw. B—AMK. C—Miller knot. D—Strangle knot. All knots were created with a 20-cm length of 2-0 monofilament (4 suture types) or braided multifilament (3 suture types) material. Braided multifilament rope was used to create the examples shown.

Statistical analysis

The continuous pressure data were evaluated for normality with the Shapiro-Wilk test and transformed into log scale if normality assumptions were not met. Data were reported as mean ± SD with coefficients of variation calculated as the ratio between the SD and the mean. Linear regression analysis was performed to compare leakage pressure among the suture materials within each friction knot type as well as among friction knot types within each suture material. Values of $P \leq 0.05$ were considered significant. Commercially available software was used for statistical analysis.[n]

Results

Mean ± SD leakage pressures and coefficients of variation for each suture type within the 4 tested knot configurations are re-

Table 1—Mean ± SD leakage pressures and coefficients of variation for four 2-0 monofilament and three 2-0 braided multifilament suture types tied in 4 friction knot configurations (n = 10 knots/suture type/construct) and used as the first throw for ligation of a mock pedicle in a vascular ligation model.

	Surgeon's throw (mm Hg)		Miller knot (mm Hg)		AMK (mm Hg)		Strangle knot (mm Hg)	
Suture type	**Mean ± SD**	**CV (%)**	**Mean ± SD**	**CV (%)**	**Mean ± SD**	**CV (%)**	**Mean ± SD**	**CV (%)**
Monofilament								
Polyglyconate	31.0 ± 5.5[a]	17.7	271.8 ± 52.4[b]	19.2	311.0 ± 4.5[c]	1.4	309.8 ± 5.1[c]	1.6
Polydioxanone	32.2 ± 8.1[a]	25.1	322.1 ± 2.05[b]‡	0.6	304.1 ± 40.0[b]	13.1	317.8 ± 3.7[b]	1.1
Poliglecaprone-25	31.9 ± 6[a]	18.8	244.9 ± 61.7[b]	25.1	219.9 ± 91.3[b]§	41.5	245.8 ± 65.6[b]§	26.6
Glycomer-631	32.5 ± 6.1[a]	18.7	267.5 ± 58.7[b]	21.9	294.1 ± 51.3[b]	17.4	288.5 ± 27.2[b]	9.4
Multifilament								
Silk	28.3 ± 6.0[a]†	21.2	285.7 ± 55.5[b]	19.2	290.7 ± 37.4[b]	12.8	307.3 ± 3.1[b]	1
Lactomer	26.8 ± 1.0[a]*	3.7	284.4 ± 50.3[b]	17.6	295.3 ± 21.8[b]	7.3	270.4 ± 41.5[b]‖	15.3
Polyglactin-910	26.8 ± 1.4[a]*	5.2	269.7 ± 36.8[b]	13.6	265.2 ± 67.1[b]	25.3	316.6 ± 5.5[c]	1.7

No locking throws were placed after the friction knot to be tested was created. A pressure > 160 mm Hg was considered a supraphysiological measurement for arterial blood pressure.

*†‡§‖Within a column, symbols indicate significant ($P < 0.05$) differences between values: *different from the values for all monofilament sutures, †different from the value for glycomer-631, ‡different from the values for all other monofilament sutures and polyglactin-910, §different from all other monofilament and all multifilament suture types, and ‖different from the values for polyglyconate, polydioxanone, and all other multifilament sutures.

[a–c]Within a row, values with different superscripted lowercase letters differ significantly ($P < 0.05$) between friction knot types.

ported **(Table 1)**. The mean maximum pressure measurement for all friction knots except for the surgeon's throw exceeded the cutoff for supraphysiological arterial blood pressure for all sutures tested.

Suture performance within friction knot type

Surgeon's throws tied with polyglactin-910 had significantly lower mean leakage pressures than surgeon's throws tied with polyglyconate ($P = 0.05$), polydioxanone ($P = 0.02$), poliglecaprone-25 ($P = 0.02$), or glycomer-631 ($P = 0.009$). Surgeon's throws tied with silk had significantly lower mean leakage pressures than surgeon's throws tied with glycomer-631 ($P = 0.04$), and those tied with lactomer had significantly lower mean leakage pressures than those tied with polyglyconate ($P = 0.04$), polydioxanone ($P = 0.01$), poliglecaprone-25 ($P = 0.01$), or glycomer-631 ($P = 0.008$).

Miller knots tied with polydioxanone had significantly higher mean leakage pressure than Miller knots tied with polyglyconate ($P = 0.03$), poliglecaprone-25 ($P = 0.001$), glycomer-631 ($P = 0.01$), and polyglactin-910 ($P = 0.03$). No other differences between suture types were detected for these knots.

For AMKs, knots tied with poliglecaprone-25 had significantly lower mean leakage pressure than knots tied with polyglyconate ($P < 0.001$), polydioxanone ($P < 0.001$), glycomer-631 ($P = 0.001$), silk ($P = 0.001$), lactomer ($P = 0.001$), and polyglactin-910 ($P = 0.02$). No other differences between suture types were detected for these knots.

Strangle knots tied with poliglecaprone-25 had significantly lower mean leakage pressure than strangle knots tied with polyglyconate ($P < 0.001$), polydioxanone ($P < 0.001$), glycomer-631 ($P = 0.001$), silk ($P < 0.001$), lactomer ($P = 0.03$), and polyglactin-910 ($P < 0.001$). Strangle knots tied with lactomer also had significantly lower mean leakage pressure than strangle knots tied with polyglyconate ($P = 0.009$), polydioxanone ($P = 0.002$), silk ($P = 0.01$), and polyglactin-910 ($P = 0.003$).

Friction knot performance within suture type

Surgeon's throws had significantly lower mean leakage pressures than Miller knots ($P < 0.001$), AMKs ($P < 0.001$), and strangle knots ($P < 0.001$), regardless of the suture material used (Table 1). Among knots tied with polyglyconate, Miller knots had a significantly lower mean leakage pressure than AMKs ($P = 0.01$) and strangle knots ($P = 0.01$). Among knots tied with polyglactin-910, strangle knots had significantly greater leakage pressures than Miller knots ($P = 0.01$) and AMKs ($P = 0.002$).

All surgeon's throws failed at a pressure of ≤ 160 mm Hg. Among Miller knots, 1 tied with polyglyconate, 1 tied with poliglecaprone-25, and 1 tied with glycomer-631 failed at these pressures. Among AMKs, 2 tied with poliglecaprone-25, 1 tied with glycomer-631, and 1 tied with polyglactin-910 failed at ≤ 160 mm Hg. Two strangle knots tied with poliglecaprone-25 failed at ≤ 160 mm Hg.

Discussion

The hypothesis of the study was partially accepted. Significant differences in knot security as measured by leakage pressure in the in vitro model were found between various friction knots tied with the same type of suture and between various monofilament and multifilament sutures used to create a given friction knot. It should be noted that even when significant differences were detected, the mean leakage pressure for all first-throw friction knots except for surgeon's throws exceeded the cutoff for supraphysiological arterial blood pressure (the upper systolic arterial blood pressure measurement for normotensive dogs[17]), independent of the suture material used. Thus, the statistical differences observed among most suture types and knot types in the present study may not have represented clinically relevant differences.

An unexpected finding was that AMKs had a significantly higher mean leakage pressure, compared with the result for Miller knots, when polyglyconate suture was used. This was in contrast with results of a previous study,[4] and the reason for this difference was not clear. The same suture sizes and study design were used in both studies, and the only difference was that in the aforementioned investigation, the esophageal balloon dilation catheter and the suture materials were passed through falciform fat to mimic the in vivo condition, whereas this was done only for suture materials before testing in the present study. We were not confident that the difference in results for the 2 studies could be attributable to this experimental method difference.

Among the suture materials tested, poliglecaprone-25 had the greatest variability in leakage pressures for Miller knots, AMKs, and strangle knots in the present study. A potential explanation for this finding is the low stiffness of this suture material, compared with polyglyconate, polydioxanone, and polyglactin-910 established in a previous study.[18] This decreased stiffness may have led to elongation of the 2 ends of the suture when the knot was tightened, which may not have allowed full transmission of the tension at the level where the suture crossed the mock pedicle, resulting in a less secure knot.

Two possible explanations exist for the lack of substantial differences in performance between monofilament and braided multifilament suture materials in the study reported here. First, braided materials are coated with water-insoluble chemicals that likely reduce the friction coefficient of the suture in the first throw.[19] As a result, braided suture could more easily slip between strand-crossing points in a manner similar to the behavior of monofilament suture. Second, it is possible that passing the sutures through fat lubricated them equally and eliminated differences in friction that exist between the 2 suture categories as manufactured.

Only small differences were found in the in vitro leakage pressures of the various suture materials used to create surgeon's throws in this study. None of the surgeon's throws, regardless of the suture material tested, would have been expected to resist loosening in the presence of a vascular pedicle arterial blood pressure considered physiologic in unanesthetized dogs.[17] A possible explanation for this result was that this type of throw has a lower coefficient of friction than the other friction knots tested, all of which involve passing the suture strand around the testing apparatus twice. On the basis of the results of the present study and previous studies,[1,4,20] we discourage the use of surgeon's knots when ligating large vascular pedicles.

Although the mean leakage pressure of every friction knot type except the surgeon's throw was greater than the cutoff used for supraphysiological arterial blood pressure in dogs, the study results suggested 2 potential recommendations for the choice of suture material to be used for vascular pedicle ligation. Polydioxanone had the least overall variability in leakage pressure for knot types other than the surgeon's throw. This consistency may be advantageous to ensure a consistently tight, secure pedicle ligation. In contrast, poliglecaprone-25 had the greatest variability in results for the same 3 knot types, and ≥ 1 sample for each knot type failed at a pressure within the normal systolic blood pressure range for dogs, suggesting the possibility of an increased risk of postoperative hemorrhage when this suture type is used for ligation.

The present study had multiple limitations. The study relied on the use of a model that could not replicate all applicable biological conditions, and therefore, the results might differ from what would be encountered in a clinical setting. The pedicle model was created in the same manner as that used in a previous study[4]; however, the amount of fat within the pedicle of a large-breed dog is likely more than what could be replicated in our model, which could result in more slippery suture and reduce the amount of tension the surgeon's hands can place on the knot strands during tying. In addition, more slippery strands in the first throw of a pedicle ligation could loosen more readily and compromise knot security. The friction knots in the present study were all tensioned with approximately the same amount of force to avoid introducing additional variability that could have caused problems in the interpretation of the results. Unfortunately, measuring the force applied to tie a knot during surgery is not feasible, and differences in force may lead to different results during clinical application. The force of 19.61 N was selected for our study on the basis of mean force used to securely tie surgical knots in 2 previous studies.[4,21] The size of suture chosen for use in the present study was selected because results of a previous study showed that 2-0 was the suture size most commonly used by surgeons for pedicle ligation during ovariectomy.[22] However, the results for other suture sizes may vary.[16,23]

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Footnotes

a. CRE Single-Use Fixed Wire Balloon Dilator, Boston Scientific, Natick, Mass.
b. Top Fin silicone airline tubing, PetSmart Inc, Phoenix, Ariz.
c. Maxon, Covidien, Mansfield, Mass.
d. PDS II, Ethicon, Cincinnati, Ohio.
e. Monocryl, Ethicon, Cincinnati, Ohio.
f. Biosyn, Covidien, Mansfield, Mass.
g. Sofsilk, Covidien, Mansfield, Mass.
h. Polysorb, Covidien, Mansfield, Mass.
i. Vicryl, Ethicon, Cincinnati, Ohio.
j. REI Compact Digital Scale, REI, Sumner, Wash.
k. Pump 22, Harvard Apparatus, Holliston, Mass.
l. Mikro-Tip catheter pressure transducer, Millar Inc, Houston, Tex.
m. CardioSOFT Pro, Sonometrics Corp, London, ON, Canada.
n. SAS, version 9.4, SAS Institute Inc, Cary, NC.

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Erratum: Ultrasonographic and hormonal characterization of reproductive health and disease in wild, semiwild, and aquarium-housed southern stingrays (*Hypanus americanus*)

In the article "Ultrasonographic and hormonal characterization of reproductive health and disease in wild, semiwild, and aquarium-housed southern stingrays (*Hypanus americanus*)" (*Am J Vet Res* 2019;80:931–942), there was an error in the sentence in the Materials and Methods that reads "Both lagoon-housed and wild southern stingrays were offered a daily diet consisting of shrimp, squid, and an aquatic gel product.[d]" The sentence should read "Lagoon-housed southern stingrays were offered a daily diet consisting of shrimp, squid, and an aquatic gel product.[d]"