In vitro evaluation of the knot-holding capacity and security, weight, and volume of forwarder knots tied with size-3 polyglactin 910 suture exposed to air, balanced electrolyte solution, or equine abdominal fat

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OBJECTIVE
To evaluate the effect of exposure to a balanced electrolyte solution (BES), or equine abdominal fat on the knot-holding capacity (KHC), relative knot security (RKS), weight, and volume of forwarder knots versus surgeon's knots.

SAMPLE
315 knots tied and tested in vitro.

PROCEDURES
United States Pharmacopeia size-3 polyglactin 910 suture exposed to air (dry [control]), equine abdominal fat (fat-exposed), or BES (BES-exposed) was used to tie forwarder knots with 2, 3, and 4 throws and surgeon's knots with 5, 6, 7, and 8 throws. A universal materials testing machine was used to test the tensile strength of suture and knots to failure, and the KHC, RKS, weight, and volume of knots were determined.

RESULTS
Forwarder knots had significantly higher KHC and RKS and lower volume, compared with surgeons' knots. Forwarder knots tied with fat-exposed suture had greater weight, but not volume, than did forwarder knots tied with dry or BES-exposed suture with the same number of throws.

CONCLUSIONS AND CLINICAL RELEVANCE
Results indicated that forwarder knots were superior to surgeon's knots when configured as start knots intended for continuous lines of suture. Exposure to media did not negatively affect mechanical or physical properties of forwarder knots and may improve specific biomechanical functions, including KHC and RKS. (*Am J Vet Res* 2019;80:709–716)

Strength and security are important attributes of surgical knots, and knots that fail under low tension or have poor knot security are not ideal for use in surgery.[1] These factors become more important for knots used in continuous suture lines, such as to close ventral midline celiotomies. Self-locking knots, specifically forwarder knots tied with dry suture and Aberdeen knots tied with large-gauge suture have higher KHC and RKS but lower weight and volume than do surgeon's knots.[2–4] Intrinsic properties of forwarder and Aberdeen knots allow some level of suture translation or suture movement in the knot, thereby reducing the coefficient of friction.[2,4,5] As tension on forwarder and Aberdeen knots increases, construction of the knots allows a small amount of suture to slide, resulting in dissipation of energy and prevention of a focal accumulation of stress.[3,6] Therefore, when compared with square and surgeon's knots, self-locking knots are stronger and can be completed with fewer throws, resulting in each having a smaller volume and weight.

Exposure of suture material to various physiological conditions and fluid media alters biomechanical properties of the suture and knots tied with it.[3,6–9] However, until recently it was unknown what effect common equine fluid media had on different knots of large-gauge suture. Surgeon's, square, and Aberdeen knots tied with large-gauge suture exposured to various fluids (eg, equine serum, equine fat, saline [0.9% NaCl] solution, and carboxymethocellulose) commonly encountered when performing a ventral midline celiotomy in horses have significantly greater KHC than do similar knots tied with dry suture, and Aberdeen knots

ABBREVIATIONS

BES	Balanced electrolyte solution
KHC	Knot-holding capacity
RKS	Relative knot security

have significantly higher KHC than do square and surgeon's knots.[3]

A forwarder knot is used as a start knot in a continuous suture line that may be completed with Aberdeen knots[2,10]; however, a forwarder knot cannot be used as an end knot of a continuous suture line because a forwarder knot will unravel if used as an end knot. Forwarder knots tied with dry United States Pharmacopeia size-1, 2-0, or 4-0 polyglactin 910, polydioxanone, or nylon suture have higher KHC and lower weight and volume than do surgeon's knots of the same suture materials.[5] In addition, forwarder knots have similar advantages when tied with size-2 and size-3 dry suture material.[2] When tested in an ex vivo equine cadaver model of midline celiotomy with an inflatable bladder placed in the abdomen, ventral midline closure with a continuous suture line that started with a forwarder knot and ended with an Aberdeen knot had substantially higher strength to prevent bursting than did a similar closure that started and ended with a surgeon's knot.[10] However, to our knowledge, forwarder knots made of small- or large-gauge suture material exposed to fluid media have not been tested.

The objective of the study reported here was to evaluate effects of exposure to air, BES or equine abdominal fat on the KHC, RKS, weight, and volume of forwarder knots, compared with surgeon's knots. To quantify our objective, we compared results for forwarder knots tied with media-exposed suture, forwarder knots tied with dry suture, surgeon's knots tied with media-exposed suture, and surgeon's knots tied with dry suture. We hypothesized that forwarder knots tied with fat-exposed or BES-exposed suture would have significantly higher KHC and RKS than would surgeon's knots tied with similarly exposed suture. In addition, we hypothesized that forwarder knots tied with fat-exposed or BES-exposed suture would be stronger than forwarder knots tied with dry suture. Lastly, we hypothesized that forwarder knots tied with fat-exposed or BES-exposed suture would have a significantly higher weight and volume than would forwarder knots tied with dry suture.

Materials and Methods

All testing was performed on United States Pharmacopeia size-3 polyglactin 910 suture in a temperature-controlled laboratory at 21°C and 65% humidity, following standard practice protocols.[a] Before knot testing commenced, 1 suture strand from each box of size-3 polyglactin 910 suture was subjected to a single cycle-to-failure test at a distraction rate of 100 mm/min. This testing involved clamping one end of the suture strand on the lower grip of the material testing machine and the other end of suture on the upper grip of the material testing machine, then moving the grips away from each other to place linear tension on the suture strand. On the basis that the mean tensile strength of size-3 polyglactin 910 was previously calculated at our laboratory as 174.08 N,[3] we established for the present study acceptable tensile strength limits of 156.67 N to 191.49 N (ie, 174.08 N ± 10%) for the single cycle-to-failure test of each representative strand of suture. For suture with results outside the acceptable limits, the entire box of suture was deemed defective and discarded.

Immediately before testing, a strand of suture was removed from its packet and either exposed to air for 15 minutes (dry [control] suture), immersed in BES[b] for 15 minutes (BES-exposed suture), or immersed in equine abdominal fat for 15 minutes (fat-exposed suture). Each 100 mL of BES contained sodium chloride (526 mg), sodium acetate (222 mg), sodium gluconate (502 mg), potassium chloride (37 mg), and magnesium chloride hexahydrate (30 mg) and had a pH range of 6.5 to 7.6 and an osmolarity of 295 mOsmol/L. The fat used had been harvested from cadavers of healthy horses associated with a different study that had been evaluated and approved by the Auburn University Institutional Animal Care and Use Committee. Harvested fat had been obtained from each cadaver with sharp dissection through a ventral midline incision, pulverized with a handheld macerator,[c] and stored at –20°C. The fat used was allowed to return to room temperature before suture immersion.

Biomechanical testing of knots was conducted in a manner similar to that reported by Coleridge et al.[3] A static load of 21 N ± 0.01% was placed on all suture before distraction. This static load was selected because it was the mean tension placed on a suture line during knot tying completed by 3 board-certified surgeons.

A new suture packet was used to tie each knot tested. All knots were tied and tested by 1 investigator (LM). Forwarder knots were tied with 2, 3, and 4 throws (**Supplementary Video S1**, available at avmajournals.avma.org/doi/suppl/10.2460/ajvr.80.7.709), and surgeon's knots were tied with 5, 6, 7, and 8 throws, with 10 knots in each test group combination of suture exposure (ie, dry suture, BES-exposed suture, and fat-exposed suture), knot, and throws. All knots were tested with a universal materials testing machine[d] with an upper and lower grip **(Figure 1)**. An 8-inch Mayo-Hegar needle driver was used to tie each knot on a loading device that consisted of a smooth metal bar clamped in the lower grip of the testing machine. Forwarder knots were tied as previously described[2,10] with the desired number of throws for testing. Surgeon's knots were completed as previously described,[11] with the desired number of throws for testing. For each knot, the tag on the working end of the suture was cut to 3 mm, and the free end of the suture was clamped in a yarn grip fastened in the upper grip of the testing machine.

The initial distance between the metal rod (on which each knot was tied) and the upper grip (to which the free end of suture was clamped) was set at 10 cm, and an intial preload of 21 N was applied to the suture strand to remove slack prior to testing as previously described.[2,3] All suture strand and knot combinations

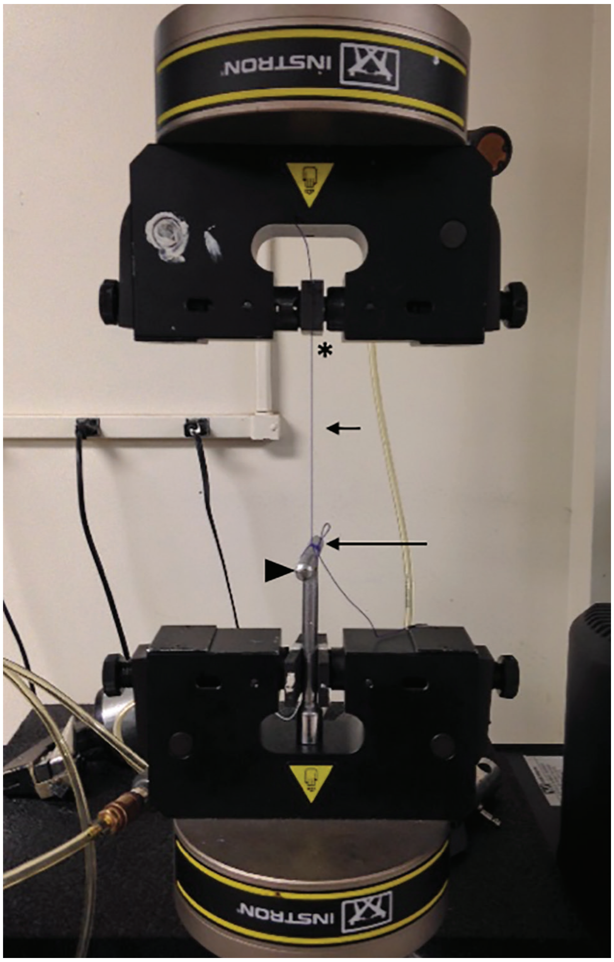

Figure 1— A representative photograph of the universal materials testing machine and configuration used to test each of 210 knots (120 surgeon's knots and 90 forwarder knots) tied with size-3 polyglactin 910 suture that then underwent distraction to failure. A surgeon's knot (long arrow) is tied on a smooth metal bar clamped in the lower grip (arrowhead) of the machine, and the free end of the suture strand (short arrow) is clamped in a yarn grip fastened in the upper grip (asterisk) of the testing machine.

were distracted at 20 mm/min until failure, defined as breakage of the suture strand, breakage of the knot, or > 3 mm of knot slippage.[2,3] All failures were recorded by a high-speed camera[e] recording at 240 frames/s. The KHC, defined as the maximum load to failure when tension was applied to a knotted suture material,[1–3] was obtained by the materials testing machine and recorded in Newtons with testing machine software.[f] The software generated a force displacement curve that was observed along with the slow-motion digital recording to determine whether knot slippage occurred.[2] The RKS, a standardized way to describe the KHC as a percentage of the tensile strength,[1,2,6] was calculated for each knot as RKS = (KHC/tensile strength) X 100.

To determine the weight and volume of knots, 105 additional knots (5 knots for each test group) were tied on the loading device as described previously and evaluated. Suture tags were cut to 3 mm, and knots were removed from the loading device for measurement. Knots were weighed to a resolution of 0.1 mg on a digital scale,[g] and the height and diameter of knots were measured to a resolution of 0.01 mm with a digital micrometer.[h] These measurements were then used to calculate the approximate volume (mm^3) with the formula $V = \pi r^2 h$ as previously described,[2,3] where V = volume, π = 3.14, r = radius, and h = height. To determine the most efficient knot, we derived the formula KE = KHC/V, where KE = knot efficiency and V = volume.

Statistical analysis

Statistical analysis was performed with commercial software.[i] Normality of data was determined by an Anderson-Darling test. For normally distributed data, parametric testing was performed with 1-way ANOVA, followed by Tukey post hoc analysis for those comparisons with significant differences to evaluate the mean difference in KHC between test groups of knots categorized by number of throws, exposure of suture, and type of knot. Values of $P < 0.05$ were considered significant.

Results

Each representative suture strand tested in a single cycle-to-failure test was within 10% of the mean tensile strength earlier calculated for size-3 polyglactin 910; therefore, no suture boxes were discarded. A total of 315 knots (180 surgeon's knots and 135 forwarder knots) were tied for testing, including 210 knots (10 for each test group) that underwent distraction to failure and 105 knots (5 for each test group) that were assessed for weight and volume. For each suture exposure group (ie, dry, fat-exposed, and BES-exposed suture), there were 3 forwarder knot groups (ie, tied with 2, 3, and 4 throws) and 4 surgeon's knot groups (ie, tied with 5, 6, 7, and 8 throws).

Findings for KHC and RKS

Mean ± SD KHC and RKS were significantly ($P < 0.001$) higher for forwarder knots tied with dry (KHC, 160.3 ± 2.3 N; RKS, 92 ± 1.3%), BES-exposed (KHC, 161.8 ± 2.3 N; RKS, 93 ± 1.3%), or fat-exposed (KHC, 165 ± 2.3 N; RKS, 95 ± 1.3%) suture, compared with surgeon's knots tied with dry (KHC, 98.9 ± 2.3 N; RKS, 57 ± 1.3%), BES-exposed (KHC, 107.6 ± 2.3 N; RKS, 62 ± 1.3%), or fat-exposed (KHC, 100.2 ± 2.3 N; RKS, 58 ± 1.3%) suture **(Figure 2)**. In addition, mean ± SD KHC was significantly ($P = 0.002$ and $P = 0.003$) higher for forwarder knots tied with 4 throws of fat-exposed suture (171.3 ± 2.9 N), compared with forwarder knots tied with 4 throws of BES-exposed (158.4 ± 2.9 N) or dry (159.0 ± 2.9 N) suture **(Figure 3; Table 1)**. The strongest group of knots was forwarder knots tied with 4 throws of fat-exposed suture, with mean ± SD KHC and RKS of 171.3 ± 2.9 N and 98.4 ± 1.7%, respectively.

Knot weight and volume

When all throw combinations were combined, forwarder knots tied with dry, BES-exposed, or fat-exposed suture had a significantly ($P < 0.001$) lower mean ± SD volume (13.9 ± 5.2, 10.5 ± 4.8, and 14.4 ± 5.2 mm^3, respectively) than did all throw combinations of surgeon's knots tied with dry, BES-exposed, or fat-exposed suture (78.7 ± 5.2, 68.2 ± 4.8, and 65.5 ± 5.2 mm^3, respectively; **Figure 4**). In addition, the mean ± SD weight was significantly ($P < 0.001$) lower for forwarder knots tied with dry, BES-exposed, or fat-exposed suture (17.8 ± 2.2, 17.8 ± 2.2, and 25.7 ± 2.2 mg, respectively) than for surgeon's knots tied with dry or fat-exposed suture (39.5 ± 2.2 and 44 ± 2.2 mg, respectively). Mean ± SD weight did not differ significantly ($P = 0.48$) between forwarder knots tied with fat-exposed suture (25.7 ± 2.2 mg) and surgeon's knots tied with BES-exposed suture (29.5 ± 2.2 mg).

When results for forwarder knots of the same number of throws were compared, the mean ± SD

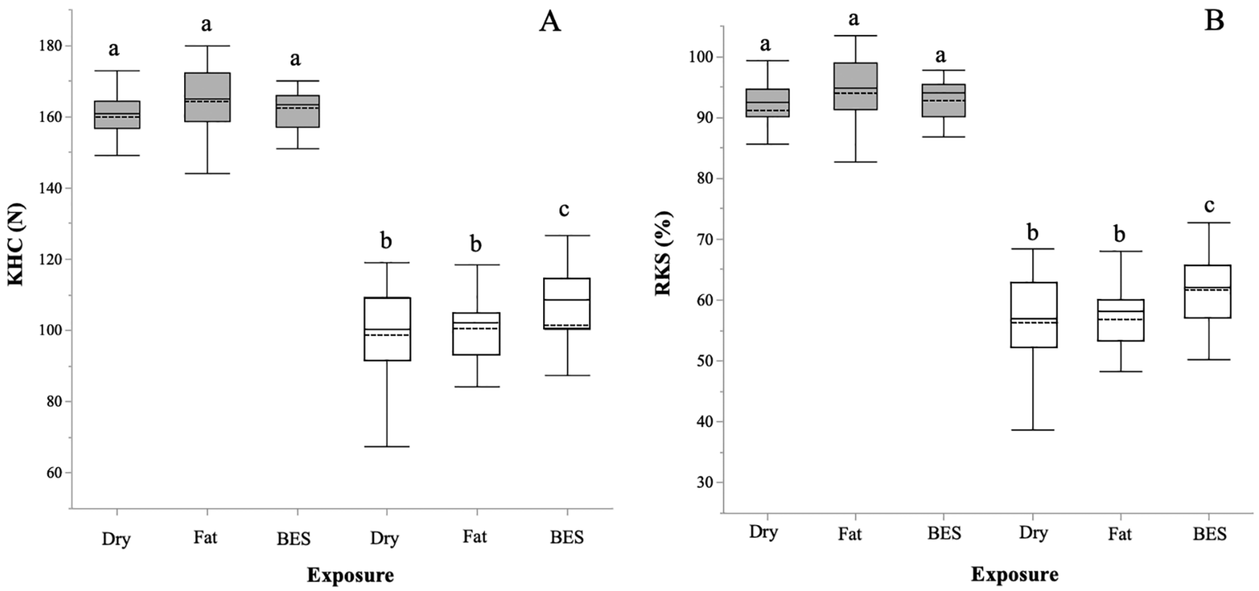

Figure 2—Box-and-whisker plots of the KHC (A) and RKS (B) calculated for forwarder knots (n = 90; gray) and surgeon's knots (n = 120; no shading) tied with dry, equine fat-exposed, or BES-exposed size-3 polyglactin 910 suture. For each plot, the box represents results from the 25th to 75th percentiles, the solid line in the box represents the median, the dotted line in the box represents the mean, and the whiskers represent the range. Plots labeled with different letters differed significantly ($P < 0.05$).

Table 1—Results ranked from highest to lowest for knot efficiency calculated for forwarder knots tied with 2, 3, or 4 throws and surgeon's knots tied with 5, 6, 7, or 8 throws of dry (control), fat-exposed, and BES-exposed size-3 polyglactin 910 suture.

Ranking	Knot type	No. of throws	Media exposure	Knot efficiency (N/mm³)*	KHC (N)*	Volume (mm³)*
1	Forwarder	2	BES	21.3 ± 2.2	163.8 ± 2.9	7.7 ± 2.2
2	Forwarder	2	Equine fat	20.3 ± 2.2	159.3 ± 2.9	7.8 ± 2.2
3	Forwarder	3	BES	15.5 ± 2.2	163.3 ± 2.9	10.5 ± 2.2
4	Forwarder	2	Dry (control)	14.5 ± 2.2	161.9 ± 2.9	11.2 ± 2.2
5	Forwarder	4	BES	11.9 ± 2.2	158.4 ± 2.9	13.3 ± 2.2
6	Forwarder	3	Dry (control)	10.4 ± 2.2	160.0 ± 2.9	15.4 ± 2.2
7	Forwarder	4	Dry (control)	10.4 ± 2.2	159.0 ± 2.9	15.3 ± 2.2
8	Forwarder	3	Equine fat	10.0 ± 2.2	164.9 ± 2.9	16.4 ± 2.2
9	Forwarder	4	Equine fat	9.0 ± 2.2	171.3 ± 2.9	19.1 ± 2.2
10	Surgeon's	5	BES	2.4 ± 2.2	104.0 ± 2.9	44.0 ± 2.2
11	Surgeon's	5	Equine fat	2.1 ± 2.2	100.7 ± 2.9	48.4 ± 2.2
12	Surgeon's	7	BES	1.6 ± 2.2	110.1 ± 2.9	71.0 ± 2.2
13	Surgeon's	6	Equine fat	1.5 ± 2.2	101.2 ± 2.9	66.8 ± 2.2
14	Surgeon's	5	Dry (control)	1.5 ± 2.2	86.9 ± 2.9	57.5 ± 2.2
15	Surgeon's	7	Equine fat	1.5 ± 2.2	103.3 ± 2.9	68.6 ± 2.2
16	Surgeon's	6	Dry (control)	1.5 ± 2.2	105.6 ± 2.9	72.3 ± 2.2
17	Surgeon's	6	BES	1.5 ± 2.2	106.4 ± 2.9	73.0 ± 2.2
18	Surgeon's	7	Dry (control)	1.4 ± 2.2	101.6 ± 2.9	71.5 ± 2.2
19	Surgeon's	8	BES	1.3 ± 2.2	109.7 ± 2.9	85.1 ± 2.2
20	Surgeon's	8	Equine fat	1.2 ± 2.2	95.9 ± 2.9	78.4 ± 2.2
21	Surgeon's	8	Dry (control)	0.9 ± 2.2	101.5 ± 2.9	113.6 ± 2.2

*Data are reported as the mean ± SD.

volumes for knots tied with 2, 3, or 4 throws of fat-exposed suture (7.8 ± 2.2, 16.4 ± 2.2, and 19 ± 2.2 mm^3, respectively) did not differ significantly (P = 0.84, P = 1.0, and P = 0.73, respectively) from those tied with 2, 3, or 4 throws of dry suture (11.2 ± 2.2, 15.5 ± 2.2, and 15.3 ± 2.2 mm^3, respectively) or of BES-exposed suture (7.7 ± 2.2, 10.5 ± 2.2, and 13.3 ± 2.2 mm^3; **Figure 5**; Table 1). However, the mean ± SD weights for forwarder knots tied with 2, 3, or 4 throws of fat-exposed suture (20.4 ± 0.9, 24 ± 0.9, and 32.6 ± 0.9 mg, respectively) were significantly (P < 0.001) higher than weights for knots tied with 2, 3, or 4 throws of dry suture (13.8 ± 0.9, 18 ± 0.9, and 21.6 ± 0.9 mg, respectively) or BES-exposed suture (14 ± 0.9, 17.2 ± 0.9, and 22 ± 0.9 mg, respectively; figure 5). As the number of throws in forwarder knots increased, the mean ± SD weight for forwarder knots tied with dry, BES-exposed, or fat-exposed suture increased significantly (P = 0.001, P < 0.001, and P = 0.021, respectively). Also, as the number of throws in forwarder knots increased, the only significant (P = 0.011) difference detected in the mean ± SD volume was between knots tied with 2 throws (7.8 ± 2.2 mm^3) and 3 throws (16.4 ± 2.2 mm^3) of fat-exposed suture.

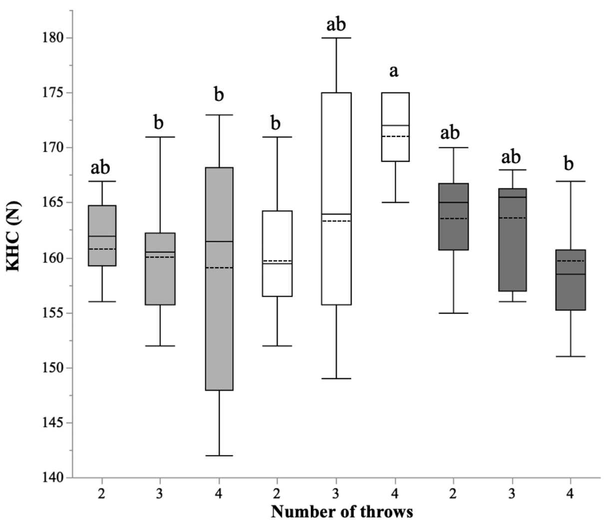

Figure 3—Box-and-whisker plots of the KHC calculated for forwarder knots in Figure 2 grouped by number of throws (ie, tied with 2, 3, or 4 throws) and suture exposure (ie, tied with size-3 polyglactin 910 suture that was dry [light gray], fat-exposed [no shading], or BES-exposed [dark gray]), with 10 knots evaluated in each throw and exposure combination group. ***See*** Figure 2 for remainder of key.

Knot efficiency

Mean ± SD knot efficiency was highest for forwarder knots tied with 2 throws of BES-exposed suture (21.3 ± 2.2 N/mm^3) and was lowest for surgeon's knots tied with 8 throws of dry suture (0.9 ± 2.2 N/mm^3; Table 1). The most efficient group of surgeon's knots was the group tied with 5 throws of BES-exposed suture; however, with a mean ± SD knot efficiency of 2.4 ± 2.2 N/mm^3, this group ranked tenth most efficient overall. Mean ± SD knot efficiency for each of the 9 groups of forwarder knots was significantly (P = 0.001) higher than that of the most efficient group of surgeon's knots.

Failure mode

Failure of each knot in each group was categorized as breakage of the suture strand, breakage of the knot, or > 3 mm of knot slippage (unraveling). No forwarder knots were observed to fail by > 3 mm of knot slippage > 3 mm, regardless of the exposure or number of throws. Except for 1 forwarder knot tied with 3 throws

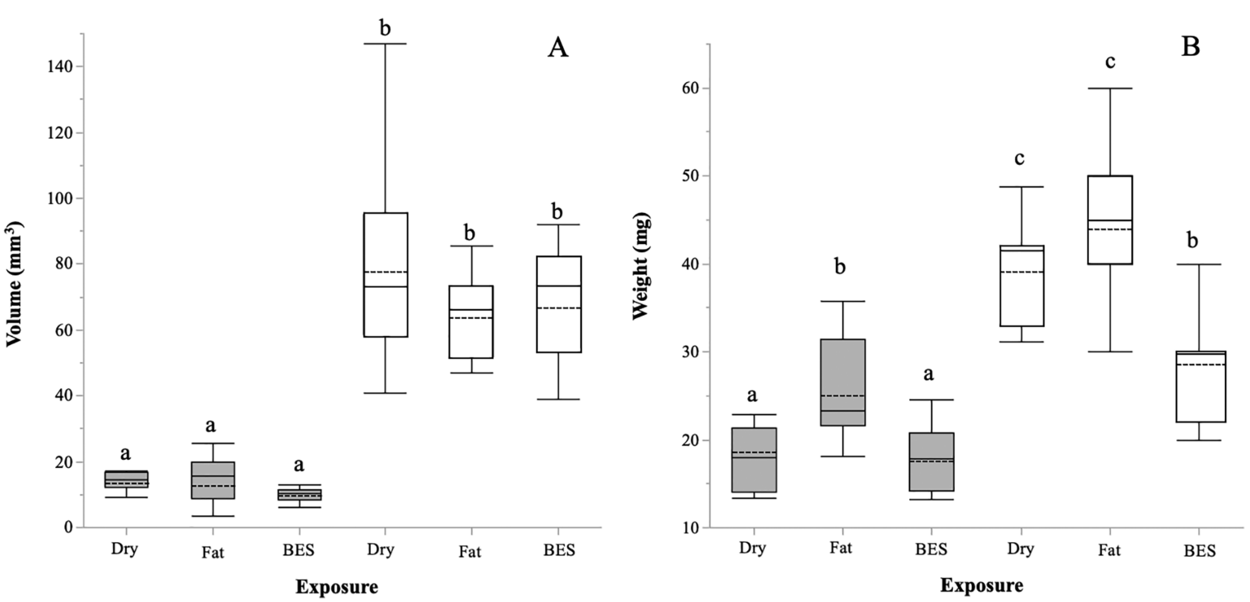

Figure 4—Box-and-whisker plots of the volume (A) and weight (B) of forwarder knots (n = 45; gray) and surgeon's knots (n = 60; no shading) tied with dry, equine fat-exposed, or BES-exposed size-3 polyglactin 910 suture. ***See*** Figure 2 for remainder of key.

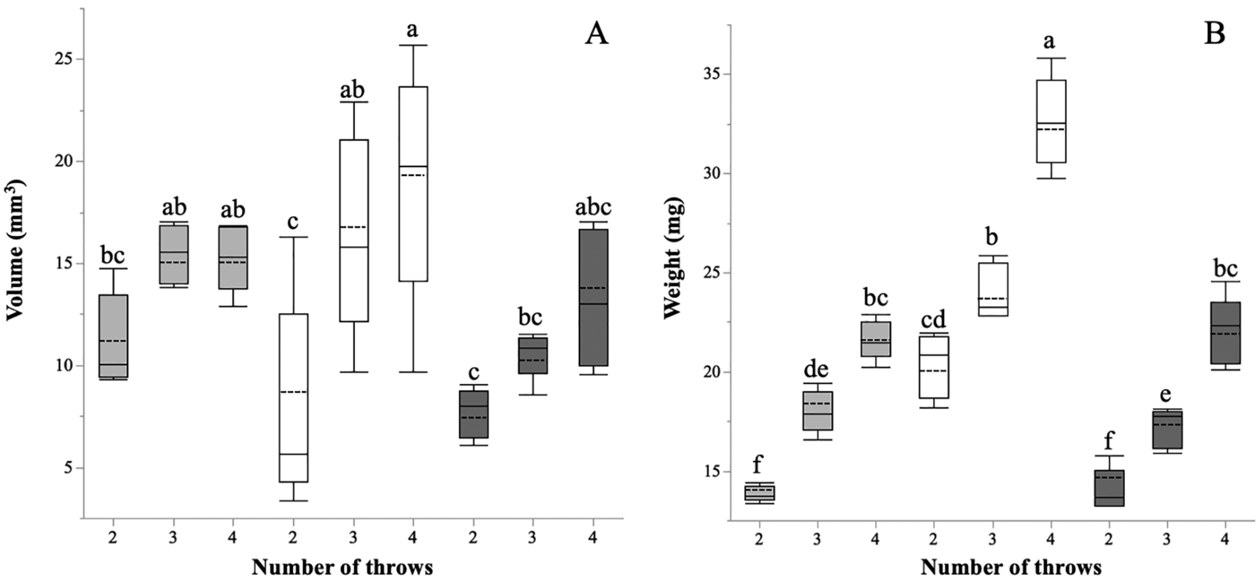

Figure 5—Box-and-whisker plots of the volume (A) and weight (B) of forwarder knots in Figure 4 grouped by number of throws (ie, tied with 2, 3, or 4 throws) and suture exposure (ie, tied with size-3 polyglactin 910 suture that was dry [light gray], fat-exposed [no shading], or BES-exposed [dark gray]), with 5 knots evaluated in each throw and exposure combination group. ***See*** Figure 2 for remainder of key.

of dry suture that failed along the suture strand, all other forwarder knots, regardless of the exposure or number of throws, failed at the knot. Three surgeon's knots tied with 5 throws of dry suture failed by > 3 mm of slippage. All other surgeon's knots, regardless of the exposure or number of throws, failed at the knot.

Discussion

Results of the present study indicated that exposure of size-3 polyglactin 910 suture to equine abdominal fat or BES, 2 fluid media commonly encountered during abdominal surgery in horses, did not negatively affect mechanical and physical properties of forwarder knots. In addition, forwarder knots tied with dry, fat-exposed, or BES-exposed size-3 polyglactin 910 suture had higher KHC and RKS and lower volume than did surgeon's knots tied with equally exposed suture of the same material in the present study. These findings were similar to results reported for self-locking knots, compared with traditional surgeon's knots, tied with small- and large-gauge suture material.[2–6,8] In addition, results of the present study suggested that a forwarder knot could be superior to a surgeon's knot when used as a start knot in a continuous suture line of size-3 polyglactin 910.

Exposing suture materials to various fluid media (eg, plasma, fat, and saline solution) affects the coefficient of friction of the suture and therefore affects knot security.[3,6–8] However, disagreement exists regarding whether the addition of media may increase[3] or decrease[6,8,12] the coefficient of friction, which has a linear relationship with tensile strength and RKS.[7] Aberdeen, square, and surgeon's knots tied with size-3 polyglactin 910 suture (commonly used in equine surgery) exposed to BES, carboxymethocellulose, equine abdominal fat, or equine serum fluid media have higher KHC than such suture not exposed to media, and it is hypothesized that the fluid medium creates a lubricating layer on the suture and thus allows some sliding to occur in the knot, distributing the forces more equally throughout the knot and avoiding focal stress accumulation in the knot, thereby increasing the KHC of the knot.[3] Similarly, we hypothesized that forwarder knots tied with fat-exposed or BES-exposed suture would be stronger than forwarder knots tied with dry suture. However, results of the present study indicated that forwarder knots tied with 4 throws of fat-exposed suture had significantly higher KHC and RKS than forwarder knots tied with 4 throws of dry or BES-exposed suture. Similar results were not detected for forwarder knots tied with 2 or 3 throws of similarly exposed suture. An explanation for these findings could have been that forwarder knots tied with 4 throws had larger volumes and therefore could have distributed tension and friction over greater surface area, compared with knots tied with fewer throws.

The minimum number of throws and minimum tag length required to complete a secure surgeon's or square knot has been established for various suture materials.[1–4,11] An interesting finding of the present study was the markedly higher RKS for forwarder knots, compared with that of surgeon's knots. The ideal RKS of a knotted suture strand is 100%; however, this is rarely the case with the addition of a knot creating a focal point of stress and decreasing the security of the suture.[6,8] In the present study, forwarder knots tied with 4 throws of fat-exposed suture had a mean ± SD RKS of 98.4 ± 1.7%, which indicted a mean decrease in RKS of 1.6% from that of an intact suture strand. To our knowledge, an RKS value this high had not been reported previously. In contrast, a surgeon's knot may have an RKS that is as much as 40% less than the intact suture strand.[2,5,13] Results of the present study indicated that of surgeon's knots, those tied with 7 throws of BES-exposed suture had the highest mean ± SD RKS (63 ± 2.6%). This finding suggested that RKS could be approximately 35% higher when a forwarder knot is used instead of a surgeon's knot. This was a substantial finding and could have been explained by the self-locking nature of forwarder knots allowing dispersal of energy within the knots.[2–4]

In addition to knot strength and security, one must consider knot volume, which is influenced by the diameter of the suture material and the number of throws used, with these factors also affecting knot security.[2,11,14,15] A minimum number of throws must be added to a knot to make it secure; however, the addition of extra throws is detrimental to wound healing.[16] For example, with nonidentical sliding knots, the addition of extra throws may increase knot volume by 150% and increase tissue reactivity by 200%.[16] Results of the present study indicated that forwarder knots had substantially lower volume, compared with surgeon's knots. Therefore, use of forwarder knots instead of surgeon's knots may be advantageous for wound healing because use of forwarder knots could possibly decrease inflammation; however, in vivo studies are needed to investigate this hypothesis. Interestingly and contrary to our hypothesis that forwarder knots tied with fat-exposed or BES-exposed suture would have higher weight and volume than forwarder knots tied with dry suture, exposure of suture to fat or BES did not meaningfully increase the volume for forwarder knots in the present study. This finding also conflicted with findings of higher volumes for square, surgeon's, and Aberdeen knots tied with suture exposure to fluid media.[3] This contrast could be explained by the fact that forwarder knots tied in the present study were completed with fewer throws (ie, 2 to 4 throws), resulting in smaller knots than Aberdeen knots; however, these parameters were not directly compared.

The presence of foreign material, such as suture, can cause tissue reaction and inflammation.[17–19] This irritation seems to be directly related to suture size, suture stiffness, knot configuration, and knot volume.[16,20] Therefore, it is advantageous to use suture knots with high KHC and RKS combined with low volume. To examine these factors, we derived a formula for knot efficiency that incorporated strength and volume of knots. On the basis of results, findings indicated that the most efficient group of knots evaluated was forwarder knots tied with 2 throws of BES-exposed suture, whereas the most efficient group of surgeon's knots ranked 10th, after all forwarder knot combinations. These results further suggested that because forwarder knots had lower volume than surgeon's knots yet retained high security and strength, use of a forwarder knots could cause less postoperative tissue irritation and inflammation, compared with surgeon's knots.

Similar to the learning curve of any new skill or technique, the time to complete each forwarder knot initially was longer than that required to complete each surgeon's knot; however, timing of knot tying was not specifically examined in the present study. Relatedly, results of a previous study[10] in which we evaluated the time taken to complete a ventral midline celiotomy in cadaver horses with a forwarder knot as the start knot and an Aberdeen knot as the end knot in a continuous suture line, compared with use of a surgeon's knot to start and end closures, showed no meaningful difference in closure times. Although we subjectively observed that the self-locking knot combination was initially slower to complete in that study,[10] once familiar with construction of these knots, we performed celiotomy closures more rapidly. It is important to note that a forwarder knot can only be used as a start knot and cannot be used as an end knot of a continuous suture line because a forwarder knot will unravel if used as an end knot. Therefore, an Aberdeen knot, which is another self-locking knot, is recommended for use as the end knot because Aberdeen knots are substantially stronger than surgeon's knots in small- and large-gauge suture material and following exposure to fluid media.[3,4,6]

For the present study we elected to test size-3 polyglactin 910 because it is reported to be the suture material of choice for closure of ventral midline celiotomies in horses[18,21] and because it offers a good size-to-strength ratio, demonstrating greater initial breaking strength and stiffness, compared with polydioxanone.[1] In addition, it was, to our knowledge, the largest-diameter suture material available in the United States for celiotomy closure. A limitation of the present study was that the results obtained for size-3 polyglactin 910 could not be extrapolated to other suture types or sizes. A second limitation of the present study was its in vitro nature. Knots were tested on a universal testing machine in a single load-to-failure cycle, which was unlikely to mimic in vivo scenarios. Cyclical loading could assess stress placed on knots over time; however, doing so could alter fluid dynamics of knots in unpredictable ways. A third limitation was that the formula to calculate knot volume included an assumption that each knot was a perfect cylinder.[2,4,6,11] Although every effort was made to approximate each knot to the shape of a cylinder, we recognize that they were not perfect cylinders, potentially impacting calculations of knot volume and efficiency.

Findings of the present study provided further evidence supporting the use of forwarder knots in veterinary surgery.[2–4,6,8] No negative effects to mechanical or physical properties or to knot security were detected for forwarder knots tied with fat-exposed or BES-exposed size-3 polyglactin 910, compared with forwarder knots tied with dry (control) size-3 polyglactin 910 in the present study. These results further supported previous studies[2,5] indicating that forwarder have higher KHC and RKS, yet lower volume, compared with surgeon's knots. Further testing is required to assess the use of forwarder knots in vivo and with use of different suture types and sizes. Specifically, inflammatory effects of forwarder knots, compared with surgeon's knots, should be investigated. In addition, evaluation of infection rate and linea alba tensile strength could be performed at certain postoperative time points after celiotomies closed with forwarder and Aberdeen knots, compared with surgeon's knots. Although results of the present study indicated that forwarder knots tied with 4 throws of fat-exposed or BES-exposed size-3 polyglactin 910 had the greatest strength and security of knots tested and that forwarder knots were superior to surgeon's knots to start a continuous suture line, in vivo investigation is necessary before making clinical recommendations.

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Footnotes

a. ASTM international, ASTM D1776-15-Standard Practice for Conditioning and Testing Textiles. Available at www.astm.org/Standards/D1776.htm. Accessed Mar 21, 2016.
b. Normosol R, Abbott Laboratories, Abbott Park, Ill.
c. Model 59762, Hamilton Beach, Southern Pines, NC.
d. Universal testing system, 5565 materials testing frame, Instron, Norwood, Mass.
e. Power Shot SX40 HS, Canon Inc, Tokyo, Japan.
f. Bluehill, version 2.24.787, Instron, Norwood, Mass.
g. AE 163, Mettler-Toledo LLC, Columbus, Ohio.
h. Digital carbon fiber caliper, Ted Pella Inc, Redding, Calif.
i. JMP Pro, version 11.0.0, SAS Institute Inc, Cary, NC.

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