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Comparative study of the holding strength of slipknots using absorbable and nonabsorbable ligature materials

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Abstract. The holding and tensile characteristics of five extracorporeal slipknots in relation to absorbable and nonabsorbable ligature materials have been evaluated in a standardized in vitro test rig. The knots studied: Tayside, Roeder, Melzer (modified Roeder), Cross square, and Blood knots were tied with the following materials: silk, polyamide, Dacron, polydioxanone (PDS), and lactomer (Polysorb). Following construction and slippage (run down) to a fixed-diameter loop around a cylinder, the knots were locked (tightened) using a standardized force after which they were removed from the test rig and subjected to holding strength (force required to induce reverse slippage) and other tensile characteristics (stress, strain, elasticity) by a tensiometer. Analysis of the data has demonstrated the following: (1) The safest slip knots (resist slippage) are the Tayside, Melzer, and Roeder knots tied with lactomer and Dacron. (2) The holding strengths of the Cross square and Blood knots are weak with all ligature materials tested. (3) Polydioxanone is a safe ligature material for the Melzer and Tayside but not the Roeder knot. (4) Extracorporeal slipknots tied with silk and polyamide are less secure than the equivalent knots tied with Dacron, lactomer, and polydioxanone.

Key words: Slipknots — Ligature materials — Endoscopic surgery

Although the majority of surgeons employ clips to occlude vessels and ducts during endoscopic surgery, this practice is unsafe when applied to tubular structures, and especially vessels, that are larger than 3.0 mm and those surrounded by adipose tissue. The poor holding strength of metallic clips has been documented [3]. Safe, reliable knotting is essential for ligation of sizable ducts and vessels and for tissue approximation. In endoscopic surgery, special techniques are required for this purpose. Intracorporeal knotting using the standard microsurgical (surgeon's) knot requires additional skills and is time consuming. By contrast, extracorporeal knots are easier to master and are less time consuming. The most commonly employed slipknot is the Roeder ligature [4], first described for use in tonsillectomy and introduced in endoscopic surgery by Semm [5]. Studies with this knot have shown that it is very secure when tied in catgut. Furthermore, its holding strength increases as it swells by hydration due to absorption of tissue fluid [1], and for this reason it is been recommended for ligature of the cystic duct in continuity during laparoscopic cholecystectomy [2].

A variety of slipknots are used by various professions and in certain leisure activities. Some of these have been adapted for use in endoscopic surgery. The holding strength of individual types of slipknots is influenced by a number of factors including the ligature material used and its caliber. Thus a slipknot may be secure when tied in catgut but unsafe with other materials. In addition, some slipknots are difficult to tie or jam lock too easily for reliable placement by push rod before locking.

The aim of the present study was to compare the performance of five slipknots in relation to type and size of commonly used nonabsorbable and absorbable ligature materials.

Materials and methods

Slip knots and ligature materials

Five slipknots were studied. Each slipknot was tied with five ligature materials, each in two sizes:

1. Nonabsorbable—silk (Mersilk, Ethicon) 1/0, 2/0, polyamide (Nurolon, Ethicon) 1/0, 2/0, and Dacron (Surgidac, USSC) 0/0, 2/0
2. Absorbable—polydioxanone (PDS, Ethicon) 1/0, 2/0, lactomer (Polysorb, USSC) 1/0, 2/0

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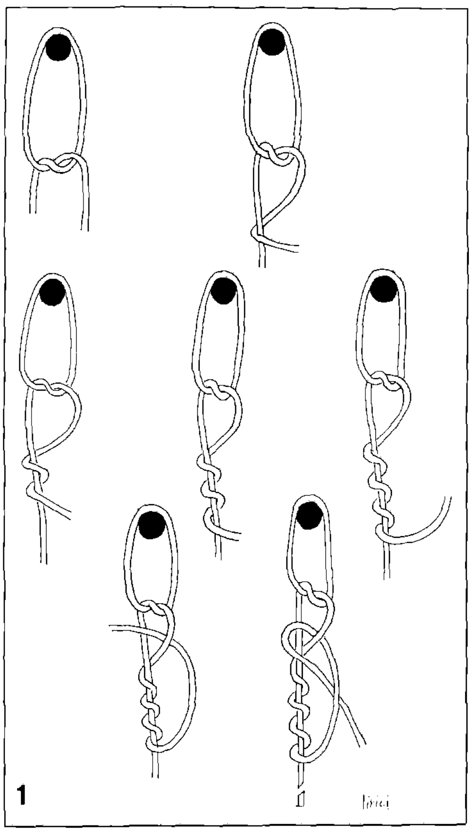
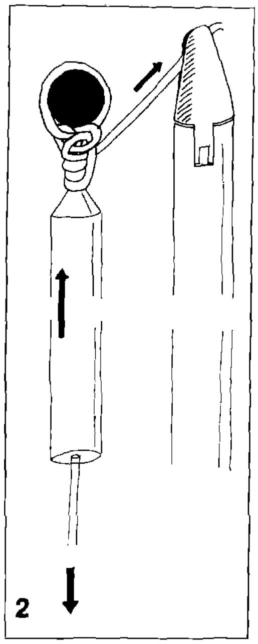
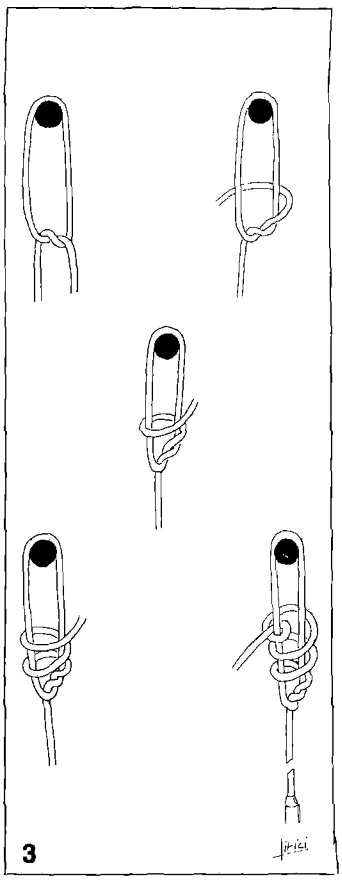






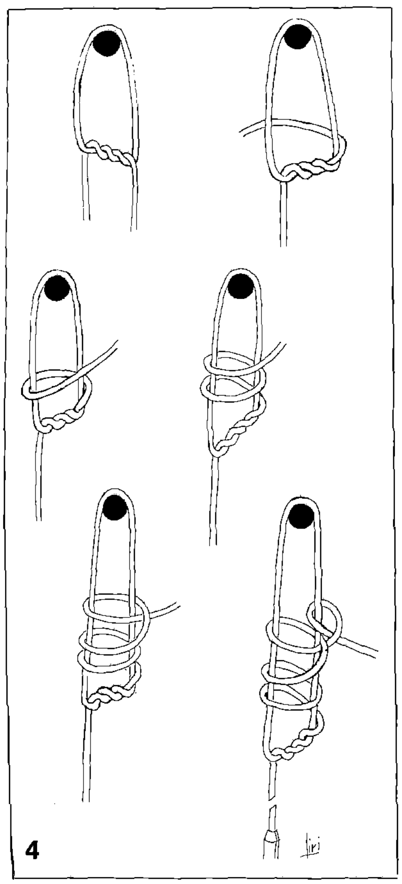
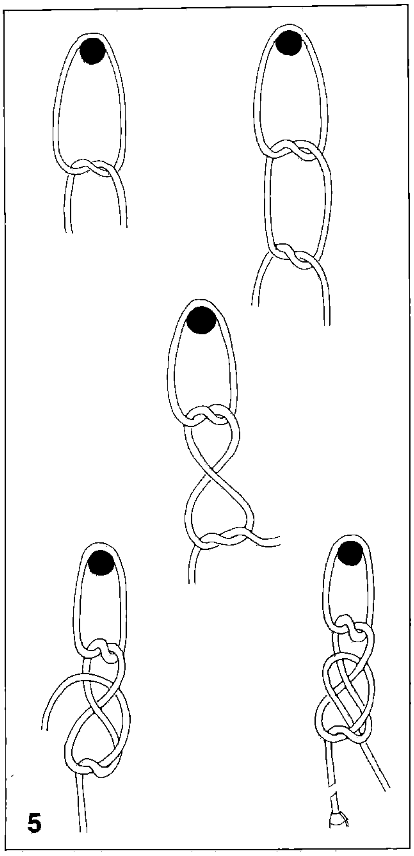


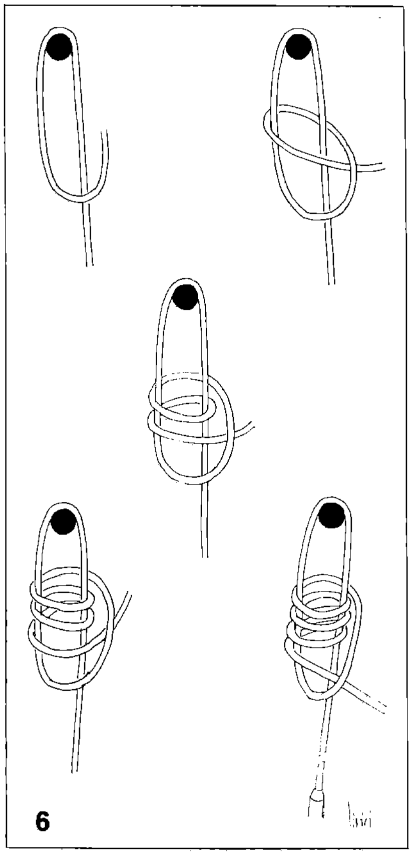
Fig. 1. The Tayside slipknot.

Fig. 2. Tightening of Tayside knot.

Fig. 3. The Roeder slipknot.

Fig. 4. Melzer slipknot.





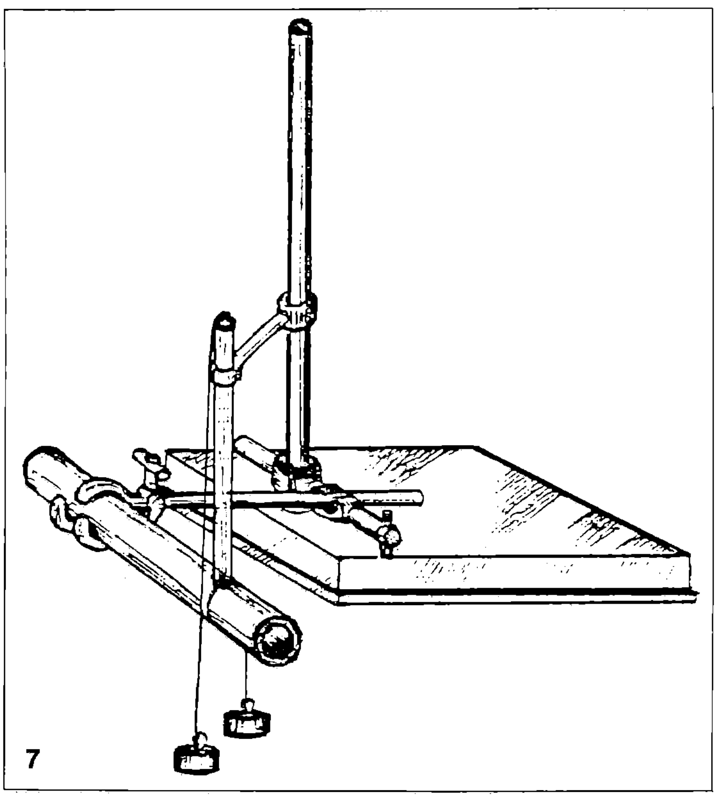


Fig. 5. Cross square slipknot.

Fig. 6. Blood slipknot.

Fig. 7. Test rig used to tie and tighten the knots under standardized conditions.

The five slip knots examined were:

Tayside: This knot is used by fishermen along the east coast of Scotland. It consists of a single cross hitch (first loop) followed by three turns around the standing part (straight limb) forming the second loop. The bight is then reversed (third loop) and passed through the second and third loops in an up-and-under fashion. The steps involved in tying the Tayside slip knot are shown in Fig. 1. The characteristics of this knot include ease of tying and smooth forward slipping during knot placement (run down). It requires simultaneous pushing with the rod against traction on the standing part and lateral traction on the tail for locking (Fig. 2).

Roeder: This knot is well known and is used in the construction of preformed catgut endoloops. When used to ligate structures in continuity, the procedure which should be followed is outlined in Fig. 3. The knot is easy to tie and locks simply by pushing with the push rod against traction on the standing part.

Melzer: This is a modification of the Roeder slipknot and was described by Melzer in 1991 for use with polydioxanone. The most important configurational change is the double hitch used to construct the loop at the beginning of the knot (Fig. 4).

Cross square: In essence, this is a modified square knot. The second loop is twisted to form a crossed figure of eight after which the bite (tail) is reversed and passed through the crossed loop in an up-and-under fashion. The steps involved in the fashioning of the Cross square knot are shown in Fig. 5. This knot is difficult to tie and can lock prematurely during knot run down.

Blood: This is a popular knot used by fisherman and is outlined in Fig. 6. It is easy to tie and slides well during knot placement.

Test rig

The slipknots were tied around a plastic cylinder 38 mm in diameter clamped at one end. The opposite end of the cylinder tapered gradually to a diameter of 35 mm. After the knot was tied, the standing part (long segment) of the ligature was threaded up the inside of a plastic carrier (10.3-cm-long push rod) and then down the outside of the push rod, the assembly being held loosely in position by an outer 10-cm-long cylinder with an internal diameter of 16 mm diameter. The outer holding tube was clamped in a perpendicular position to the tying cylinder. Two weights, each 250 g, were then attached to the free ends of the assembled ligature for 3 min to achieve standardized tightening (Fig. 7). The weights and nylon carrier were subsequently removed and the loop around the plastic cylinder was gently eased to the narrower end and removed. The free ligature ends were shortened to 10 mm each. The 38-mm-diameter ligature loop was then divided at the opposite pole to the knot and the two ends were inserted between the jaws of the pneumatic clamps of an Instron tensiometer (model 1026, Instron Ltd., Switzerland), the distance between the clamps being 13 mm. The tension load cell was 5 or 50 kg depending on the forces required: 50 kg for Tayside and Melzer slipknots using PDS, lactomer, and Dacron; 5 kg for other slipknots. The chart speed was set at 50 mm/min.

For each experiment, the following were calculated: *force required for reverse slipping* of the knot (F), *stress* = F/A where A is the cross-sectional area of the suture material used, *strain* = stretch/original length, and *elasticity* = stress/strain. Data on the cross-sectional area of the ligature materials was obtained from the manufacturer's specifications.

Statistical analysis

The median and inter quartile ranges of 10 measurements for each knot obtained. Comparisons between the tensile characteristics of the various knots were performed using the Mann Whitney U test.

Results

Force required to induce reverse slippage

The data for the median force in Newton required to initiate reverse slipping of the slip-knots from the ligature materials used are shown in Table 1 and Figures 8A, B. These data show that the force required to cause reverse slipping of the slipknots is directly related to the diameter of the suture material used. Thus, reverse slippage of slip-knots formed with ligature materials of sizes of 1/0 or 0/0 is induced by forces which are generally twice as strong as those needed to achieve the same end point for knots fashioned in equivalent 2/0 materials. All slip knots formed with silk and polyamide slipped on the application of weak forces (5–10 Newton). These materials are therefore less safe for extracorporeal slip-knots in endoscopic surgery.

Tayside and Melzer slipknots formed with lactomer, Dacron, and polydioxanone of either diameter required substantially greater force to commence reverse slipping ($p < 0.05$) than the Cross square and

Table 1. Force measurements (median and interquartile ranges) in Newtons, required to initiate reverse slippage ofthe knots

				Quartile	
Knot	Material	Size	Force	1	3
Tayside	Silk	1/0	9.8	6.7	12.9
Melzer	Silk	1/0	6.5	5.9	9.7
Roeder	Silk	1/0	6.2	4.2	8.3
Cross	Silk	1/0	5.6	4.4	7.3
Blood	Silk	1/0	4.9	3.0	5.7
Tayside	Silk	2/0	6.5	5.9	9.4
Melzer	Silk	2/0	5.3	4.3	7.4
Roeder	Silk	2/0	5.6	3.7	6.4
Cross	Silk	2/0	4.4	2.9	6.1
Blood	Silk	2/0	3.9	2.8	4.8
Tayside	Polyamide	1/0	8.6	6.1	9.0
Melzer	Polyamide	1/0	7.6	7.4	16.6
Roeder	Polyamide	1/0	4.1	3.5	4.7
Cross	Polyamide	1/0	7.1	4.7	8.8
Blood	Polyamide	1/0	5.7	4.3	6.8
Tayside	Polyamide	2/0	6.5	6.4	7.1
Melzer	Polyamide	2/0	6.1	5.0	7.1
Roeder	Polyamide	2/0	4.9	3.9	6.9
Cross	Polyamide	2/0	5.4	5.0	7.1
Blood	Polyamide	2/0	4.4	2.9	5.9
Tayside	PDS	1/0	26.5	22.0	45.2
Melzer	PDS	1/0	59.2	48.9	66.3
Roeder	PDS	1/0	8.1	7.1	10.2
Cross	PDS	1/0	16.8	14.6	18.5
Blood	PDS	1/0	13.4	9.2	15.8
Tayside	PDS	2/0	18.5	15.9	25.6
Melzer	PDS	2/0	28.0	24.0	29.5
Roeder	PDS	2/0	5.5	4.3	5.9
Cross	PDS	2/0	7.5	6.9	8.7
Blood	PDS	2/0	5.9	4.8	6.3
Tayside	Lactomer	1/0	84.3	78.0	85.5
Melzer	Lactomer	1/0	74.0	65.0	78.4
Roeder	Lactomer	1/0	86.7	84.0	90.4
Cross	Lactomer	1/0	21.1	14.1	26.0
Blood	Lactomer	1/0	10.3	2.8	17.2
Tayside	Lactomer	2/0	41.2	39.3	44.3
Melzer	Lactomer	2/0	38.7	37.6	40.9
Roeder	Lactomer	2/0	42.6	36.7	46.9
Cross	Lactomer	2/0	14.0	9.1	16.2
Blood	Lactomer	2/0	8.6	4.2	15.6
Tayside	Dacron	0/0	33.1	31.8	36.4
Melzer	Dacron	0/0	37.0	36.1	42.1
Roeder	Dacron	0/0	35.8	35.0	38.3
Cross	Dacron	0/0	3.9	2.8	8.2
Blood	Dacron	0/0	7.6	5.2	10.4
Tayside	Dacron	2/0	26.5	25.0	28.7
Melzer	Dacron	2/0	32.3	31.0	33.6
Roeder	Dacron	2/0	31.1	29.8	32.1
Cross	Dacron	2/0	4.4	3.3	4.5
Blood	Dacron	2/0	5.4	3.2	8.5

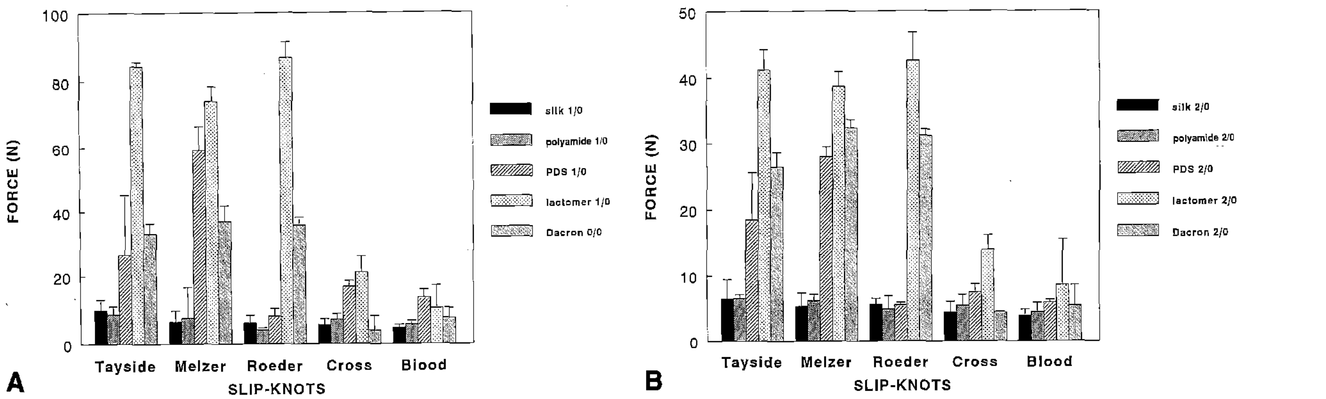


Fig. 8. **a** Bar graph of the median forces (and third-quartile range) in Newtons required to initiate reverse slippage of the slipknots formed in size 1/0 or 0/0 of the suture materials. **b** Bar graph of the median forces (and third-quartile range) in Newtons required to initiate reverse slippage of the slipknots formed in size 2/0 of the suture materials.

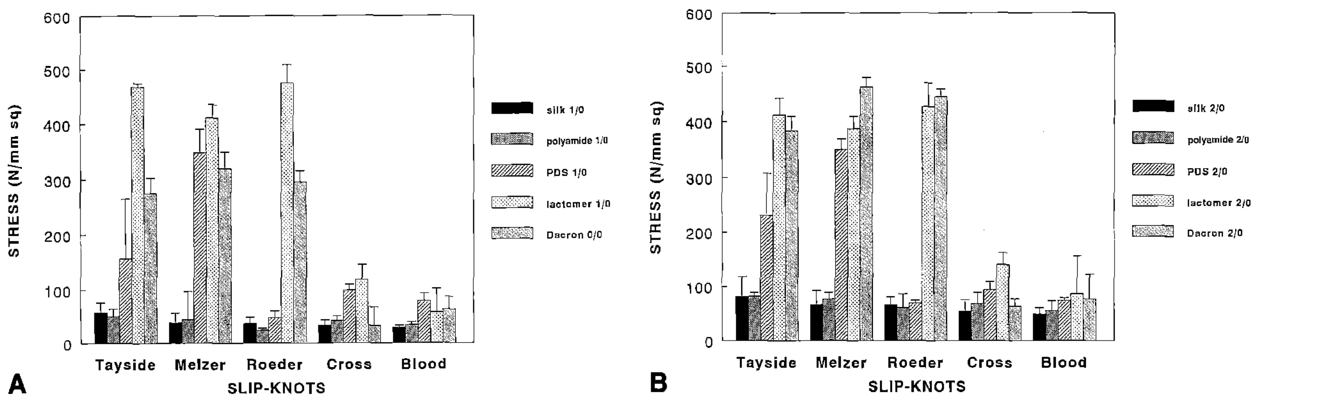


Fig. 9. **a** Bar graph of the median stress (and third-quartile range) in Newtons/mm^2 required to initiate reverse slippage of the slipknots formed in size 1/0 or 0/0 of the suture materials. **b** Bar graph of the median stress (and third-quartile range) in Newtons/mm^2 required to initiate reverse slippage of the slipknots formed in size 2/0 of the suture materials.

Blood knots. Tayside and Melzer slipknots fashioned with lactomer in sizes 1/0 and 2/0 had a knot-holding capacity of approximately 80 and 40 Newtons respectively. The Roeder slipknot exhibited a higher knot-holding capacity (similar magnitude to that of Tayside and Melzer slip-knots) when formed with lactomer and Dacron of either diameter but had a significantly lower and unsafe holding capacity (similar magnitude to silk and polyamide) when fashioned in polydioxanone of either diameter ($P < 0.005$).

Stress and strain

The median stress data at the time of reverse slipping of the slipknots with the ligature materials used are represented graphically in Fig. 9a,b. The data mirror image those for the force required to initiate reverse slippage and again demonstrate that the performance of the slipknots is largely influenced by the nature of the ligature material used.

Median strain measurements calculated as a ratio of increase in length over original length between the tensiometer clamps are outlined in Fig. 10a,b. This variable combines the stretch of the ligature material and the enforced stacking (additional tightening) of the knot before the start of reverse slipping. All slipknots formed with silk or polyamide exhibited a low strain (0.25–0.3). These materials are relatively flexible, with low torsional stiffness, and once tightened, the knots made from these materials are relatively well stacked. Thus for silk and polyamide knots, the strain is largely due to the stretching of the suture material itself.

Cross square and Blood slipknots with all suture materials and the Roeder knot with polydioxanone also had comparatively low strain measurements (0.25–0.5). These two slipknots required relatively low stress before reverse slipping occurred. This prevents slipknots tied with these suture materials from reaching their full stretch potential.

Tayside, Melzer, and Roeder slipknots formed with polydioxanone, Dacron, or lactomer had higher strain measurements. The highest strain was obtained with the Roeder knot fashioned with lactomer (3.1 and 2.3 using 1/0 and 2/0 lactomer, respectively).

Elasticity

The median elasticity (stress/strain) measurements for the five slipknots with the different suture materials are shown in Fig. 11a,b. This variable is a reflection of the elasticity of the suture material and that of the knot between the tensiometer clamps. It is a measure of the

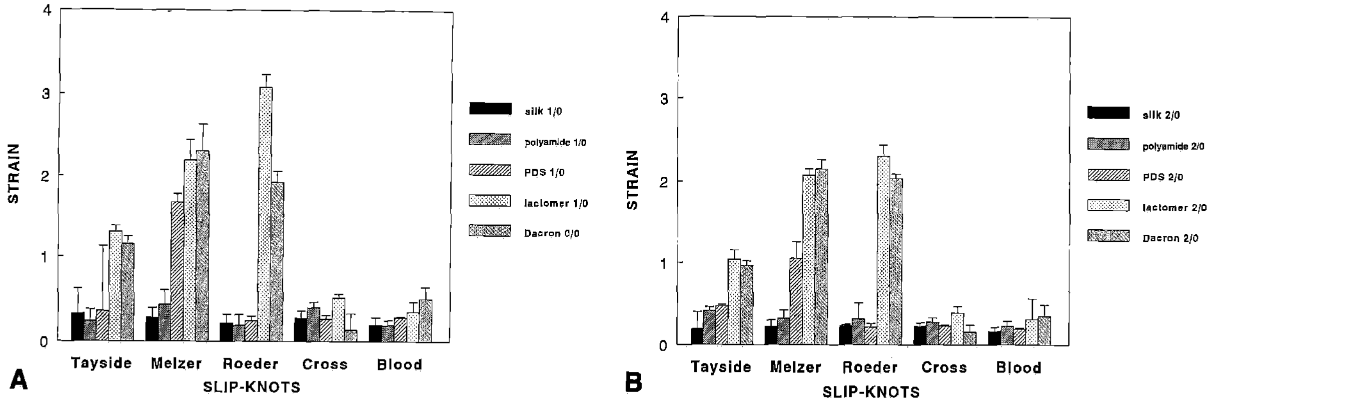


Fig. 10. **a** Bar graph of the median strain (and third-quartile range) which occurred before reverse slippage of the slipknots formed in size 1/0 and 0/0 of the suture materials. **b** Bar graph of the median strain (and third-quartile range) which occurred before reverse slippage of the slipknots formed in size 2/0 of the suture materials.

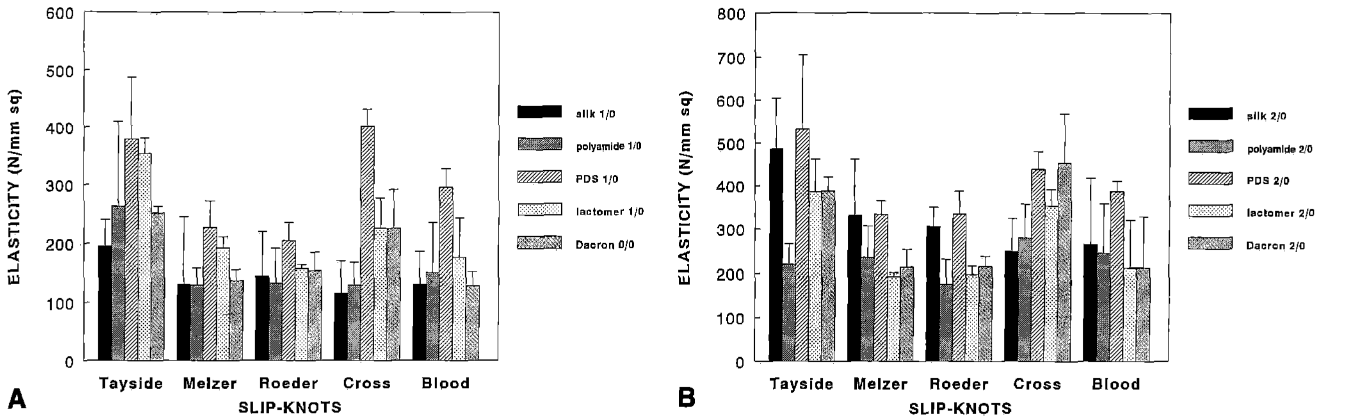


Fig. 11 **a** Bar graph of the median elasticity (and third-quartile range) in Newtons/mm^2 of the slipknot and suture materials of size 1/0 and 0/0. **b** Bar graph of the median elasticity (and third-quartile range) in Newtons/mm^2 of the slipknots and suture materials of size 2/0.

stress required to effect a standard elongation of the distance between the clamps prior to reverse slippage of the knot.

Silk, polyamide, and Dacron manifested similar elasticity in all the knots examined. This was lower than the elasticity of lactomer and polydioxanone.

Melzer and Roeder knots had similar elasticity for the ligature materials tested but this was lower than the elasticity of Tayside, Cross square, and Blood knots ($P < 0.05$).

Slipknots tied with materials of small diameter (2/0) tended to be more elastic than those tied with thicker materials (1/0, 0/0) although the differences between ligature sizes for this variable were not significant.

Discussion

This in vitro study has identified key issues relating to extracorporeal slipknotting in endoscopic surgery. In the first instance, the holding strength of a slipknot is directly related to the material used and its cross-sectional area. There are no available data on the minimal holding strength required for a knot around a vessel except for the report by Nathanson et al. [1] on the tension exerted by arteries and veins of different diameters perfused at a constant pressure of 147 mmHg in an in vitro test rig. In this study, a 9.0-mm porcine artery under these test conditions was observed to exert a wall tension of 0.55 Newtons (N). According to this, the minimal effective holding strength of a knot for securing a pressurized vessel of this calibre should be 1.2 N. If allowance is made for the systolic changes (max of 180–200 mmHg), the calculated minimal holding strength in vivo is 1.6 N. A threefold safety margin which would cover all arteries that could possibly be tied in surgical practice (open and endoscopic) yields a figure of 5.0 N. If one accepts this level of holding strength, then silk and polyamide provide less security when used for extracorporeal slipknots in endoscopic surgery than the other ligature materials examined in this study, although they exceed the safety margin of 5.0 N when used to tie Tayside and Melzer knots. This is in sharp contrast to their established safety when used in tying surgeon's knots during conventional open surgery. By the same criterion, the Cross square and the Blood knots are less secure than the other knots tested in this study and are therefore not recommended.

The effect of size of ligature material is demonstrated by the observation that a slipknot, irrespective of its configuration, fashioned with 1/0 has a holding strength which is double that of the same slipknot tied with the same but smaller-caliber (2/0) material. Factors other than surface area are involved since the average volumetric difference between the two gauges is 33–50%. These include surface frictional properties (roughness) and the weave, coating, and torsional stiffness.

Overall the best absorbable material for extracorporeal slipknots is lactomer and this can be safely tied using the Tayside, Melzer, and Roeder techniques. Polydioxanone is safe with the Melzer knot, acceptable with the Tayside knot, and unreliable with the Roeder knot. Of the nonabsorbable materials tested, only Dacron provided a knot of sufficient security when tied by the Tayside, Melzer, or Roeder knot.

The difference in strain between different suture materials for each slipknot relates to the surface friction properties, the torsional stiffness, and the flexibility of the suture material, all of which affect the stacking or tightening of the knot in addition to the elasticity of the suture material, which influences its ability to stretch. While some of these properties will be influenced by the diameter of the suture material we found no difference in strain between different diameters of each suture material.

Polydioxanone, Dacron, and lactomer are less flexible materials with relatively high torsional stiffness. The variability between the knots for each ligature material is an indication of the amount of additional tightening that a knot requires for its loops to be well stacked. The variability between the suture materials for each knot represents differences in elasticity, flexibility, and surface frictional properties of the different suture materials. It follows that for knots with high stress measurements (Tayside, Melzer, and Roeder), a low strain indicates a well-stacked slipknot and vice versa. The Tayside slipknot had a relatively high stress and comparatively low strain. In the present study, the ligature materials which provided slipknots with a high-stress:low strain ratio (indicative of optimal stacking) were lactomer and Dacron.

The "elasticity" of a knot is inversely related to its ability to stack. Thus Tayside, Cross square, and Blood knots, which become maximally stacked when tightened, require higher stress to effect a standard elongation. Melzer and Roeder knots have a similar configuration, and for this reason, a similar "knot elasticity." For these two knots less stress is required to effect a standard elongation since some of the energy is expanded in incremental stacking of the knots. For a given slipknot tied with different ligature materials, the differences observed are a function of the elasticity of the various materials. Silk, polyamide, and Dacron are relatively inelastic materials and were found to have a lower elasticity than polydioxanone or lactomer in all the knots examined. Polydioxanone exhibited the highest elasticity in all the knots. As expected, the smaller-diameter suture materials resulted in slightly more elastic knots.

There are two limitations to the present study. The first relates to the experiments being performed on dry ligature materials. In vivo hydration by absorption of tissue fluid will vary with different materials. Hydration causes swelling of the ligature and may alter the surface frictional properties, torsional stiffness, and elasticity to varying extent depending on the nature and composition of the ligature material. The more a ligature swells by hydration the greater the subsequent increase in its holding strength. Although this effect can be reproduced in the in-vitro situation [1] by immersion in physiological solutions at 37°C, the influence of hydration on knot performance was not examined in the present study. The second limitation relates to the size of the loop demarcated by the slipknot. In the present study, the size of the loop was standardized to 38 mm to enable sufficiently long ends on either side of the knot for secure jamming within the pneumatic clamps of the tensiometer. The countertension that this wide loop exerted on the cylinder when the knots were tightened is less than the tension that would be applied if the knots were run down and tightened around vascular pedicles and ductular structures where the resulting diameter of the encircling loop would be much smaller. Thus the tensiometric values recorded for the knots are representative of but different from those which apply when the same knots are employed to ligate vessels in vivo. However, this consideration does not invalidate the comparative performance of the various slipknots or the effect of material used or its size.

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