Changes in Knot-Holding Capacity of Sliding Knots In Vivo and Tissue Reaction

Zeina Babetty, MS; Aykut Sümer, PhD; Sabri Altintas, PhD; Sabri Ergüney, MD; Suha Göksel, MD

Objectives: To evaluate and compare the in vivo strength, knot efficiency, and knot security of 4 types of sliding knots, and to assess tissue reaction to study the effect of knot configuration, knot volume, and suture size.

Design: Randomized trial.

Setting: Experimental Medical Research Institute, Istanbul, Turkey.

Subjects: Wistar rats.

Intervention: To assess the tissue reaction, a midline laparotomy incision was made in 112 rats and sutured with various interrupted knots in silk and nylon sutures of 2/0 and 4/0 (United States Pharmacopeia) sizes. Suture loops were implanted in subcutaneous pouches in the rat abdomen. Sutures were all extracted at days 4, 7, 11, and 20 to determine their knot-holding capacity.

Main Outcome Measures: Knot efficiency and percentage decrease in knot-holding capacity were examined. Knot, tissue reaction, and inflammatory sheath volumes were measured.

Results: The 4/0 knots lost more strength than the 2/0 knots. The alternating knots with different patterns were more efficient and secure than the simple alternating ones. The alternating parallel knot was found to be unreliable. The tissue response to all the knots, except 2/0 nylon, was similar. The inflammatory sheath volume varied depending on the knot volume, suture size, and knot configuration.

Conclusion: The use of alternating sliding knots with different patterns is recommended to replace simple alternating sliding knots.

Arch Surg. 1998;133:727-734

Few investigations on the holding power of knots in vivo have been published. In 1976, Tera and Aberg1 cited that Herrman found no significant difference in knot-holding power with synthetic suture materials, metallic sutures, and silk after 24 hours of soaking in plasma, whereas catgut showed reduction. As reported by Tera and Aberg, Herrman confirmed these findings in 1973 in a series of experiments on rats and rabbits.1 The knot type tested was the 3 squared throw. Tera and Aberg1 reported the strength of 12 types of suture thread in combination with 12 types of knots outside the living organism. The results obtained indicated that the type of knot was crucial to the holding power of the knotted thread. Trimbos and associates2 studied the knot strength of different sliding knots. They indicated that the knot strength is dependent on both the type of the knot and the type of suture material. In an earlier study, Trimbos3 showed that the properties of various knots used in surgical practice differ considerably. Therefore, he declared that sufficient knowledge about knot configuration and knot strength seems to be an important aspect of surgical handcraf.

Magguilian and DeWese4 showed that, in general, a degree of knot security approaching 4 squared throws can be achieved with synthetic suture materials by 2 slip and 3 squared throws. Their study compared knot security of various synthetic suture materials with the use of silk as a standard.

In this study, van Rijssel et al5 concluded that the outcome of the comparison of square and sliding knots depends on knot configuration, suture material, and suture size. Brown6 examined 3 groups of knots to identify the most effective and efficient knotting techniques (square, surgeon’s, and double-throw knot). He used different suture materials (absorbable vs nonabsorbable and monofilament vs braided) to determine their loop-holding capacity and breaking force.

Shimi et al7 evaluated the holding and tensile characteristics of 5 extracorporeal slip knots in relation to type and size of ligature materials. Trimbos et al8 compared the 3-throw and 4-throw nonidentical sliding knots and the 3-throw square knot properties among 5 synthetic absorbable sutures.

All of these studies examined the in vitro tensile strength or the knot-holding capacity (KHC) and knot security of currently available suture materials. Perhaps of more importance to the surgeon are the changes that may occur in these important properties of suture knots during the postoperative period.

From the Biomedical Engineering Institute (Ms Babetty and Dr Sümer) and Mechanical Engineering Department (Dr Altintas), Bogazici University, and Departments of Pathology (Dr Ergüney) and Surgery (Dr Göksel), Istanbul University Cerrahpaşa Hospital, Istanbul, Turkey.
MATERIALS AND METHODS

Silk and nylon sutures of USP (United States Pharmacopeia) sizes 2/0 and 4/0 were used for this study. They were chosen as multifilament (silk) and monofilament (nylon) nonabsorbable sutures. Four knot configurations were used: the parallel alternating sliding knot (S/S/S/S), the non-identical alternating sliding knot (S#S#S#S), the parallel alternating with different patterns (S = S/S = S), and the non-identical alternating with different patterns (SXS#SX.S). They are illustrated in Figure 1.12

Wistar rats weighing about 230 g each were used for this study. Animal care was in conformity with National Institutes of Health regulations. A total of 112 rats were used for the combination of every suture material, size, and the 4 knot configurations, examined at the 4th, 7th, 11th, and 20th days postoperatively. One rat was used for every 4 knot configurations. Seven rats were used for every material and size (2/0 silk, 2/0 nylon, 4/0 silk, and 4/0 nylon). Accordingly, on the 4th day, groups of 28 rats were killed. The same was true for the 7th, 11th, and 20th days, to give a total of 112 rats.

EXPERIMENT 1

For tensile strength measurement, the loops of the suture material were tied around 2 cylindrical rods (made of wood) attached to a board.3 The diameter of each rod was 1 cm, and the distance between them was 8 cm to fit for implantation. The knots were tied by the same person to minimize variability and snugged down by moderate force.

The alternating sliding knots were tied with alternating right- and left-hand throws, the standing part and the hitch alternating strands with each successive throw. Alternating the hitches is most easily accomplished by alternating the hand that snugs down the throw, with the standing part held in the other hand.13 With the alternating knots of different patterns, 2 throws were made on a single standing part, and then the standing part alternates to perform the other 2 throws.

The rats were anesthetized with an intramuscular ketamine hydrochloride injection (80 mg/kg). The skin was undermined (midline incision) so as to create 4 subcutaneous pouches, 2 on each side. Every loop corresponding to a different knot configuration was implanted in 1 of these pouches, giving a total of 4 knots implanted in 1 rat. The incision was then closed with a running suture. For every suture material and every size, a group of 7 rats was used. The rats were then killed at the specified day, and the loops were dissected free from surrounding tissue, placed in saline solution to prevent drying, then mounted on a tensile machine (Zwick 1446 Universal; Zwick GmbH and Co, Ulm, Germany) and distracted at a rate of 30 mm/min. The loop method was followed.12

EXPERIMENT 2

For tissue reaction, the scoring system of Sewell et al13 was adopted. It assigns a total tissue reactivity score composed of 8 variables, as illustrated in Table 1. The average values are calculated for each variable, graded, multiplied by a specific weighting factor, and summed, resulting in the total tissue reactivity score. Accordingly, the overall grade of tissue reaction is read (Table 2).5

The volume of each knot was determined as follows: the diameter and the height of the knot were determined by means of a micrometer. From these values, the content of the cylinder fitting the particular knot was calculated. Therefore, the volume of the knot cylinder was calculated mathematically (V = πR²h).2

By measuring, under microscopy, the width and height of the inflammatory reaction surrounding the knot, it was possible to calculate the volume of the inflammatory cylindrical tissue reaction surrounding the knot. The difference between the volume of the inflammatory cylinder and that of the knot cylinder was calculated to represent the amount of tissue reaction sheath surrounding the knot.11 Knot volume cylinder was V1 = πR²h1. The tissue cylinder volume was V2 = πR²h2. The tissue reaction sheath was V2 - V1.

Seid et al9 used an animal model for measurement of incision strength after suture repair in an attempt to compare interrupted and continuous mass closure for abdominal incisions. Herrmann10 designed experiments to evaluate changes in breaking strength and knot security in the early postoperative period. Changes in tensile strength of sutures after implantation in animals are of concern because the in vivo environment is thought to alter the physical properties of sutures, whether in strand or knot configuration.

In addition to the need for the suture to maintain an adequate tensile strength to make certain that the knot does not slip, surgeons demand a suture that does not produce tissue reactions, which considerably weaken the holding power of the wound and delay healing. Many studies have been done to assess tissue reactions to various suture materials. Recently, more attention has been devoted to the knot site of the surgical loop. van Rijssel et al14 studied tissue reaction to the simple nonidentical sliding knot with the use of polyglactin 910 and polyglyconate and correlated the degree of tissue reaction surrounding the knot with the suture size, number of throws added, and knot volume.

The aim of this study was to evaluate changes in KHC or strength, knot efficiency, and knot security in vivo with a newly introduced sliding knot: the alternating sliding knot with different patterns.12 We also compared this knot with simple alternating sliding knots after several periods of implantation subcutaneously in the abdominal wall of rats. In addition, we assessed the tissue reaction to these knots by the scoring system of Sewell et al.13
RESULTS

EXPERIMENT 1

Knot-Holding Capacity

The loop-holding capacity was defined as the maximum force calculated from the load-elongation curve required to break the tied suture loop, by loading the part of the suture that forms the loop. Knot failure was defined as the break of the knot or its slippage exceeding 2 mm used as standard. The KHC is the force that a specified suture can sustain without failing through either the suture breaking or the knot slipping. The formula for determining the KHC varies according to the testing method; KHC equals half the force required for rupture, ie, the loop-holding capacity. For the single-strand method, KHC equals the force required for rupture.

Figure 2 and Figure 3 show the changes in tensile strength or KHC in newtons for silk and nylon sliding knots of 2/0 and 4/0, respectively. The mean KHCs of the knots were recorded at the time of implantation and 4, 7, 11, and 20 days postoperatively. Statistical differences between the KHC values were determined by a multivariate analysis of variance with a significance level of \( P = .05 \).

For loops of both sizes, the knot configuration, postoperative day, and suture material were all important factors in determining the KHC (\( P < .001 \)) (Table 3). The knot configuration along with the suture material seemed to have some significant effect on KHC (\( P = .002 \) for 2/0 loops and \( P < .001 \) for 4/0 loops), whereas the factor of both the suture material and the postoperative days was not significant, nor was the interaction of all 3 factors together (knot configuration, postoperative days, and suture material) (Table 3). The relatively small sample size (\( N = 7 \)) might have influenced the levels of significance corresponding to the factor of days and material together (\( P = .58 \) for 2/0 loops and \( P = .53 \) for 4/0 loops). Therefore, it is probable that a greater number of experiments would change these results.

As illustrated in Figures 2 and 3, all the knots of both materials and both sizes showed a decrease in KHC during 20 days of implantation. The alternating nonidentical knot of different patterns (SXS#SXS) recorded a decrease in KHC ranging from 14.5% to 33.4% for silk and nylon of both sizes. The alternating parallel knot with identical patterns (S=S//S=S) decreased 20.0% to 38.5%; the alternating nonidentical knot (S#S#S#S), 17.6% to 40.0%; and the alternating parallel knot (S//S//S//S), 27.7% to 49.0%, as shown in Table 4. Obviously, the parallel alternating knot (S//S//S//S) presented the highest range.
of decrease in KHC among all the knots and the highest percentage value, ie, the greatest decrease in KHC (49% for 4/0 nylon).

All the knots showed a higher percentage decrease in KHC for 4/0 gauge size than for 2/0 (Table 4) with the exception of the S/S/S/S knot in silk. The multivariate analysis of variance (Table 5) showed that the knot configuration and the suture size were significant factors in determining the percentage decrease in KHC. The factor of suture material could not be interpreted as significant (P = .06). Because of the small sample size, its contribution could be determined more precisely with more experiments; however, it seems reasonable to accept suture material as a significant factor. The interactions of knot configuration and suture size, suture material and size, and all 3 factors (knot configuration, suture material, and size) were significant (Table 5). However, the knot configuration and suture material interaction did not have an important effect.

Knot Efficiency

Knot efficiency \( ^3 \) is the KHC expressed as a percentage of the breaking strength (in vivo) of the unknotted thread. The in vivo tensile strength of the single strand, taken from separate experiments, is shown in Figure 4. The in vivo knot efficiencies of the tested knots are shown in Figure 5 and Figure 6, corresponding to silk and nylon knots of 2/0 and 4/0, respectively, throughout the postoperative days. Most of the in vivo knot efficiency values were higher throughout the postimplantation days because the suture loses strength in the tissue. Among the silk knots, the highest in vivo knot efficiency value belonged to the alternating parallel knot with different patterns (S = S/S/S/S) on the 11th day. For 2/0 size, knot efficiency was 79% compared with the in vitro value of 74%, which was also the highest among the in vitro knot efficiency values for 2/0 silk. For 4/0 size, the S = S/S/S/S knot achieved a value of 67.4% compared with the in vitro value, 68.8%, which was also the highest among the 4/0 knot efficiencies.

Among the nylon knots of 2/0 size (Figures 5 and 6), the alternating nonidentical knot with different patterns (SXS#SXS) achieved the highest in vivo knot efficiency value, again corresponding to the 7th day (60%) compared with the in vitro value (53.9%). For the 4/0 nylon
knots, the alternating parallel knot with different patterns (S = S/S = S) gave the highest in vivo value (63.4%) at the 20th day, compared with the in vitro value (66.7%).

As shown in Figures 5 and 6, among the 2/0 and 4/0 silk knots, the alternating parallel knot with different patterns had the highest knot efficiency at the 20th day. Among the 2/0 nylon knots, the nonidentical knot with different patterns had the highest knot efficiency. The parallel one with different patterns showed the highest knot efficiency among the 4/0 nylon knots again at the 20th day.

Knot Slipping

Knots that slipped more than 2 mm were considered to fail by slippage.12 The most slipping was seen with the parallel alternating knot (S/S/S/S). In 2/0 silk, this knot slipped at the 11th day (1 of 6 at 11 N) and at the 20th day (1 of 7 at 11.3 N) (Table 6). (N stands for newtons, the force at which slippage occurred.) In 2/0 nylon, it slipped again at the 11th and 20th days (1 of 6 at 13.3 N and 2 of 6 at 12 N, respectively). In 4/0 nylon, the S/S/S/S/S knot slipped at the 4th day (1 of 7 at 2 N) and at the 20th day (2 of 7 at 3.6 and 3.5 N). Slippage was more common in nylon knots than in silk knots. The nonidentical alternating knot slipped in 2/0 silk and 4/0 nylon (Table 6). None of the knots slipped with 4/0 silk. The alternating knots with different patterns showed no slippage for both silk and nylon of both sizes (Table 6).

EXPERIMENT 2: TISSUE REACTION TO KNOTS

Figure 7 presents the mean overall grade of tissue reaction for the sliding knots of silk and nylon sutures of both sizes throughout the 20 days of implantation. The overall grades of reaction varied between moderate, moderate to marked, marked, and marked to extensive (Table 2).13 There were no great variations between the grades among the knots of the silk and nylon materials, for both sizes. However, the knots of 2/0 nylon showed the high-

![Figure 4](image-url) Changes in tensile strength of the unknotted strand of 2/0 and 4/0 nylon and silk sutures during 20 days of implantation.

![Figure 5](image-url) Changes in knot efficiency of the sliding knots of 2/0 and 4/0 silk sutures during 20 days of implantation.

![Figure 6](image-url) Changes in knot efficiency of the sliding knots of 2/0 and 4/0 nylon sutures during 20 days of implantation.

![Table 6](image-url) Characteristics of Knots That Slipped

<table>
<thead>
<tr>
<th>Suture Material</th>
<th>Day</th>
<th>KHC, N</th>
<th>No. of Slipped Knots/Total Knots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silk 2/0</td>
<td>11</td>
<td>12</td>
<td>1/7</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>12.75</td>
<td>1/7</td>
</tr>
<tr>
<td>Nylon 2/0</td>
<td>11</td>
<td>NA</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>NA</td>
<td>0</td>
</tr>
<tr>
<td>Nylon 4/0</td>
<td>11</td>
<td>NA</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>3</td>
<td>1/7</td>
</tr>
</tbody>
</table>

*No silk knots slipped, and no knots with SX/SX/SX or S=S/S=S configurations slipped. KHC indicates knot-holding capacity; NA, not applicable. See “Materials and Methods” section for explanation of knot code.

†Knot slipped twice.
est overall grade at the 4th day (Figure 7) for the alternating parallel knot with different patterns ($S = S//S = S$) and the alternating nonidentical knot ($S#S#S#S$), which had a grade of 8, corresponding to an extensive reaction. Of lesser grade were the alternating nonidentical knot with different patterns (SXS#SXS) and the parallel alternating one ($S/S/S/S/S$) of 2/0 nylon, which had a grade of 7, corresponding to a marked to extensive reaction. The rest of the knots showed reactions varying between marked and moderate to marked.

All the knots showed a decrease in overall tissue reaction from the 4th day to the 20th. With regard to the 20th day, the lowest grade belonged to the alternating nonidentical knot with different patterns (SXS#SXS) for 4/0 silk, as shown in Figure 7, while the highest grade belonged to the alternating parallel knot with different patterns ($S = S/S = S$) of 2/0 nylon and the alternating nonidentical one ($S#S#S#S$) for nylon of both sizes.

Microscopic examination was performed on the tissue reactions on the 4th day, when a maximum of exudation is found in the wound, and on the 20th day, when the degree of exudation has decreased and fibroplasia is normally predominant. In addition, statistical analysis of the average values of histological variables among the postoperative days showed a significant difference in these values between the 4th and the 20th days for all the knots of the 2 materials and 2 sizes as well.

Histologically, as shown in Figure 8 and Figure 9, the tissue reaction to the suture knots consisted of edema, ie, the formation of an inflammatory zone around the knot. The diameter and depth of the inflammatory zone varied throughout the postoperative period. The reaction was mainly a neutrophilic infiltration accompanied by a mononuclear reaction that decreased all the way to the 20th day postoperatively. Lymphocytes, eosinophils, and giant cells varied in both occurrence and number among the knots and throughout the postoperative period. Fibroblast formation began at the 7th day and predominated at the 20th day.

Table 7 gives the knot volume ($V_1$), tissue cylinder volume ($V_2$), and tissue reaction sheath volume $V_2 - V_1$ for the corresponding knots of silk and nylon of both sizes. In the dry state, all knots of 2/0 silk had similar volume (because they consisted of 4 throws). Those of 4/0 size likewise had the same volume. This was also true of nylon knots. In the dry state, nylon knots of 2/0 had higher volume values than silk knots of the same size (3.62 mL vs 2.28 mL). However, the difference in volume values was smaller between knots of nylon and silk of 4/0 size (Table 7).

When the tissue reaction cylinder volume $V_2$ was compared, nylon knots demonstrated higher values than silk knots for both sizes. There was a decrease in the tissue reaction cylinder volume when the gauge size was smaller. In silk, the percentage volume decrease was in a range of 62.6% to 79.2%. Nylon showed a percentage decrease range of 52.5% to 76% as deduced from Table 7.

The tissue reaction sheath volumes are shown in the last column in Table 7. Among nylon knots, for both sizes, the alternating nonidentical knot showed the highest sheath volume for both sizes. Table 7 shows that the alternating nonidentical knot had the highest volume in both silk and nylon and both sizes.
In clinical practice the sliding knots are considered unreliable, but despite this they are widely used because of convenience. However, systematic studies on the physical qualities of the various sliding knots are still lacking. We were interested in comparing alternating knots with different patterns with simple alternating knots under in vitro conditions. We wanted to test the applicability of different patterns with simple alternating knots under in vivo conditions. More specifically, the tissue reaction to these knots was examined. A decrease in the KHC of all the knots was observed throughout the 20 days of implantation. Herrmann reported a decrease of 30% in strength for silk served throughout the 20 days of implantation. Herrmann et al found that the in vitro efficiency values of these knots. For silk, the 2/0 knots showed this superiority. However, among the 4/0 knots, only the alternating parallel knots with different patterns showed the highest in vivo efficiency. The high efficiency of the alternating sliding knot with different patterns is advantageous and encourages its use, even in place of the alternating knots. It is worth noting here that this statement applies only to the 4 thrown alternating sliding knots.

Even though knot slipping was more common in vivo than in vitro, a finding that supports Tera and Aberg's observation, only the alternating parallel knot was found to be unreliable under in vivo conditions. It was also found unreliable under in vitro conditions (previously performed).

The relevance of knot slippage in clinical surgery is important. When a suture loop surrounding a vessel unties (because of lack of security) or breaks (because of insufficient suture strength), internal hemorrhage may be the outcome. Wound dehiscence or incisional hernia may occur when a suture in the abdominal wound is disrupted. Consequently, knot security is as crucial a factor as suture loop strength in wound closure.

From another point of view, secure knots, by definition, fail by knot breakage in more than 9 of 10 cases. Insecure knots fail by slippage or breakage in a 50:50 distribution. This combination is responsible for their unreliable consistency, indicating the risk of extrapolating the findings of a laboratory study to clinical practice. The S/S/S/S knot showed some good KHC values in 2/0 silk at the 11th and 20th days: 11 to 16 N and 11 to 20.8 N, respectively. These values were comparable to the KHC values of the knots that failed by breaking (eg, the S = S). However, because this knot failed by slippage in some cases, it is considered insecure. A KHC value of 20.8 N might be clinically adequate, but a value of 11 or 2 N as recorded with 4/0 nylon (compared with the maximum value of 7.8 N) might well be a disaster. Therefore, insecure knots should be avoided in clinical practice where the mechanical reliability of the suture and not only the suture strength in tissue is important.

One factor that affects knot security is the knot configuration. The findings by Trimbos et al indicate that knot strength is dependent not only on the type of suture material but on the type of suture knot as well. Macguillian and DeWeese compared the knot security of 4-throw knots in 2 configurations (all squared and 2 slip and 2 squared) with 5 throws (2 slip and 3 squared). They used 3/0 suture materials. For silk, they reported the best knot security with the 4 throws squared configuration and 5 throws. The 2 slip, 2 squared configuration afforded the least knot security. It has been shown, when tying slip knots, that adding an additional squared throw increased knot security. Whether the alternation of strands and use of different patterns in the sliding knot construction is more likely to affect knot security than adding a squared throw to the slip or sliding knot shall be investigated.

In this study, the knot configuration element was found to be crucial in determining the KHC and the percentage decrease in KHC for the 2 materials of both sizes. Regarding knot security, the knot type was also a factor. The alternating sliding knots with different patterns were found to be secure in both silk and nylon (no slippage). Therefore, it seems acceptable to advocate their use and compare them not only with the sliding knots but also with the currently used ones, such as the square and surgeon's knots.

The importance of the knot type in clinical surgery arises from the fact that some factors other than knot security should be considered when the knot strength loss

### Table 7. Knot, Inflammatory Tissue Cylinder and Tissue Reaction Sheath Volumes for the Sliding Knots of Silk and Nylon Sutures With Both Sizes at the 20th Day Postoperatively

<table>
<thead>
<tr>
<th>Knot Code</th>
<th>Suture Material</th>
<th>Knot Volume, mL (V₁)</th>
<th>Tissue Cylinder Volume, mL (V₂)</th>
<th>Tissue Reaction Sheath Volume, mL (V₁–V₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SXS#SXS</td>
<td>Silk</td>
<td>2/0</td>
<td>2.28</td>
<td>2.35</td>
</tr>
<tr>
<td>S=S/S=S</td>
<td>Silk</td>
<td>2/0</td>
<td>2.28</td>
<td>2.62</td>
</tr>
<tr>
<td>S#S/S#S</td>
<td>Silk</td>
<td>2/0</td>
<td>2.28</td>
<td>3.42</td>
</tr>
<tr>
<td>S/S/S/S</td>
<td>Silk</td>
<td>2/0</td>
<td>2.28</td>
<td>2.32</td>
</tr>
<tr>
<td>SX#XS</td>
<td>Silk</td>
<td>4/0</td>
<td>0.56</td>
<td>0.61</td>
</tr>
<tr>
<td>S=S/S=S</td>
<td>Silk</td>
<td>4/0</td>
<td>0.56</td>
<td>0.60</td>
</tr>
<tr>
<td>S#S#S</td>
<td>Silk</td>
<td>4/0</td>
<td>0.56</td>
<td>0.71</td>
</tr>
<tr>
<td>S/S/S/S</td>
<td>Silk</td>
<td>4/0</td>
<td>0.56</td>
<td>0.60</td>
</tr>
<tr>
<td>SXS#XS</td>
<td>Nylon</td>
<td>2/0</td>
<td>3.62</td>
<td>5.13</td>
</tr>
<tr>
<td>S=S/S=S</td>
<td>Nylon</td>
<td>2/0</td>
<td>3.62</td>
<td>4.59</td>
</tr>
<tr>
<td>S#S/S#S</td>
<td>Nylon</td>
<td>2/0</td>
<td>3.62</td>
<td>6.06</td>
</tr>
<tr>
<td>S/S/S/S</td>
<td>Nylon</td>
<td>2/0</td>
<td>3.62</td>
<td>5.18</td>
</tr>
<tr>
<td>SX#XS</td>
<td>Nylon</td>
<td>4/0</td>
<td>0.77</td>
<td>1.60</td>
</tr>
<tr>
<td>S=S/S=S</td>
<td>Nylon</td>
<td>4/0</td>
<td>0.77</td>
<td>1.23</td>
</tr>
<tr>
<td>S#S#S</td>
<td>Nylon</td>
<td>4/0</td>
<td>0.77</td>
<td>2.88</td>
</tr>
<tr>
<td>S/S/S/S</td>
<td>Nylon</td>
<td>4/0</td>
<td>0.77</td>
<td>1.25</td>
</tr>
</tbody>
</table>

*See “Materials and Methods” section for explanation of knot codes.*
is assessed under in vivo conditions. These factors include the change in tissue-holding power resulting from the presence of the suture and also the presence or absence of tissue strangulation caused by the actual stitch. Both factors cause loss of tissue-holding power. In other words, not only can the strength of the suture loop be reduced by the in vivo environment, but also the suture-bearing tissue can be weakened by the suture loop.

In abdominal wounds, the suture loop has to withstand the cumulative effects of intra-abdominal pressure, lateral pull of abdominal muscles, and edema, or inflammatory pressure within the loop itself. These tensions are applied in different directions, which may cause the suture loop to break if it is not strong enough or to untie or slip if it is not secure enough, emphasizing the importance of knot configuration and type.

The overall tissue reaction grades showed slight differences between the knots of 2/0 and 4/0 sizes in both materials. However, the 2/0 knots showed higher tissue reaction cylinder volume and sheath volume than the 4/0 knots. van Rijssel et al showed the suture size to be a significant independent factor in determining the score for tissue reactivity, a finding that agrees with our experimental results. The suture size is considered an important factor because increasing the size resulted in an increase in the knot volume by a factor of 4 to 5. Therefore, more foreign material is introduced in the wound, resulting in an increase in the sheath of the inflammatory reaction, a fact that is confirmed in this study. This conclusion is based not only on the width of the inflammatory zone but also on the height.

The factor of knot configuration in determining tissue reaction shear volume depended on the material used. The alternating nondiagonal knot was similar in both materials, in having the highest shear volumes for both sizes.

The total knot body or volume for nylon was much higher than that of silk for the 2/0 size. This is because nylon is more difficult to handle than silk, especially when tying a knot with alternating axial strands. Because of its monofilament structure, this suture is relatively stiff, resulting in difficulty with handling and tying. It is more difficult to tie the nylon knot as tightly as that of silk, leaving empty spaces between the alternating throws. This contributes to the significantly larger size of a nylon knot over a silk knot with the same number of throws (here, 4). However, smaller gauges of a monofilament suture are thought to have higher pliability than larger gauges because the diameter is smaller. Accordingly, as the suture size decreases, the nylon becomes more supple and easier to handle, and then the knot can be tightly tied in such a manner that it approximates the size of the silk knot. This was proved with the 4/0 size.

The difference in knot volume between nylon and silk of the same size may account for the higher degree of inflammation provoked by nylon knots.

In general, the alternating knots with different patterns demonstrated better performance than the alternating ones under in vivo conditions. Obviously, depending on the intended use and ultimate function of the suture, some knots will be subjected to greater tension than others. Therefore, in situations where the use of sliding knots is convenient, we recommend the alternating sliding knots with different patterns as a substitute for the alternating ones. It seems more logical to use these new configurations than to rely on adding additional throws to the sliding knot to enhance its security. Addition of more throws is undesirable because it introduces more foreign body to the wound, thus generating a greater amount of inflammation. The new configurations proved to be strong and secure without provoking more inflammation of the wound, since maximal wound strength requires a careful balance between maximal support and minimal foreign-body reactivity. In abdominal wounds, where the risk of dehiscence exists because of untying of the suture loop, knot security turns out to be as important as the knot strength. Accordingly, a careful balance should be sought between knot-tissue strength (a very strong suture pulls out from the tissue, a weak one breaks), knot security (secure knot type or configuration that does not slip or become untied), and minimal tissue reaction.

We thank Burak Erman, PhD, for the approval to use facilities in the polymer research center laboratory, Dogsan Company, Istanbul, Turkey, for providing the surgical sutures, and Bogaziçi University Research Fund, Istanbul, under project 95HX0009.

Reprints: Zeina Babette, MS, Biomedical Engineering Institute, Bogaziçi University, 0815 Bebek, Istanbul, Turkey (e-mail: babette@cyberia.net.lb).

REFERENCES