Original Article

Which Knots Are Recommended in Laparoscopic Surgery and How to Avoid Insecure Knots

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ABSTRACT Study Objective: To investigate why security of identical knot sequences is variable and how to avoid occasionally insecure knots.

Design: A factorial design was used to assess factors affecting the security of half knot (H) and half-hitch (S) knot combinations. The effect of tying forces and the risk factors to transform H knots into S knots were investigated. The risk factors evaluated were as follows: starting with an H1 or H2 instead of an H3 knot, inexperience, short sutures, and monomanual knot tying. Security of transformed knots, S2S1 and S2S2 knots, and their recuperation with 2 additional half hitches, SSb or ShSb, were evaluated.

Setting: Training center for laparoscopic suturing.

Patients: Not applicable.

Interventions: Security of knots was evaluated in vitro.

Measurements and Main Results: The forces that caused knot combinations to open before breaking of the suture were used to calculate the risk of opening with low forces. Tying more strongly increased the security of half knots (H2H1sH1s) (p < .02) and half hitches (p < .001). The forces needed to transform an H3 into an S3 are higher than those for an H2 (p < .001), and the risk increases when the surgeon is inexperienced (p < .001), when sutures are short (p < .001), and when monomanual knot tying (p < .001) is used. Inadvertently made S2S1 and S2S2 knots are dangerous, with the exception of the symmetric S2S2, which is stable. Unstable knots such as S2S1a and S2S2a knot combinations improve with 2 additional blocking half hitches (ShSb), but S2S2aShSb remains occasionally insecure.

Conclusion: To reduce the risk of accidentally transforming a first H into an S knot, it is recommended to start with an H3, tie with force, avoid short sutures, and use bimanual suturing. This permits the recommendation to use preferentially H3H2 knots or 5 half hitches (SSSbSbSb). When in doubt, half knot combinations should be secured with at least 2 blocking half hitches. Journal of Minimally Invasive Gynecology (2019) 00, 1−10. © 2019 AAGL. All rights reserved.

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Suturing and knot tying are basic skills employed in surgery to approximate tissues and for hemostasis. The security of the knot combinations used is fundamental. Over 250 different knot combinations have been described, but our understanding of the mechanisms of their security is limited. More knots or more throws are considered to have a better security, but it is unclear whether security requires 3 [1], 4 [2], 5 [3], or even 6
throws. A systematic evaluation of all reasonable knot combinations [4] demonstrated the lower security of monofilament sutures, indicating that security of most knot combinations was highly variable and that they occasioned at low forces of less than 10 newton (N). Only H2H2 and H3H2 half knot combinations and SSSbSbSb, a sequence of 5 half hitches with 3 blocking sequences, were always secure. During traction, knot combinations reorganize, and the angulation of threads explains the systematic, although small, differences in breaking forces [4] between symmetric and asymmetric knot sequences.

The forces required to hold tissues together in gynecologic surgery have not been well documented. It is most likely that the forces required are less than those required in palatal [5] and orthopedic surgery, where knots should resist to 120 N cyclic testing [6–8]. Clinically, it seems logical to consider knot combinations that occasionally open with forces of less than 1 N unsafe and dangerous. In addition, knots that occasionally open at less than 10 N can probably be dangerous, and there is a possibility that those opening at less than 30 N may be dangerous as well. The knots that never open below 50 N are probably safe considering that the breaking force of 2.0 sutures is around 80 N.

The clinical importance of the variable security of identical knot combinations, with occasional unsafe and dangerous knots prompted us to investigate the mechanism of this occasional instability to prevent their occurrence. This should permit recommendations regarding which knot combinations and which knot tying techniques should preferably be used in laparoscopic surgery to avoid occasionally insecure knots.

Materials and Methods

Knot Classification and Abbreviations Used

As described previously [4,9], a knot can be a half knot (H) or a half hitch (S from Sliding or from “Semi Chiave”) (Fig. 1). In a half hitch, the (long) end on traction is called the passive thread or end, and the other end that slides freely along the passive end is called the active thread or end. The H or S knots are characterized by the number of throws and for subsequent knots by the rotation in comparison with the previous one. If the rotation of the same suture end is the same, and the suture ends thus leaves the knot in the same plane, a knot is symmetrical (s); otherwise, it is asymmetrical (a). Intracorporeal knot combinations can be made with monomanual or bimanual knot tying when the active hand is the same or when 2 hands are used, respectively. To avoid confusion concerning symmetrical and asymmetrical knot sequences, it should be understood that with monomanual suturing, symmetrical sequences are obtained when the rotation of the subsequent knot is the opposite of the previous one. With bimanual suturing, symmetric knot sequences are obtained when the sense of rotation is the same. Symmetric and asymmetric knot sequences also apply to half hitches. A series of half hitches made monomanually with the same rotation, that is, asymmetrical, makes a perfect sliding knot. However, it should be realized that a sequence of 2 symmetrical half hitches, that is, monomanually with alternate rotation (known in sailing as a mast throw) is still a sliding knot, but forces required are slightly higher. Besides being symmetric or asymmetric, subsequent S knots are, in addition, characterized by the passive or traction thread in relationship with the previous one. In series of half hitches, the second half hitch is sliding (s) when

Fig. 1

Knots and knot combinations. A half knot can have 1, 2, or 3 throws, which can be transformed into S [1], S2, and S3 knots, respectively. From the second knot onward, knots are characterized in addition by their relationship with the previous knot. When the sense of rotation of the same thread is the same, the 2 knots are in 1 plane, and the second knot is symmetric (H1H1s) and can be transformed in sliding (SSs) or blocking (SSsb) half hitches. An alternate sense of rotation results in 2 knots in 2 planes, and the second knot is asymmetric (H1H1a) and can be transformed into a sliding SSA or a blocking SSab. For half-hitch combinations, 1 throw, sliding and an asymmetric rotation, are not indicated on account of being considered the standard.
the passive thread remains the same, or blocking (indicated by b) when the passive thread is changed.

Sequences of half knots are described as “H,” followed by the number of throws, and from the second knot onward, by the rotation in comparison with the previous knot, that is, symmetric (s) or asymmetric (a). For half-hitch (S) sequences, throws are indicated only if more than 1, and rotation only when symmetrical. SSSbSbSb are thus 5 single-throw half hitches, all made in the same sense of rotation and thus asymmetric. The first 2 are sliding SS, followed by 3 blocking SbSbSb. It should be realized that an H1 and S1, and even an H2 and S2 and an H3 and S3, can be easily transformed from one to the other. However, S2 and S3 always result from the accidental transformation from H2 or H3, respectively.

**Knot Tying and Testing**

The tying and testing of knot combinations was performed as described [4], using either dry 2-0 polyglactin 910 (PP) or 2-0 polyglactinacron 25 (MS) (United States Pharmacopeia size), which are polyfilament and monofilament sutures, respectively. Standardized laparoscopic knots were made using Romeo’s gladiator rule knot tying technique [10], in the second-generation laparoscopic simulator ETX A2 EVE (Prodelphus Surgical Simulators, Olinda, Pernambuco, Brazil) using the Karl Storz Full HD Imaging System (IMAGE 1 HUB HD and a 3-chip HD camera head) and 2 Karl Storz needle holders (KARL STORZ KOPH Macro Needle Holder). Sutures measuring 18 cm were tied around a 15-mm plastic tube using different knot combinations. After knot tying, the suture threads were cut at exactly 10 mm. These loops were subsequently mounted for analysis.

Knot sequences are described as “H,” followed by the number of throws, and from the second knot onward, by the rotation in comparison with the previous knot, that is, symmetric (s) or asymmetric (a). For half-hitch (S) sequences, throws are indicated only if more than 1, and rotation only when symmetrical. SSSbSbSb are thus 5 single-throw half hitches, all made in the same sense of rotation and thus asymmetric. The first 2 are sliding SS, followed by 3 blocking SbSbSb. It should be realized that an H1 and S1, and even an H2 and S2 and an H3 and S3, can be easily transformed from one to the other. However, S2 and S3 always result from the accidental transformation from H2 or H3, respectively.

**Experiments**

The first 2 experiments were designed to test the hypothesis that security of knot combinations varied with the force of knot tying. In a first experiment with half knot combinations, we used the surgical knot combination H2H1sH1s because previous experiments had demonstrated that this combination occasionally slid open at very low forces. Using a factorial design with 30 knots/cell (120 knots in total), we compared security of monofilament vs polyfilament sutures, when tied more forcefully (estimated at 30 N) with the force maintained for 5 seconds or with a normal or moderate force (estimated at 10–20 N) maintained for 1 sec. In a second experiment with half-hitch combinations, we compared security of intracorporeal (estimated at 10–20 N) vs extracorporeal (estimated at 40 N) knot tying (N = 415 knots) for SSSb, SSSbSb, SSSSS, SSSSbSb, and SSSbSbSb knot combinations.

The third and fourth experiment evaluated the risk of inadvertent destabilization of H knots. The review of the video registration of the H2H1sH1s knots, especially of those that had slid open at low forces, had revealed that inadvertent traction on one of the threads or tails of the first or second half knot when tying the subsequent half knot, was much more frequent than anticipated. Because this inadvertent traction only rarely transformed the half knot into a clear half hitch, we concluded that destabilization probably caused the H knot to be transformed occasionally into an S knot during tying with force or during testing in the dynamometer. To test this hypothesis, we evaluated whether the number of insecure knots increased with factors increasing the risk of inadvertent traction, such as inexperience, short sutures, and monomano nual suturing. The third experiment evaluated the risk of destabilization of an H2H2a knot, known as a knot with high security, when formed with shorter sutures of 12 cm (instead of 18 cm). A factorial design was used to evaluate the effect of bimanual vs monomano nual suturing, and of a more vs a less experienced surgeon. In a fourth experiment, we evaluated an H2H1sH1s knot combination with ultrashort sutures of 10 cm vs sutures of normal length.
As inadvertent traction on one of the tails with destabilization of the H knot, had been determined as the major cause of insecure knots we measured in a fifth experiment (N = 30) the forces needed to transform an H1, H2, and H3 into an S1, S2, or S3, respectively. These knots were formed on a soft tissue with friction forces similar to those of human tissue.

A sixth experiment (N = 240) evaluated the security when a first H2 had been intentionally transformed into an S2. We evaluated the security when the second knot was a symmetric or asymmetric rotation, and with a blocking (pulling the active end, i.e., MT or TM) or sliding (pulling the same passive end, i.e., MM or TT) sequence. This allowed for a 4-way analysis of variance analyzing simultaneously the effect of the traction on the long or short end of the first knot, of an S1 or S2 as second knot, being symmetric or asymmetric, and blocking or sliding.

Given the poor security of most S2S1 or S2S2 combinations, a seventh experiment was performed to evaluate whether these irregular asymmetric half hitches, that is, S2S1ab or S2S2ab, 2 knots with a very poor security, could be stabilized by adding 2 additional half hitches, either an SS or an SbSb. A factorial design (N = 336 knots; 42 knots/cell) was used with 3 variables, 1 or 2 throws for the second knot, which could be symmetric or asymmetric, and finally, an additional SbSb or ShSb.

Statistics

To evaluate the quality of the knots, arbitrary classes were used, based on the clinical judgment of the combined authorship, when the suture combination opened at <1 N, between 1 and 5 N, 6 and 10 N, 11 and 15 N, 16 and 30 N, and >30 N. Opening at less than 10 N is indicated in the figures in shades of red because they are considered potentially clinically dangerous. Knots that never opened below 30 N are indicated in the graphs in shades of darker green because they are considered clinically safe.

Means and SDs are given unless indicated otherwise. Statistical evaluation was performed using the SAS system [13]. Differences in breaking strengths were evaluated with Student t test or by Wilcoxon signed rank test, and differences in opening of knot combinations were evaluated by the Mantel-Haenszel chi-square test for trend analysis. Analysis of a factorial design was performed using a 2-way analysis of variance.

Results

The hypothesis that knot security increased when tied more strongly was confirmed for the flat knot H2H1sH1s (p <.02) (Fig. 2) and for half-hitch combinations (p <.001) (Fig. 3). As expected, H2H1sH1s was less secure with monofilament sutures (p <.001) and had lower breaking forces (p <.001) (Fig. 2). Breaking forces increased slightly when traction forces were higher both for H2H1sH1s (p <.001) and for half-hitch combinations (p <.001), suggesting less knot rearrangement and angulation during traction. Breaking forces for extra or intraperitoneal suturing were 52.6 ± 6.6 N and 47.7 ± 4.2 N for SSSSS, 66.4 ± 1.4 N and 57.9 ± 1.3 N for SSSbSb, 50.8 ± 1.4 N and 62.7 ± 1.0 N and 62.7 ± 0.8 N for SSSb, 57.5 ± 2.3 N and 59.2 ± 1.0 N for SSSbSb, 62.6 ± 1.1 N and 62.7 ± 0.8 N for SSSbSbSb, respectively. Furthermore, experiment 2 confirmed by 2-way analysis of variance, that as expected, security of 5 half hitches (SSSSbSb, SSSbSbSb) increased with 3 instead of 2 blocking half hitches (p <.001), that security of 2 sliding S followed by 2 or 3 blocking S (SSSbSb and SSSbSbSb) increased with more blocking S (p <.001), and that security of 2 or 3 sliding S followed by 2 blocking S (SSSbSb and SSSbSbSb) did not differ.

Experiment 3 (Fig. 4) confirmed our hypothesis that with shorter sutures, the risk of insecure H2H2a knots, probably as a consequence of inadvertent traction with destabilization of the first knot and/or transformation of the H2 into an S2, increased when the surgeon was less experienced (p = .01). By 2-way analysis of variance, the effect of monomanual knot tying was not significant. However, monomanual knot tying by a less experienced surgeon led to 3% of knots that opened at less than 5 N. The increased risk of destabilization with short sutures (Fig. 5) was confirmed in the fourth experiment. H2H1sH1s knots made with ultrashort sutures were less secure (p ≤ .001), and 3% of knots opened at less than 10 N and 3.3% at less than 15 N. Breaking forces were slightly higher with monomanual suturing (p <.001) and when the surgeon was less experienced (p <.001).

The risk of destabilizing an H3 is as expected less than for an H2 or an H1. The forces needed to transform them into an S3, S2, or S1 were 18.8 ± 2.8 N (p <.001 vs H2), 10.0 ± 2.0 N (p ≤ .001 vs H1), and 7.1 ± 0.9 N, respectively (experiment 5, N = 30).

The security of erroneously made knot combinations starting with an S2, followed by an S1 or S2 (Fig. 6) is very low, except for the S2S2s. These results are unexpected and surprising. First, it is surprising that security of an S2S2s is good, whereas security of an S2Sa and S2S1s and S2S1a is very poor. It is also surprising that none of the blocking sequences (MT or TM) had a clearly better security than the sliding sequences (MM and TT) if judged on Fig. 6. The highly significant differences found by 4-way analysis of variance are considered the consequence of the high power of 480 knots, with little clinical importance: when pulling the T or M of the first knot, (p <.001), when pulling T or M of the second knot (p <.001), when the second knot was symmetric or asymmetric (p <.001), and when the second knot was a S1 or S2 (p <.001). A 4-way analysis of variance of the forces at which the sutures break is only significant for pulling the short or long end of the first knot. (p <.001).
The S2S1a and S2S2a combinations with a low security were recuperated to a large extent with 2 additional half hitches SSb or SbSb (Fig. 7). However, while S2S1a knots became reasonably secure, the S2S2a followed by SSb or ShSb still had 3% knots that opened at less than 5 N and 2.5% at less than 10 N, respectively. By 2-way analysis of variance, security is higher with S2S2 than with S2S1 (p = .009) and when SbSb is used instead of SSb for recuperation (p = .03). Breaking of the thread occurred between 56 and 60 N. Only the ShSb group had slightly higher (p = .01) breaking forces than SSb.

**Discussion**

These data confirm that the behavior and security of a knot combination varies with the sequences of knots used, and with a series of factors that influence knot reorganization under traction. Of importance are the number of throws, the rotation resulting in symmetric and asymmetric knot sequences, and the forces used to tie the knots. A key factor causing occasional insecure knots seems to be the probability of accidentally destabilizing a knot, with the eventual transformation of H knots into S knots under traction.
traction. The same mechanism of reorganization under traction could explain the occasional transformation of a Sb knot into an S. This risk decreases, as expected, when the first knot is an H3 instead of an H2 or H1, when knots are tied forcefully, with polyfilament sutures, when the surgeon has more experience, when the suture is longer, and when the knots are tied bimanually. This reorganization of knots under traction probably also explains the small but systematic variability in breaking forces owing to angulation of the threads.

By common sense, we did consider in gynecologic surgery knot combinations as safe, unsafe, or dangerous according to the percentage that never slides open below 30 N, the percentage sliding open at forces below 10 N, and those sliding open at forces below 1 N, respectively. However, traction by the mesh on the knot on the promontory is
probably higher, thus requiring more secure knot combinations. In addition, forces on abdominal wall sutures, although divided over the number of sutures, might be higher during muscle contraction and increasing intraperitoneal pressures known as bursting pressures [14,15]. If the abdomen is approximated as a cylinder, wall traction (forces) equal the radius times the intraperitoneal pressure in Pascal, the unit of pressure. (1Pa = 1 N/m²).

This multifactorial probability of knot reorganization and of the resulting probability of security of knot combinations will remain clinically undetected when occurring in only a few percent. However, it might explain occasional postoperative complications. Therefore, prevention of unstable or insecure knots is clinically important. Knowledge is needed to ensure use of correct knot sequences. Some sequences are not obvious such as the necessity to use at least 5 half hitches with 3 of them blocking, or the use of an H2H2 or H3H2 combination with asymmetric sequences that are surprisingly even slightly better in contrast with poor security of the H1H1a knot. Awareness of the risk of inadvertent destabilization of half knots is equally important. Awareness translates clinically in a correct suturing technique with individual knots tied with sufficient force. When using half knot combinations, the 2
Fig. 5
Opening and breaking of H2H1sH1s knot combination using dry polyfilament 2-0 polyglactin 910 (PP). Security of knots is less (p = .0004), and 3% opened at less than 10 N when sutures are very short (10 cm) in comparison with sutures of normal length. The colors indicate in shades of red opening at <1 N, 1 to 5 N, and 6 to 10 N; in yellow opening at 11 to 15 N; and in shades of green opening at 16 to 30 N or >30 N, or break.

Fig. 6
After reorganization of the first H2 into an S2, the second knot was an S1 or/and S2, symmetric or asymmetric, blocking or sliding. If the first and second knot are pulled by the same short (T) or long end M, TT and MM are sliding sequences. TM and MT are blocking sequences. Surprising is that S2S2 symmetric knot is reasonably secure, whereas blocking sequences are not obviously better than sliding sequences. The colors indicate opening in shades of red opening at <1 N, 1 to 5 N, and 6 to 10 N; in yellow opening at 11 to 15 N; and in shades of green opening at 16 to 30 or >30 N, or break.
Needle holders and the first knot should always remain visible during suturing. This prevents inadvertent traction when grasping the end of the suture. It seems wise to minimize the risk by using an H3 to start with. Because a second H2 requires a long thread, observation of spatial organization shows that a second H2 is easier with bimanual suturing. Finally, careful observation by the authors (AR, PRK, and AU) during live surgeries suggests that the risk of destabilization during suturing is higher than what is spontaneously anticipated. Common sense suggests that fatigue, the pressure to perform fast knot tying, and the distraction caused by talking and explaining during live surgery all contribute to the risk, together with making the last suture with a short end to save time.

Destabilization with the formation of S2S1 and S2S2 combinations should be avoided at all costs. Most of them have a very low security, with the exception of the symmetric S2S2, which is an unexpectedly secure knot. For this reason, we would suggest rather using H2H2s knots because H2H2a knots, although slightly more secure, are highly unstable after transformation into S2S2a. In doubt of destabilization, 2 or even 3 additional SbSbSb knots should be added because the S2S2aSbSb still occasionally opens with less than 10 N.

**Fig. 7**
Recuperation of S2S1a and S2S2a, 2 highly insecure knots, with an SSb or SbSb (p = .03). However, S2S2 followed by SSb and SbSb still has 3% that opened at less than 5 N and 2.5% at less than 10 N, respectively. The colors indicate in shades of red opening at <1 N, 1 to 5 N, and 6 to 10 N; in yellow opening at 11 to 15 N; and in shades of green opening at 16 to 30 N or >30 N, or break.
This knowledge of security of knot combination and of the risk of destabilization leads to the following suggestions for laparoscopic suturing and for teaching knot tying. First, secure knot combinations, especially with monofilament sutures, require strongly tied 5 throws, that is, preferably an SSSbSbSb or an H3H2, eventually an H2H2s combination. Second, the awareness of the risk of destabilization also favors the SSSbSbSb combination because the risk of mistake is minimal, or the H3H2, which starts with an H3. However, the latter unfortunately requires bimanual suturing with a sufficiently long suture. Third, teaching should emphasize that during suturing, both needle holders and the knot should always be visible. This means a correct suturing technique, and a short end that is not too long when grasping the end. Finally, awareness of the risk of destabilization should counterbalance our pride to show off and make a final knot with a suture that is really short. Whenever in doubt, the knot should be recovered with 2 or even 3 blocking half hitches.

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