Surg Endosc (2010) 24:1746–1751
DOI 10.1007/s00464-009-0854-z

# Incisions do not simply sum

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Received: 3 April 2009 / Accepted: 14 October 2009 / Published online: 7 January 2010


**Abstract**

*Background* Critics of minimally invasive methods sometimes argue that the summed lengths of all trocar sites have a morbidity similar to that for an open incision of equal length. This argument assumes correctly that pain and scarring are proportional to the total tension normal to a linear incision. But the argument also assumes that total tension sums linearly with incision length. This report demonstrates why that premise is not valid.

*Methods* Wounds of various sizes are compared using a simple mathematical model. The closing tension perpendicular to any linear incision is a function of the incision's length, varying symmetrically together with a maximum at the midpoint of length. If tension rises linearly across an incision, integration of the tension relationship demonstrates that the total wound tension actually is proportional to the square of the length. In this report, incisions of various lengths are modeled, and plausible alternative incision scenarios for various procedures (e.g., Nissen, appendectomy) are compared.

*Results* Total tension rises nonlinearly with increasing wound length. Thus, total tension across multiple incisions is always less than the total tension for an incision of the same total length. For example, an open appendectomy creates 2.7-fold more wound tension than a laparoscopic appendectomy. Similarly, two 3-mm trocars create less total tension than a single 5-mm trocar.

*Conclusion* Conventional incisions are subject to more total tension than any combination of trocar incisions of equal total length. This inequality yields three clinically relevant corollaries. First, it supports the practice of using the smallest effective trocars (or even no-trocar methods) to minimize pain and scar. Second, addition of a trocar in difficult cases adds relatively little morbidity. Finally, using two small trocars is better than using a single larger trocar.

**Keywords** Morbidity · Pain · Tension · Trocar · Wound

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Critics of minimally invasive surgery (MIS) sometimes still argue that MIS actually offers no real advantage because some common operations can be performed via open surgery using a small incision. More specifically, critics assert that the summed lengths of all trocar incisions in a MIS procedure are similar to the incision length for an open operation, and that the morbidity, therefore, also is similar. For example, it was recently argued that open appendectomy "can be performed with a single incision that competes easily with multiple trocar sites." [1]. This idea has not been challenged in the literature, perhaps because it "seems right." On the other hand, this argument has always seemed manifestly wrong to those who routinely perform a mix of MIS and open surgery in their practices, yet no one has answered this criticism.

The idea that a single long incision can "compete" with several smaller incisions of the same total summed length is a testable notion. Whether they realize it or not, those who make this assertion really are making a mathematical assertion that surgical morbidity is proportional to the simple sum of several incisions.

To make the concept of "morbidity" meaningful, we must first tie it to some measurable quantity. Thus, we assume that morbidity from any linear incision is a function of the tension across the incision [2, 3]. The literature provides ample evidence for this assertion. Mechanical forces powerfully influence wound healing at the molecular level [4], and pathologic scarring (e.g., keloids) is consistently worse at high-tension wound sites [5]. Meanwhile, a large reduction in inguinal hernia recurrence historically came not by tinkering with the details of traditional repairs but by adoption of new tension-free repair methods [6]. Moreover, low-tension techniques demonstrably hurt less, even with other abdominal wall repairs [7]. In other words, pain, risk of dehiscence [8], risk of hernia, risk of infection, and cosmetic results of any linear incision depend (excluding suture material, technique, and the like) on the total closing tension normal to the long axis of the incision (Fig. 1).

Given this assumption, the purposes of this report are to falsify the assertion that summed trocar incisions are comparable with open surgical incisions of similar length, to derive a better model for comparing wound morbidity based on tension, and to demonstrate how this relationship can inform both daily clinical practice and surgical innovation to the patient's advantage.

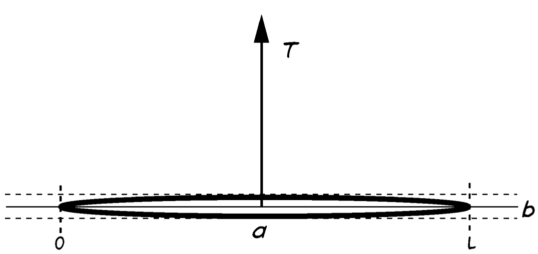



**Fig. 1** All linear incisions and trocar incisions can be modeled as ellipses, with the major axis (*a*) much greater than the minor axis (*b*). The essential features of the incision include its length $L = a$ and the closing tension, *T,* normal to the major axis (*arrow*)

## Materials and methods

A simple model of a linear incision is concerned with finding the total closing tension normal to the incision or any highly elliptical incision with a major axis much greater than the minor axis (i.e., $a >> b$, Fig. 1), in which the incision length, *L,* is the major axis length *a*.

Assume that various incisions in a "generic" abdominal wall differ only in their lengths such that abdominal wall thickness and the different layers of abdominal wall (each with its own compliance) can be modeled as a constant, *C*. This constant incorporates tissue mechanical properties for the passive abdominal wall, assumed to be directionally-independent within the plane of the body wall, and does not vary with the strain rate for any applied load on the incision.

Closing tension, *T,* the total force required to close a given incision, is a function T(*L*) of the length, *L,* of the incision, which varies symmetrically along *L* from 0 at $L = 0$ to a maximum at $L = L/2$. It is a matter of speculation exactly what type of function T(*L*) is. Wound models show a nonlinear development of tension along L, confirming that maximum tension is seen at *L*/2 [9, 10]. For simplicity, assume that tension develops linearly, or more particularly, for $L = 0$ to $L/2$:

$$T(L) = CmL,$$

where *m* is the slope, invariant for incisions of various lengths (Fig. 2). To define the total tension along the incision, we must add all the segmental tensions along the

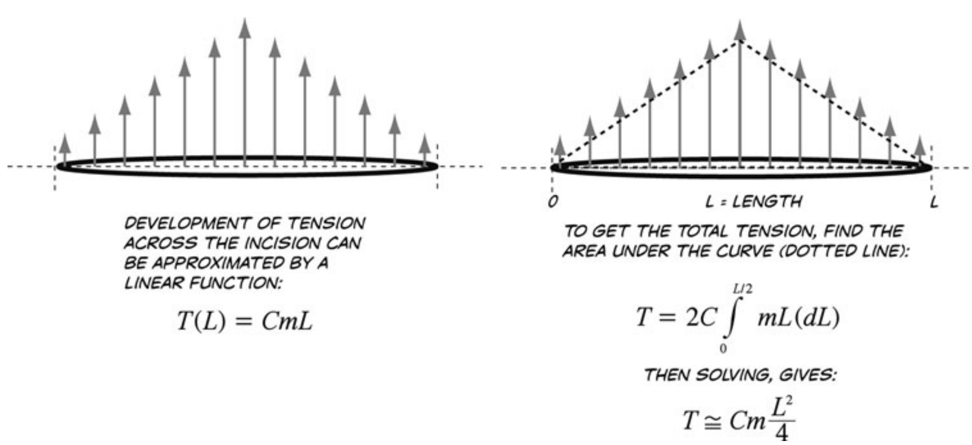



**Fig. 2** Total tension across an incision of a given length, *L,* is the sum of normal fractional closing tensions across the incisions (*grey arrows*). Assume that tension develops from 0 at the corners along a linear function of slope *m* (multiplied by a constant *C* that incorporates tissue thickness and mechanics). The total tension is the area under the curve bounded by the tension arrows, found by integration of *T*(*L*)*dL*. This shows that the relationship between the length of the incision and its closing tension is not $T \propto L$, but $T \propto L^2$

incision. In other words, the total closing tension is the integral of $T(L)$:

$$T_{\text{total}} = 2C\int_{0}^{L/2} mL(dL)$$

Solving for this equation gives

$$T_{\text{total}} \approx Cm \cdot \frac{L^2}{4}.$$

For the purposes of this model, it is irrelevant what the values of $C$ and $m$ are, so discarding the constants shows that the total tension for a linear incision of a given length, $L$, is not a function of the length but of the square of the length:

$$T \propto L^2.$$

Using this relationship, it is straightforward to compare various typical procedures that might be performed in an open or laparoscopic manner to determine whether total tension (and thus morbidity) is indeed comparable. Calculated relative tension is reported in arbitrary tension units.

## Results

Laparoscopic appendectomy is commonly performed using a pair of 5-mm trocars and a 10-mm trocar. Using the assumptions in Box 1 in Appendix, a total trocar incision length of 31.4 mm, or roughly 3 cm, is derived, a plausible incision length for an open appendectomy for a thin patient. However, the total relative tension for the laparoscopic appendectomy is 370 arbitrary tension units, compared with 986 units for open appendectomy. In other words, the total tension for the open incision is 2.67-fold greater than the total tension for all the trocar incisions. Still, MIS is advantageous even if it is asserted that the open appendectomy can be performed via a single-incision method.

Assume that three 5-mm instruments are inserted through a single incision at the umbilicus. From the calculations in Box 2 in Appendix, it can be seen that the minimal incision length that can accommodate these instruments is 16.6 mm. This size must be somewhat larger to accommodate special single-port trocars and to allow the instruments free movement (e.g., one industry brochure recommends a 20-mm incision), but for this analysis, we can take the extreme case of the minimal possible size. The relative tension of a 16.6-mm incision versus three 7.85-mm incisions is approximately 1.5. In other words, we can expect that, at best, single-port laparoscopy yields incisions adding about 50% of the tension required by three conventionally-positioned trocars. It is plausible that single-port methods offer some cosmetic advantage, but it cannot be claimed that they produce a mechanically less morbid wound.

Other comparisons are made in Table 1. Analysis of several different plausible operative scenarios shows that open surgery methods always produce relative wound tension several-fold higher than that produced by MIS methods. For example, laparoscopic Nissen fundoplasty often is performed using two 5-mm trocars and three 3-mm trocars. Even assuming that an open Nissen fundoplasty could be performed well in an infant through a 29.8-mm open incision, the open method still would create a 4.7-fold greater wound tension than its MIS counterpart.

## Discussion

The model shows that conventional open incisions are always subject to substantially more total closing tension than any combination of trocar incisions of equal total length. The difference between open surgery and MIS is

**Table 1** Calculation of relative tension for minimally invasive surgery (MIS) versus open surgery (OS) operative wounds[a]

| Operation | Trocars | | | | | OS Incision (mm) | MIS Tension[b] | OS Tension[c] | Open:MIS[d] |
|---|---|---|---|---|---|---|---|---|---|
| Appendectomy | 5 | 5 | 10 | | | 31.4 | 369.7 | 986.0 | 2.7 |
| Nissen | 5 | 5 | 3 | 3 | 3 | 29.8 | 189.8 | 889.8 | 4.7 |
| Ladd's | 5 | 3 | 3 | 3 | | 22.0 | 128.2 | 483.1 | 3.8 |
| Colectomy | 5 | 5 | 10 | 10 | | 47.1 | 616.2 | 2,218.4 | 3.6 |

[a] Calculations assume trocar incision lengths of $\pi$*D/2, as described in Box 1 in Appendix. The OS incisions are the linear sum of the trocar incisions. The descriptions of trocars are intended to be plausible trocar uses in performing common MIS procedures for babies and children, not "the" way to use trocars for these procedures. Tension is given in arbitrary units

[b] MIS Tension is the sum tension of all wounds in an MIS procedure

[c] OS Tension is the total tension required to close the single incision of an open surgery case

[d] Open:MIS is the ratio of these, showing the fold-increase of OS tension over MIS tension

large (Table 1). This inequality leads to at least three clinically relevant corollaries.

First, this relationship supports the practice of using the smallest effective trocars for a given procedure. For example, since optics have been improved, a good 4-mm telescope gives a very good image comparable with a 10-mm telescope, so a 10-mm trocar can be substituted by a 5-mm trocar yielding a fourfold decrease in relative tension at this site. Moreover, the relationship between tension and incision length suggests that it would be advantageous to use "no-trocar" or "needlescopic" techniques [11], and indeed the benefits of these methods are confirmed in randomized controlled trials [12]. Industry should be encouraged to continue developing miniaturized instruments (e.g., 3-mm ultrasonic shears) that could benefit both pediatric and adult patients. It may be obvious to suggest that smaller trocars hurt less, but because using a trocar half the size produces around one-fourth the tension, we can say that smaller trocars hurt *much* less.

Second, it is plain that adding a trocar for better exposure, retraction, or control adds little morbidity. For example, if a laparoscopic Ladd's procedure is performed for an infant using two 3-mm and a single 5-mm trocar, adding a fourth 3-mm assistant's trocar for improved exposure not only simplifies the procedure vastly, but also adds only about 21% more total tension and a trivial worsening of cosmesis. It often is more advantageous to add a trocar than to struggle through an operation using too few. This analysis shows that the mechanical advantage of an extra port yields an unexpectedly larger net benefit because the added morbidity cost to the patient is small, whereas the benefits (faster, more precise procedure) can be large.

Third, it is more advantageous to use two small trocars than to use a single slightly larger trocar (e.g., two 3-mm trocars instead of a single 5-mm trocar). Although "single-trocar" methods have been described in several recent publications [13], it is plain from our analysis that single-trocar methods offer no advantage to the extent that morbidity is related to tension (Box 2 in Appendix). Moreover, it is clear on inspection that passing all instruments through a single point vastly diminishes the operator's mechanical advantage, a shortcoming purported to be offset by a decrease in morbidity. It is possible (and hoped) that the mechanical disadvantages of trying to operate with two instruments and a camera through a single access site will drive development of clever new MIS tools (e.g., articulated instruments, "snake" robots). But it should not be claimed that one 20-mm port is superior to three 5-mm ports in terms of port-site morbidity. Single-port surgery does not offer a wound advantage.

This simple model has the weaknesses of all models, specifically that its validity depends on its assumptions. The main assumptions of this model are that morbidity depends on wound tension, that the complex abdominal or chest wall biomechanics can be neglected (by lumping them into a constant), and that tension develops linearly according to the length of the incision. Of these assumptions, only the last is imprecise. Tension will almost certainly follow patient-dependent nonlinear increases toward the center of the incision. However, modeling the tension function with a more complex nonlinear relationship, such as a cycloid or hemi-ellipse, still shows $T$ as proportional to $L^2$, not to $L$. In other words, the simplifications of this linear model show the essence of the relationship without oversimplifications that might qualitatively alter the findings. It would be a mistake to overinterpret the model by suggesting that the relative differences in tension are precise.

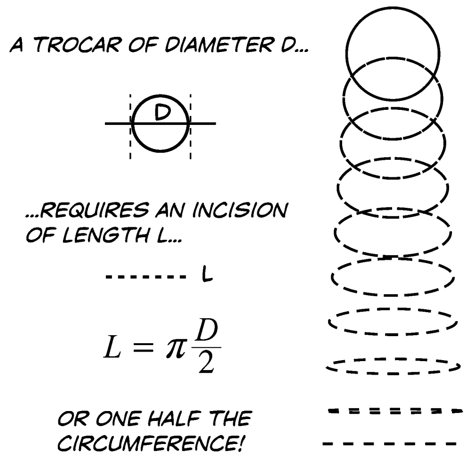
Moreover, this model says nothing about the contribution of incision direction (e.g., transverse, vertical, inline with tissue fibers) on the abdominal wall, the role of local anesthetics, the contribution of intraabdominal pressure, or the materials or techniques used in closures. Nevertheless, we can say with certainty that tension does not sum by the lengths of trocar incisions, as some have implied, but by the square of the lengths. Therefore, critics are incorrect when they claim they can perform an open procedure via an open incision that "competes" with its MIS counterpart. Theory supports clinical observations [12, 14] that minimally invasive surgery offers substantial wound tension advantages compared with open surgery.

**Disclosures** Thane Blinman has no conflicts of interest or financial ties to disclose.

## Appendix

Box 1

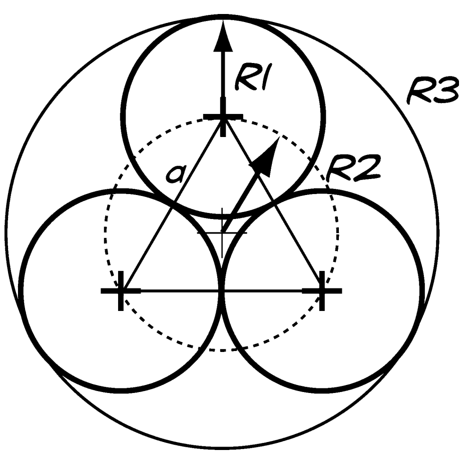
How long is a trocar incision? Most trainees, when asked how long to make an incision for trocar placement, underestimate the incision length required. For instance, when asked how long to make an incision for a 5-mm trocar, most answer, surprisingly, "4 mm." However, a little geometry shows the correct answer. First, it is assumed that skin is inelastic. Second, it is assumed that a trocar has an outer diameter of 5 mm (most commercial trocars actually have an outer diameter slightly greater than 6 mm). To create a linear incision that produces a circular aperture large enough for the trocar, it is plain that the incision needs to be one-half of the circumference of that circle:




A trocar with an outer diameter of 5 mm therefore requires an incision length of approximately 3.14 × 5/2 = 7.85 mm. Why does this matter? If the surgeon makes the incision too short, dangerous force may be required to place the trocar as the skin is forced open around the trocar shaft, leading to injury of the organs below. Then, the extra shear also will crush skin edges, leading to ugly closures more prone to failure and infection. Conversely, incisions that are too large will leave the trocars too loose. Consequently, they may slide in and out of the abdominal wall during the case, leading to decreased precision and delays as the trocars are constantly repositioned. On the other hand, understanding this geometry allows the surgeon to make correctly sized incisions for trocars of any size.

Box 2

What about "single-port" laparoscopy? Single-port laparoscopy is advocated by those who assume that one single port, of whatever size, is less morbid than three trocars positioned in the abdomen for maximal mechanical advantage. Is this true? Assume that a given operation can




be done with either three 5-mm ports or one single aperture that contains all three 5-mm ports. How large must the diameter of the aperture be to accommodate all three ports? We can calculate the inner diameter, $R_3$, required to contain most efficiently three circular ports of given radius, $R_1$:

From the figure, it is apparent that the minimal inner diameter, $R_3$, required for a trocar of an outer diameter, $R_1$, is the sum:

$$R_3 = R_1 + R_2$$

$$R_2 = \frac{a\sqrt{3}}{3}$$

where $R_2$ is the radius of the circle circumscribing a triangle connecting the centers of the three trocar circles [15]:

$$R_2 = \frac{a\sqrt{3}}{3},$$

where $a$ is the length of the triangle. But because $a = 2 \times R_1$, $R_2$ is: Thus the inner radius of the circle $R_3$ is:

$$R_3 = R_1 + \frac{2R_1\sqrt{3}}{3}.$$

This means that the inner radius of a circle required for three 5-mm trocars is roughly 5.4 mm, or a diameter of 10.8 mm. From Box 1, we see that this requires an incision of 10.8 × $\pi$/2, or approximately 16.6 mm. The relative tension of a 16.6-mm incision versus three 7.85-mm incisions is approximately a 1.5-fold increase. In other words, it can be expected that, at best, single-port laparoscopy produces an incision adding about 50% of the tension required by three conventionally-positioned trocars.

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