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Research Article

Measurement of Closure Forces During Abdominal Wall Closure as a New Parameter for Incisional Hernia Prevention: an Experimental Animal Study

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Abstract

Background: Many factors have been related to the appearance of an incisional hernia. The level of tension in the sutured laparotomy is one of them so an experimental animal study was carried out to understand the forces applied during the closure of a laparotomy.

Method: Twenty-seven female pigs were divided into three groups depending on their weight 20 kg, 50 kg and 100 kg, respectively. Each group was subdivided into three subgroups depending on the distance measured from the fascial edge to the stitch (5 mm, 10 mm and 15 mm). All animals underwent a laparotomy and the closure forces were measured at different levels and distances with a digital dynamometer (designed by our group). Variables were divided into 3: response (closure force), experimental (weight, distance from the fascial edge to the suture points, level of the laparotomy) and confounding (abdominal circumference., fascial thickness, laparotomy length, laparotomy width) variables.

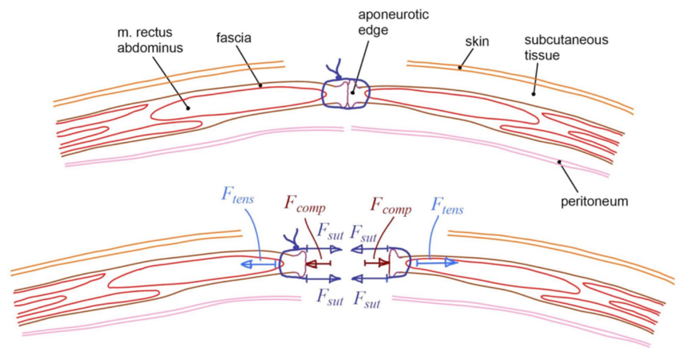
Results: Closure forces were measured along the different levels showing higher closure forces in the 5 mm subgroup than in the other 2 subgroups. The statistical analysis showed that the weight, the distance from the fascial edge and the level of the laparotomy, were all statistically significant ($p=0.0001$, 0.04 and <0.0001, respectively). Neither the fascial thickness nor the abdominal circumference affected the closure forces. The behaviour of the closure forces was different in the supra-umbilical and in the infra-umbilical areas.

Conclusion: Closure forces along a midline laparotomy are variable since a different behaviour in both supra-umbilical and infra-umbilical areas was described.

Introduction

Many factors have been related to the appearance of an incisional hernia and despite the development of new techniques and technological advances, its incidence remains high. These factors depend on multiple variables, including patient comorbidities, surgical technique and peri-operative conditions (materials, immediate wake-up, postoperative ileus, etc.). One important parameter, that has not yet been taken seriously into account as a risk factor for developing an incisional hernia, is the tension of the suture. The literature is scarce regarding this issue, but it has been demonstrated that sutures with high tension can cause failure of the fascial tissue [1] by producing tears or hypoxia of the tissue. The tension of a suture is one of the mechanical vectors involved during the closure of a laparotomy. Unfortunately, there are no available tools for its measurement, which is also one of the reasons why studies are so scarce. Previous to measuring the tensile force that is needed to approximate the fascial edges, two main causes that are involved must be considered: Intra-Abdominal Pressure (IAP) and musculoaponeurotic forces. These forces, described by Förstemann et al [2], are involved in the development of an incisional hernia. On the other hand, the suture is responsible for supporting the tension between the fascial edges during the first 3 weeks [3]. After this period, the healing tissue should support the tensile forces. A mechanical overload on the fascial edges over time contributes to an alteration of the organization of collagen fibers [4] and finally leads to failure in wound healing. The closure of a laparotomy with excessive tension of the suture is considered the most prevalent intra-operative risk factor in developing an incisional hernia [5].

For a better understanding of the forces involved, consider that the resulting suture forces (Closure forces) during the closure of a laparotomy are the addition of two force vectors: the tensile force needed to approximate the wound edges and the compression force in the contact area between them. These concepts are defined later on (Figure 1). In the literature, different authors [6-10] have studied the closure of a laparotomy focusing on the design of the technique (short stitches, continuous or interrupted suture, absorbable or non-absorbable sutures, needle size etc.), some have analyzed the tensile strength after closure in animals after increasing the IAP with a balloon and others by removing a tissue sample for study in the lab [11-15]. Studies about closure tension are limited. Some authors have described results in human cadavers [16-18], some in experimental settings [19-21] and others in patients with incisional hernias [22,23], but none have described the tension of the closure forces during an abdominal wall closure. Jenkins et al [5] described a mechanical approach to the burst abdominal wound, considering there is a 30% of sutured wound stretch after abdominal distension. They concluded that the length of the suture material (LS) should be four times greater than that of the wound (LW) to have sufficient suture to avoid high tension on the fascial edges when stretching occurs. Israelsson et al [24] in a prospective trial, demonstrated that the incidence of incisional hernia was lower when the closure of a laparotomy was sutured with a ratio of LS to LW ≥ 4. Sanders et al [14], based on the description of Nelson and Denis in 1938, studied, in rats, the tensile strength in laparotomies closed with tight and loose sutures, demonstrating that the strongest closure was with large bites (1 cm from the fascial edge) and loose ties.



Cengiz et al [25] described, in an animal study in rats, a higher strength to wound bursting with stitches placed 3 to 6 mm from the wound edge than with those at a distance of 10 mm, 4 days after closure of a midline laparotomy. Höer et al [13], using a digital dynamometer clamped to the tissue, analyzed the tensile strength of a laparotomy closure in rats, with different SL/WL ratios. They concluded that a ratio above 4:1 avoided high suture tension and provided a significantly positive effect on the mechanical strength of the suture. They further concluded the necessity for experimental studies dealing with the development of initially applied suture tensions, thus allowing surgeons to do a suture according to tissue-specific tension. Unfortunately, as shown above, there are few studies related to the measurement of closure forces using a dynamometer in patients or in cadavers. Villalobos et al [26] analyzed the closure forces in patients that underwent a midline laparotomy using a force gauge (Mecmesin AFG 1000N®) and concluded that the closure forces are variable along a midline laparotomy, as was described in human cadavers. The closure force is one of the few variables that can be assessed and controlled intra-operatively by a surgeon, but neither a suitable device to measure this force nor studies about this parameter along a laparotomy exist. This article describes an animal experimental study that uses a new digital dynamometer designed by our team [27], to analyze the closure forces along a midline laparotomy and thus describe a new parameter that could decrease the risk of developing an incisional hernia. The study was approved by the ethics committee for animal experimentation number 61/13 of the Vall d´Hebron Research Institute (VHIR), given by the Ministry of Agriculture, Ranching, Fishing and Food of the Generalitat de Catalunya (B69900062), Barcelona, Spain.

Material and Methods

There are some mechanical concepts related to the forces at the fascia, before and after a laparotomy, that must be defined for a better understanding of this study:

-**Tensile force (F_{tens}):** the fascia at the midline has to withstand a tensile or traction force in a transversal direction. This force can be evaluated as the addition of the musculoaponeurotic traction force (F_{musc}) and the circumferential force due to intra-abdominal pressure (F_{IAP}).

$$\mathbf{F}_{tens} = \mathbf{F}_{musc} + F_{\mathbf{IAP}}$$

When a midline laparotomy is performed, this force is responsible for the separation between the edges of the incision.

-Closure Force, (F_c) is the force requested to maintain the abdominal wound edges just in contact with each other at the time of surgery. In this study, a digital dynamometer was constructed in order to measure this variable. This force was measured when the dynamometer's tines grabbing the tissue, placed it at the same distance from the incision as prior to the laparotomy

$$\text{Formula: } \mathbf{F_c = F_{tens}}$$

-**Compression force (F_{comp}):** after the borders of the cut tissues are brought together by the suture, or by other means, the tissue of both fascial edges starts compressing with each other, creating a new force called compression force. This force rises exponentially as the suture is stretched and as the distance between the suture points becomes shorter.

-**Suture force (F_{sut}):** the force exerted by the suture to close the fascial edges. Although there is no commercial device to measure it, the surgeon applies a certain tension depending on the suture caliber, based on his experience, in order to ensure the contact between the wound edges. In general, the suture force can be defined as the sum of the closure force plus a certain compression force.

$$\mathbf{F_{sut} = F_c + F_{comp}}$$

This suture force is transmitted by the caliber of the suture to the healing tissue, distributing the tension along the incision, depending on the suture technique applied.

Variables

The variables in the study were divided into 3 categories as follows:

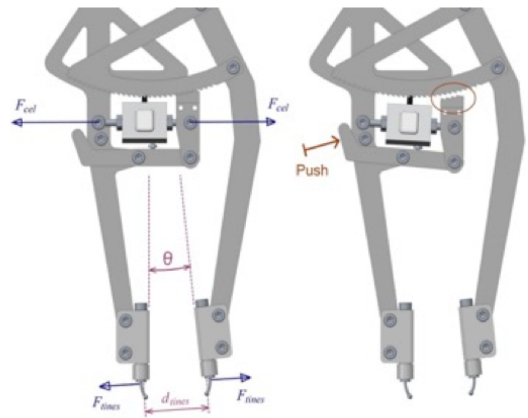
-Response variable: Closure force (F_c)

-Experimental variables: Pig weight, distance from the fascial edge to the suture entry points, level of the laparotomy (distance upward or downward from the umbilicus)

-Confounding variables: Abdominal circumference, fascial thickness, laparotomy length, laparotomy width.

Digital dynamometer

Accurate and reliable measurements of the closure force were key factors for this study. So, our group developed and validated a digital dynamometer designed for this purpose [27]. It is a compass-like instrument with two articulated legs that can bring closer or move further away two sets of tines that grab the tissue allowing both sides of the incision to be pulled together in a way similar to that of the suture during closure of the laparotomy. The dynamometer measures both the forces applied when approximating the tissues between the opposite grabbing points as well as the distance between them. Our team named this device DynaSurg (Figure 2) Patent ES-2630977_B1.

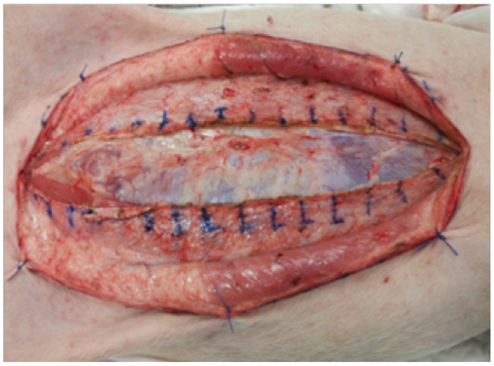


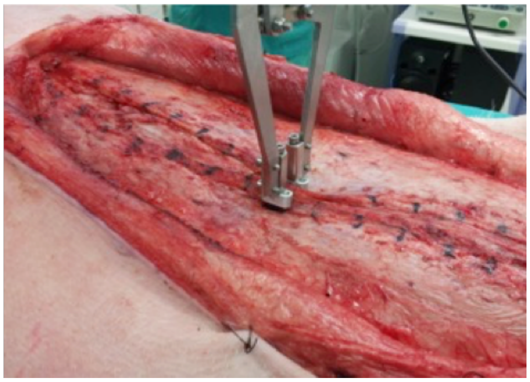
Experimental Animals

Twenty-seven female pigs were divided into three groups, A, B and C, depending on their weight (20 kg, 50 kg and 100 kg, respectively). Each group was in turn subdivided into three subgroups depending on the distance measured from the fascial edge to the suture entry point (5 mm, 10 mm and 15 mm). All these suture points were marked every 20 mm and were named SU2, SU4 ….SU16 and IU2, IU4…. IU16, if they were localized in the Supra-Umbilical (SU) or in the Infra-Umbilical (IU) area, respectively.

Surgical Procedure

The study was initially carried out at the Vall D´Hebrón Research Institute (VHIR) in Barcelona and was later concluded at the Applied Biomèdic Experimental Research Center (CREBA) in Lleida. Once the pigs were under general anesthesia, transversal lines, named levels, were drawn at the suture points, every 20 mm, starting from the umbilicus (U) and moving upwards (supra-umbilical, or SU) and downwards (infra-umbilical, or IU). Next, a measurement of the abdominal circumference was taken at every level using a measuring tape. The animals then underwent a xiphopubic laparotomy with dissection of the skin, the subcutaneous fat and the cutaneous trunk muscle, in order to expose the anterior rectus sheath, 5 cm away from the midline on each side. The resulting subcutaneous flap was attached laterally with 3 silk stitches on each side. Transversal lines were marked on the fascia, in the same way as the ones previously described on the skin (levels). The linea alba was subsequently incised, sparing the peritoneum to avoid evisceration that could interfere with the measurements (Figure 3). Afterwards, small orifices were made at every level at varying distances from the fascial edge, depending on the subgroup (5, 10 or 15 mm), followed by a measurement of the fascial thickness at these points. Finally, the closure forces at every level were measured individually (Figure 4). These forces were measured as soon as the fascial edges contacted each other, in order to avoid or minimize the compression force.





Statistical Analysis

The R Statistical Package was used with a statistical significance of 0.05. When assessing the experimental variables, median and typical deviations were used to analyze the response variables, while mixed lineal models were used to interpret the repeated measurements for each animal. These models analyzed the effect of varying distances on the different levels using cubic splines and statistical interactions. Finally, after including the confounding variables, an adjusted p- value was obtained.

Results

Twenty-seven female pigs underwent a midline laparotomy. Group A had a mean weight of 21.6 kg (20-24); group B of 50.2 kg (43-54,5) and group C of 98.5 kg (95-102). Confounding variables, like the abdominal circumference, thickness of the fascia and length of the laparotomy, showed statistical differences, but not so the width of the fascia. Table 1 shows the differences at the umbilical level. Fascial edges were thicker in the supra-umbilical area and the musculoaponeurotic thickness increased as the distance from the wound edges increased in all 3 groups.

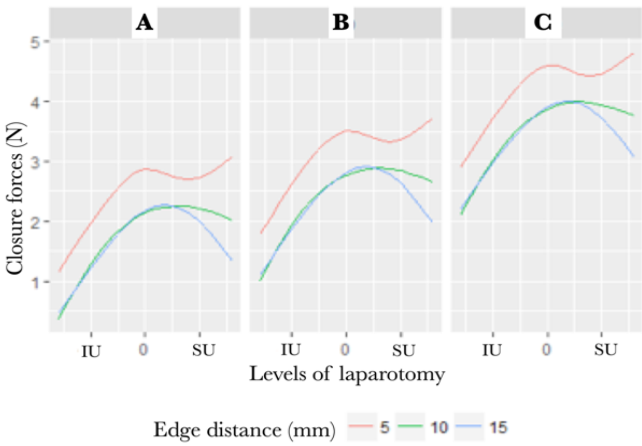
Variable Group	Weight (kg) SD	Umbilical abdominal perimeter (cm) SD	Umbilical thickness (mm) SD	Length of laparotomy (cm) SD	Umbilical amplitude (cm) SD
A	21.6 (1.47)	62.4 (3.19)	1.40 (0.57)	29.6 (2.12)	76.7 (9.32)
B	50.2 (3.18)	81.4 (4.57)	1.76 (0.53)	33.8 (2.26)	81.6 (10.8)
C	98.5 (2.01)	100 (2.94)	2.79 (1.05)	39.25 (4.03)	72.0 (16.2)
	$p < 0.001$	$p < 0.001$	$p = 0.002$	$p < 0.001$	$p = 0.0283$

Table 1: Different results at the umbilical level.

Closure forces were measured along the different levels and subgroups of the laparotomy, showing higher closure forces in the 5 mm subgroup than in the other 2 subgroups. These forces also tended to increase in all the subgroups as the umbilicus was approached from the infra-umbilical levels, and stabilized at the supra-umbilical level, with some variations depending on the subgroup. For this reason, in order to obtain a better understanding and to be able to extrapolate the distribution of the closing forces throughout the laparotomy, a statistical model of these forces was carried out (Figure 5). Table 2 shows the statistical analysis for each group and subgroup, which demonstrates that the weight, the distance from the fascial edge and the level of the laparotomy, are all statistically significant ($p=0.0001$, 0.04 and <0.0001, respectively). The values of the predicted closure forces, obtained by statistical modeling, showed that the greater the weight, the greater the closure forces. This was observed as an increasing tendency when group B and C were compared with group A ($p=0.04$ and $p<0.0001$, respectively). Additionally, the distance from the fascial edge showed differences in closure forces mainly at 5 mm, which was higher than at both 10 mm and 15 mm. Neither the fascial thickness nor the abdominal circumference affected the closure forces, whereas an increase in the length of the laparotomy decreased them.

	Beta (ee)	p-value	LRT test	
			p-value	p-value ajust.[1]
Intercept	1.15 (0.31)	0.0002		
Weight			0.0001	0.04
50kg	0.64 (0.29)	0.04		
100kg	1.74 (0.29)	<0.0001		
	Diference 50 vs 100	0.0003		
Distance fascial edge			0.04	0.00 5
10mm	-0.79 (0.37)	0.04		
15mm	-0.70 (0.37)	0.07		
	Diference 10 vs 15	0.96		
Levels of laparotomy				
Grade 1	1.96 (0.23)	<0.0001		
Grade 2	1.02 (0.27)	0.0002		
Grade 3	2.70 (0.51)	<0.0001		
Grade 4	1.30 (0.31)	<0.0001		
Interaction distance of fascial edge*level of laparotomy			0.02	0.00 2

Table 2: Statistical analysis of the experimental variables.



Discussion

The animals were divided into 3 groups depending on their weight, because our team had the hypothesis that differences in abdominal circumference and fascial thickness, would influence the closure force. We normally believe that the fascial thickness is an important factor to achieve an adequate bite of tissue, when suturing. For this reason, it is possible to think that differences in this parameter could alter the closure forces, but the statistical analysis of this study showed no differences. This result is very important because it demonstrates that the closure forces along a midline laparotomy don't depend on the fascial thickness. This means that the closure force will not be higher with thicker fascias than with thinner ones, or vice versa. The other parameter, abdominal circumference, didn't influence the closure forces either. The anteroposterior or transverse diameter could have a relevant role in these forces, as described by Villalobos et al [26]. In this study, closure forces had a tendency to increase in patients with a greater anteroposterior diameter. There are no studies, however, about this relationship, even though Van Mieghem et al [28] observed a poor correlation between abdominal circumference and intra-abdominal pressure (IAP). The length of the laparotomy revealed an inverse relationship with the closure forces. This doesn't mean, (on the other hand) therefore, that a larger laparotomy is better, since the risk of an incisional hernia is also increased, even more so if the laparotomy is vertical and not transversal [29,30]. The width of the laparotomy at different levels showed a direct relationship with the closure forces. In physical terms, the distance between two points doesn't influence the force necessary to approximate them. Then again, it is important to take into account that the abdominal wall is not an inert structure, its elastic and contractile components act in opposite directions since a longer distance is needed to close the wound.

The importance of the distance of the suture from the fascial edge is a parameter that has been studied in many ways. Classically, a laparotomy is closed with a 10 mm margin from the fascial edge and with a 10 mm distance between two consecutive stitches. This is called the long stitch method. Over the last 10 years, different studies have described a new way of closing, using short stitches [8,31]. This variant uses a 5-8 mm margin to the fascial edge and a 5 mm distance between stitches. These studies showed that the short stitch technique decreases the risk of developing an incisional hernia and improves wound healing. Some authors [32] have described that long stitches compress and tear the tissue, devitalizing it. This leads to suture dehiscence and has a two-fold increase in wound infection rate. In order to differentiate and analyze the closure force, this study divided the patients into 3 subgroups depending on the distance between the suture and the fascial edge, as was described before. The results showed that the closure forces were different along the laparotomy, contradictory to the data described by some authors [17,18,33]. One of the most interesting results was how the closure forces had a tendency to increase from the suprapubic level towards the umbilicus area in all the subgroups, but not so in the supra-umbilical area, where the behaviour of these forces was variable. A relevant factor when explaining this, is the anatomic components that are attached to the musculoaponeurotic structure in the supra-umbilical and the infra-umbilical areas. While in the supra-umbilical area the ribs are present, the iliac bone is where most infra-umbilical structures attach. Despite the fact that these two areas have bones to attach to, the iliac bone is static, whereas the ribs are dynamic. This probably explains why the closure forces have a regular increasing pattern from pubis to umbilicus, and but not so in the supra-umbilical area, where they have a more irregular behaviour. Moreover, the muscular components are not similar either. The supra-umbilical area has the external oblique and transverse muscles that interact with the serratus anterior and diaphragmatic muscles respectively, whereas the internal oblique is the most predominant muscle in the infra-umbilical area. Additionally, the pectoralis major muscle is present in the upper abdomen and the abdominal rectus muscle is wider, both of which can influence the closure forces. Our results agree with those described by Smietanski et al [34], that found major strains in the epigastric area, as well as those described by Van Ramshorst et al [35], that showed a greater tension in this area. Although they didn't study the closure forces, these authors agreed that the supra-umbilical area has more tension than the infra-umbilical area, which is what we also found in our results.

As was explained above, this study describes a different behaviour in both the supra-umbilical and the infra-umbilical areas with closure forces increasing upwards from the pubis to the umbilicus but irregularly in the supra-umbilical area, depending on the fascial edge. For all of these reasons, the closure of the laparotomy should probably be done differently in these two areas (needle, suture caliber, distance to fascial edge, etc.…).

The long stitch is a very good technique compared to the short stitch, but unfortunately it has been undervalued in the last few years. The study described by Albertsmeier et al [36] showed a similar incisional hernia rate using these 2 techniques, so the design of the closure is probably as important as the tension with which a laparotomy is closed. A short stitch technique is done with care and without tension, because the thin suture used creates a sensation of thread fragility, so the surgeon pulls delicately and with less tension than with a larger caliber thread. There is no evidence about this hypothesis, but we think that the long stitch done in such a way as to avoid tension and minimize the appearance of compression forces, could improve the results. In this experimental study we focused on the closure forces, as a relevant parameter to take into account during the closure of a laparotomy, by using a digital dynamometer designed by our group. This shouldn't be confused with other studies that have measured the tensile strength in sutured and un-sutured tissue, when the tissue had been previously removed and placed in a traction gauge. We consider that the closure forces should not only be measured to ensure a tensionless closure, but also to determine whether an additional procedure is needed (relaxing incisions, mesh placement). This parameter should be followed by a correct closure of the laparotomy, attempting to only approximate the fascial edges and avoiding compression of the tissue, which would increase the closure forces exponentially.

The study of the closure of a laparotomy has always been orientated towards DESIGN (continuous or interrupted suture, needle size, suture caliber, suture type or distance from fascial edge). As we found, the closure forces are variable along a midline laparotomy, therefore it seems reasonable to considerer different closure techniques in each area in order to optimize tension in the healing tissue. For this reason, we state that TENSION should also be considered as a major contributor, not only to this study, but also in incisional hernia repair. Moreover, the abdominal wall biomechanics should consider, not only the study of the tension distribution along the laparotomy, but also the physical characteristics of the abdominal wall structure (stiffness, elasticity, stretching, etc..) that can vary depending on the area and the anthropometric measurements of the patient (weight, BMI, abdominal diameter, etc.…).

Furthermore, a clinical assay should be developed to find the optimal points at which the closure forces should be measured. Additionally, a more ergonomic and user-friendly dynamometer, for the surgeon, needs to be designed. This study is the first of its kind in describing the biomechanical closure forces along a midline laparotomy. Nevertheless, our study has limitations and the results must be taken with care since the closure forces were measured individually and not as a whole. The next step is to study the simultaneous closure forces along a laparotomy, which will allow us to have a better perspective of the behaviour of the laparotomy closure.

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