Lesch *et al. Mini-invasive Surg* 2023;7:20
DOI: 10.20517/2574-1225.2023.24

Mini-invasive Surgery

Original Article

Open Access

Cyclic pulse loads generate the new concept in abdominal wall reconstruction: suture closure

Carolin Lesch[1], Fabio Kugel[1], Katharina Uhr[1], Matthias Vollmer[2], Regine Nessel[3], Friedrich Kallinowski[1], René H. Fortelny[4]

[1]Visceral and Transplantation Surgery, University Hospital Heidelberg, Heidelberg 69120, Germany.
[2]Hamburg University of Technology, Biomechanics, Hamburg 21073, Germany.
[3]Visceral and Pediatric Surgery, Klinikum Am Gesundbrunnen, Heilbronn 74078, Germany.
[4]Fakultät für Medizin der Sigmund Freud PrivatUniversität, Freudplatz 3, Österreich.

Correspondence to: Carolin Lesch, Visceral and Transplantation Surgery, University Hospital Heidelberg, Im Neuenheimer Feld 410, Heidelberg 69120, Germany. E-mail: carolin.lesch@stud.uni-heidelberg.de; carolesch@gmx.de

How to cite this article: Lesch C, Kugel F, Uhr K, Vollmer M, Nessel R, Kallinowski F, Fortelny RH. Cyclic pulse loads generate the new concept in abdominal wall reconstruction: suture closure. *Mini-invasive Surg* 2023;7:20. https://dx.doi.org/10.20517/2574-1225.2023.24

Received: 20 Mar 2023 **First Decision:** 11 May 2023 **Revised:** 24 May 2023 **Accepted:** 30 May 2023 **Published:** 8 Jun 2023

Academic Editors: Giulio Belli, Luca Gordini **Copy Editor:** Dong-Li Li **Production Editor:** Dong-Li Li

Abstract

Aim: Incisional hernias frequently occur after open abdominal surgery. Up to 30% of elective midline laparotomy closures result in an incisional hernia. The properties of a safe abdominal wall reconstruction must be assessed under lifelike conditions to obtain a realistic estimate of the durability. The interplay of the biomechanical qualities determines the long-term stability of a repair. Various suture materials and techniques for optimal closure of the abdominal wall are still under discussion. The results of this experimental study might significantly affect the active discussion about optimal suturing techniques for median abdominal wall closure.

Methods: For this purpose, a bench test was developed that delivers repetitive cyclic pressure impacts to the abdominal wall, simulating coughs. This allows the assessment of the reconstructed abdominal wall as a compound. We used stiff porcine abdominal walls and elastic bovine flanks as model tissues. We chose two different types of defects. Type one consisted of a 15 cm long medial incision, whereas for type two, a 5 cm circular defect was added in the center of the incision. The incisions were solely sutured in large-bite (0.8-1.2 mm bites) or small-bite (0.5-0.8 mm bites) technique with Monomax® or PDS® sutures USP 2-0 or USP 1. The suture to wound length (SWL) ratio had to exceed 4:1. After suturing, the tissues were subjected to repetitive cyclic loading on a validated bench test.

Results: We found that regardless of technique and material thickness, secure closure of median abdominal wall incisions is feasible by suturing. In larger defects, the small bites technique using Monomax® sutures achieves a safer closure compared to PDS® sutures.

Conclusion: Based on the results of this experimental study, a tailored standardized closure technique after midline incision of the abdominal wall, including an optional mesh augmentation, is recommended.

Keywords: Incisional hernia, suture technique, abdominal wall reconstruction, biomechanical repair, multiaxial tissue assessment

INTRODUCTION

In daily life, the abdominal wall gets stressed by repetitive peaks of intraabdominal pressure while moving, defecating, or coughing. Therefore, an existing abdominal wall reconstruction needs to withstand these repetitive loads[1]. However, currently, up to 20% of the sutured incisions reopen results in hernias[2]. A reconstructed abdominal wall behaves as a coherent compound and must, therefore, be assessed as such[3,4]. To improve clinical care, abdominal wall closure should be examined closely and need to be tested under lifelike conditions to obtain a realistic estimation of their behavior and durability.

For this purpose, we built a bench test that delivers repetitive cyclic pressure impacts, simulating coughs[5,6]. Increasing the amount of the pressure impacts and their height leads to the development and enlargement of a hernia. This process of reconstruction failure starts early after closure[7,8].

The formation of an incisional hernia reveals an insufficiency of the compound, specifically the sutured abdominal wall. The long-term success of a repair is determined by the creation of a successful synergy among the individual components. The suture technique determines the load distribution of the intraabdominal pressure on the abdominal wall. Additionally, the combination of the chosen material, the individual tissue qualities, the type of defect, and the load determines the durability of the reconstruction[3,9].

In a randomized controlled study (ESTOIH study), the best results to date were achieved by means of the short stitch technique compared to the long stitch technique (4.23% *vs*. 8.24%) in the 1-year follow-up, with both groups using Monomax®[10]. The current EHS guidelines recommend a continuous small-stitch-small-bite technique with a suture to wound length (SWL) of at least 4:1. It is recommended to use a slowly resorbable suture. No specific recommendation is suggested regarding the suture material and size[11,12]. Previous studies showed that the careful execution and standardization of surgical sutures enhance the outcome significantly[13,14].

Despite active research to continually improve hernia reconstruction, recurrence rates remain high[2]. The performed experiments contribute to the active discussion about the optimal suturing techniques for median abdominal wall closure.

MATERIAL AND METHODS

The bench test for generating cyclic pulse loads

We used stiff porcine and elastic bovine tissues as models for the abdominal wall. German pigs and cattle were butchered at one to two years of age and delivered to the lab cooled on the same day. The porcine tissues consist of the entire abdominal wall with similar properties to the human abdominal wall[15]. The bovine tissues include the oblique abdominal muscles, simulating thin and soft abdominal walls. The two

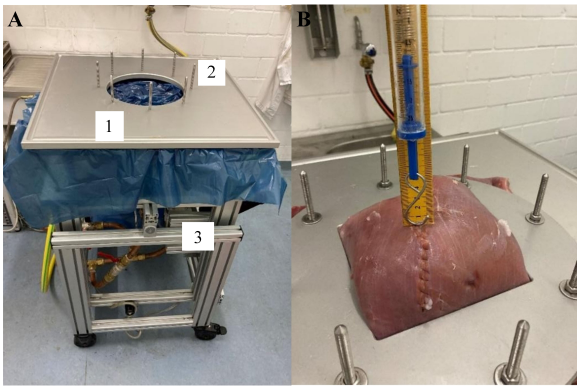

Figure 1. (A) Photo of the bench test and its elements (1: water cylinder with cover plate, 2: tank opening where pressure impacts are applied to the mounted tissue, 3: base frame with pipe system including inlet and outlet valves and pressure tank); (B) Mounted sutured tissue on the bench test during maximum pressure impact, suture tension is measured.

tissue types differ in their distinct median elasticity[16]. The model tissues were repeatedly loaded with cyclic impacts on our validated bench test, as previously described[13,16]. The test bench simulates high pressure impacts on the sutured tissue with a customizable pressure plateau phase and maximum pressure, as it can occur during heavy coughing. One out of three of our patients coughs over 400 times in the first 24 hours postoperatively[17]. Accordingly, we loaded the reconstructed tissues 425 times with cyclic pressure impacts. The bench test is shown in Figure 1.

We investigated the performance and stability of various suture techniques for midline abdominal incisions. We chose two different types of defects. For defect type one, we cut a 15 cm long medial incision into the tissues. For defect type two, we punched an additional 5 cm large circular defect in the center of the incision. The incisions were solely sutured in large-bite (0.8-1.2 cm bites) or small-bite (0.5-0.8 cm bites) technique with Monomax® or PDS® sutures USP 2-0 or USP 1. * Monomax® suture material is manufactured of poly-4-hydroxybutyrate. It differs from PDS® in its ultra-long resorption time of 18 months and elasticity of 90%. The SWL ratio had to exceed 4:1[10,18]. The incisions with defects were closed in a standardized technique[13] by two surgeons experienced in suture technique research. The nomination terminology is given in Table 1. The exact test setup for each test is shown in Table 2.

The test was terminated if the reconstruction failed or if 425 DIS impacts were delivered. Failure was defined as slackening of the suture, tearing of the suture through the tissue, or tearing of the tissue itself. The occurrence and onset of the failure pattern were observed in the experiments. The study comprises a total of 15 experimental series (ES), each involving ten experiments [Table 2].

Statistical analysis

For the groups with skewed results, the Kruskal-Wallis test was used for non-parametric testing. The significance was analyzed with a Mann-Whitney *U* test. We used curves similar to survival curves that illustrate the likelihood of a durable closure.

RESULTS

In eight ES (1-8), we performed a structured investigation of four influencing factors on the suture durability. We varied the stitch spacing (Large-Bite *vs*. Small-Bite), the suture material (Monomax® *vs*. PDS®) and the suture thickness (USP 1 *vs*. 2/0), and the tissue type (bovine and porcine). The WSL showed no significant variation with values between 4.3 to 4.4 throughout ES 1-8 [Table 2]. In series 9-15, we

Table 1. Nomination system

	Abbreviation	Meaning
Tissue	B:	Bovine tissue
	P:	Porcine tissue
Test bench settings	120 /150 /180 /210 /240	Maximum pressure in mmHg
Cover plate	sO	Square opening, A = 256 cm^2
	cO	Circular opening, A = 490 cm^2
Defect	IN	Incision 15 cm
	DC5	Defect circular 5 cm
	INDC5	Incision + defect circular
Materials	MM 20 /1	Monomax® USP 2-0 or 1
	PDS 20	PDS® USP 2-0
Technical details	SBu SBs	Small-stitch-small-bite unstandardized suturing Small-stitch-small-bite standardized suturing
	LBu LBs	Large-stitch-large-bite unstandardized suturing Large-stitch-large-bite standardized suturing

investigated further influencing circumstances such as the standardization of the suture, a different suture material, an additional defect, a larger impact area, or a lower peak pressure.

Figure 1 illustrates the comparison of unstandardized Small-Bite stitches *vs*. Large Bite stitches performed with a USP 2/0 or USP 1 Monomax® suture, closing midline incisions (ES 1 + 2, 5 + 6). 100% durability was obtained in all series, regardless of the stitch spacing, thread thickness, and tissue type.

The durability drops by 10%-50% when adding a circular defect into the incision and using the cover plate with the larger opening. We used a standardized small-stitch-small-bite technique with USP 2/0 Monomax® or PDS® sutures.

The standardized small-bite Monomax® suture (triangles) provided secure closure in 9 out of 10 experiments [Figure 2]. It showed a 50% higher likelihood of secure closure (LOSC) (P = 0.064) than the PDS® suture (dots).

Series 11-13 and series 14 + 15 had the same experimental setup, with a peak pressure of 210 mmHg or 180 mmHg. 30%-40% of the sutures held securely when exposed to 210 mmHg [Figure 3]. When the peak pressure lowers by 30 mmHg, the LOSC rises by 20%-30%. Figure 4 the upper and lower graph show differences in the durability between 200 and 400 DIS impacts due to the stochastic nature of the process. The graphs converge at 425 impacts. This demonstrates the reproducibility of the process with 425 impacts[15].

DISCUSSION

The bench test we used allows the simulation of everyday loads on the abdominal wall. According to modern biomechanics, the tissue and reconstruction need to be considered and assessed as a compound.

The durability of a suture closure does not solely depend on the accurate execution of one specific factor. The interplay of the individual influencing factors determines the outcome of the suture closure of the abdominal wall. This applies to any experimental and clinical setting. It is the base of the existing GRIP/CRIP concept[19,20]. The standardized suture, used in ES 9 - 15, provides an instruction for secure suture

Table 2. List of the 15 test series performed with a total of 150 tests with each setup and the likelihood of secure closure (LOSC)

Series	Title	Tissue	Defect shape	Defect size (cm)	Suture USP	SSSB / LSLB suture	Standardization	Amount of stitches (n)	S:W-L-Ratio	LOSC until ST (%)
ES 1	P-210-0.2sP-sO-**IN-MM20-SBu**	porcine	incision	15	2-0	SSSB	no	23.7	4.4	100
ES 2	P-210-0.2sP-sO-**IN-MM20-LBu**	porcine	incision	15	2-0	LSLB	no	13.8	4.4	100
ES 3	B-210-0.2sP-sO-**IN-MM20-SBu**	bovine	incision	15	2-0	SSSB	no	23	4.3	100
ES 4	B-210-0.2sP-sO-**IN-MM20-LBu**	bovine	incision	15	2-0	LSLB	no	13.8	4.4	100
ES 5	P-210-0.2sP-sO-**IN-MM1-SBu**	porcine	incision	15	1	SSSB	no	22.4	4.4	100
ES 6	P-210-0.2sP-sO-**IN-MM1-LBu**	porcine	incision	15	1	LSLB	no	13.9	4.4	100
ES 7	B-210-0.2sP-sO-**IN-MM1-SBu**	bovine	incision	15	1	SSSB	no	22	4.3	100
ES 8	B-210-0.2sP-sO-**IN-MM1-LBu**	bovine	incision	15	1	LSLB	no	13.9	4.3	100
ES 9	P-210-0.1sP-sO-**INDC5-PDS20-SBs**	porcine	incision+circular	15 + 5	2-0	SSSB	yes	21	4.1	100
ES 10	P-210-0.1sP-cO-**INDC5-MM20-SBs**	porcine	incision+circular	15 + 5	2-0	SSSB	yes	27	4.5	90
ES 11	P-210-0.1sP-cO-**INDC5-PDS20-SBs**	porcine	incision+circular	15 + 5	2-0	SSSB	yes	23.5	4.3	40
ES 12	P-210-0.1sP-cO-**INDC5-PDS20-SBs 1**	porcine	incision+circular	15 + 5	2-0	SSSB	yes	24	4.2	30
ES 13	P-210-0.1sP-cO-**INDC5-PDS20-SBs 2**	porcine	incision+circular	15 + 5	2-0	SSSB	yes	22	4.1	30
ES 14	P-180-0.1sP-cO-**INDC5-PDS20-SBs-1**	porcine	incision+circular	15 + 5	2-0	SSSB	yes	22	4.1	50
ES 15	P-180-0.1sP-cO-**INDC5-PDS20-SBs-2**	porcine	incision+circular	15 + 5	2-0	SSSB	yes	22	4.1	40

closure by combining the influencing factors[13]. However, the success of a suture is limited by external influences, e.g., defect size, retention force of the tissue, applied strain, and impact area.

Previous experiments have shown that the addition of a circular defect to the incision reduces the durability of unstandardized wound closure with MonoMax® to 0%. Standardization of the suture technique can increase the durability to 100%[13]. Increasing the impact area and using PDS® instead of Monomax® sutures again lowered the durability. Our experiments revealed clear differences in the durability of sutures with Monomax® or PDS® sutures. This is in contrast to the literature, which indicates only minor differences between various sutures[12,21].

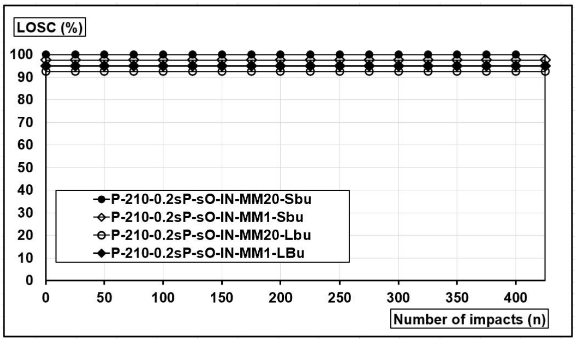

Figure 2. Likelihood of secure closure (LOSC) until suture failure of USP 2/0 or UPS 1 Monomax® sutures in Small-Bite (SB) or Large-Bite (LB) technique closing a 15 cm long midline incision in porcine and bovine tissue depending on the amount of DIS impacts with 210 mmHg.

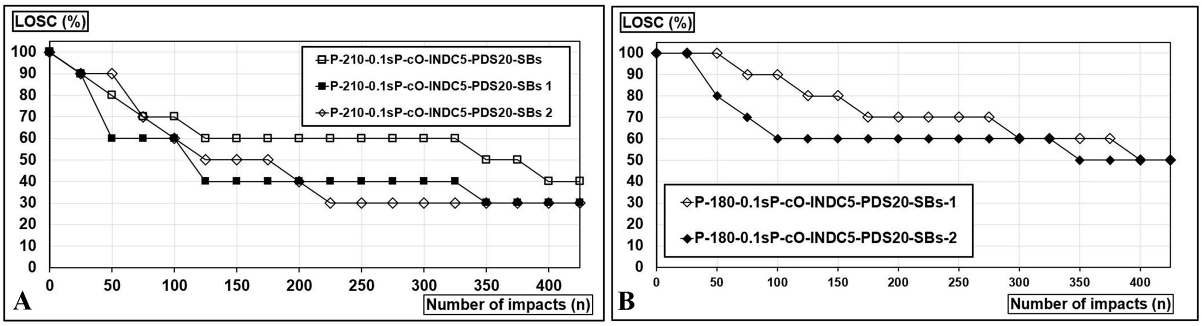

Figure 3. Likelihood of secure closure (LOSC) until suture failure of USP 2/0 PDS® sutures in standardized Small-Bite (SSSBs) technique closing a 15 cm long midline incision with a 5 cm large circular defect (INDC5) in porcine tissue depending on the amount of DIS impacts with 180 mmHg (B) or 210 mmHg (A).

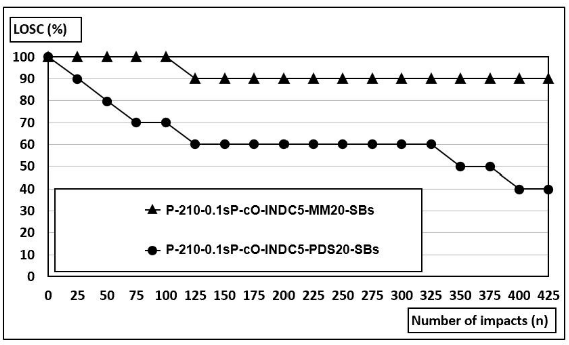

Figure 4. Likelihood of secure closure (LOSC) until suture failure of USP 2/0 Monomax® (MM) or PDS® sutures in standardized Small-Bite (SSSBs) technique closing a 15 cm long midline incision with a 5 cm large circular defect (INDC5) in porcine tissue depending on the amount of DIS impacts with 210 mmHg.

In low-risk cases, an unstandardized suture closure seems to be stable, regardless of the chosen technique and material. In high-risk cases, such as larger defects or unstable tissue, Monomax® small-stitch-small-bite sutures in standardized protocol appear to be a safer choice[13].

CONCLUSION

Secure closure of median abdominal wall incisions is achievable with sutures regardless of small or large bite technique and material thickness. But as can be seen from the GRIP/CRIP concept, larger defects require more complex reconstruction. For larger defects, suture closure alone may not be sufficient, depending on the circumstances. A larger impact area, for example, lowers the durability. This experimental study revealed that Monomax® sutures provide a higher level of closure security than PDS® sutures. The thickness of the suture showed no difference. It is advisable to choose the safest suture technique and mesh reinforcement in larger abdominal wall defects.

DECLARATIONS

Acknowledgments

We thank the financial support by the Heidelberger Stiftung Chirurgie (grants 2016/ 22, 2017/ 171, 2018/ 215, 2019/ 288, 2020/ 376, and 2021/ 444).

Authors' contributions

Performed the data analysis and wrote the article: Lesch C
Performed the experiments: Kugel F, Uhr K
Lead the construction of the bench test and its maintenance: Vollmer M
Contributed important thoughts and discussions for the construction of the experiments and the paper: Nessel R
Closely guided the execution of the experiments, designed parts of the experiments, and continuously supervised the paper: Kallinowski F
Designed parts of the experiments and proofread the paper: Fortelny RH

Availability of data and materials

The raw data supporting the conclusions of this article will be made available by the authors, without reservation.

Financial support and sponsorship

We thank the financial support by the Heidelberger Stiftung Chirurgie (grants 2016/ 22, 2017/ 171, 2018/ 215, 2019/ 288, 2020/ 376, and 2021/ 444).
Disclaimer FK received financial and material support from Baxter, Becton Dickinson, Corza, Dahlhausen, Ethicon, FEG, GEM, Medtronic, Olympus, and PFM medical based on a Third-Party-Funding-Agreement with the Heidelberg University and / or with Asklepios proresearch. Fortelny RH. Received speaker's honorarium by B.Braun, Becton Dickinsin, and Medtronic and research grants by the Wiener Gesundheitsverbund, Klinik Ottakring, 523403.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

The research was conducted after building a bench test for low cyclic loading of tissues. Human material was not used. Accordingly, no informed consent from patients was required. The ethical approval to use animal tissues was given by local authorities according to European law with the permission DE 08 221 1018.

Consent for publication

Not applicable.

Copyright

REFERENCES

1. Iqbal A, Haider M, Stadlhuber RJ, Karu A, Corkill S, Filipi CJ. A study of intragastric and intravesicular pressure changes during rest, coughing, weight lifting, retching, and vomiting. *Surg Endosc* 2008;22:2571-5. DOI PubMed
2. Bosanquet DC, Ansell J, Abdelrahman T, et al. Systematic review and meta-regression of factors affecting midline incisional hernia rates: analysis of 14,618 patients. *PLoS One* 2015;10:e0138745. DOI PubMed PMC
3. Kallinowski F, Ludwig Y, Löffler T, et al. Biomechanics applied to incisional hernia repair - Considering the critical and the gained resistance towards impacts related to pressure. *Clin Biomech* 2021;82:105253. DOI PubMed
4. Nessel R, Löffler T, Rinn J, et al. Primary and recurrent repair of incisional hernia based on biomechanical considerations to avoid mesh-related complications. *Front Surg* 2021;8:764470. DOI PubMed PMC
5. Siassi M, Mahn A, Baumann E, et al. Development of a dynamic model for ventral hernia mesh repair. *Langenbecks Arch Surg* 2014;399:857-62. DOI PubMed PMC
6. Kallinowski F, Baumann E, Harder F, et al. Dynamic intermittent strain can rapidly impair ventral hernia repair. *J Biomech* 2015;48:4026-36. DOI
7. Xing L, Culbertson EJ, Wen Y, Franz MG. Early laparotomy wound failure as the mechanism for incisional hernia formation. *J Surg Res* 2013;182:e35-42. DOI PubMed PMC
8. Pollock AV, Evans M. Early prediction of late incisional hernias. *Br J Surg* 1989;76:953-4. DOI PubMed
9. Nakano K, Popov VL. Dynamic stiction without static friction: the role of friction vector rotation. *Phys Rev E* 2020;102:063001. DOI PubMed
10. Fortelny RH, Andrade D, Schirren M, et al. Effects of the short stitch technique for midline abdominal closure on incisional hernia (ESTOIH): randomized clinical trial. *Br J Surg* 2022;109:839-45. DOI
11. Muysoms FE, Antoniou SA, Bury K, et al; European Hernia Society. European Hernia Society guidelines on the closure of abdominal wall incisions. *Hernia* 2015;19:1-24. DOI
12. Deerenberg EB, Henriksen NA, Antoniou GA, et al. Updated guideline for closure of abdominal wall incisions from the European and American Hernia Societies. *Br J Surg* 2022;109:1239-50. DOI PubMed
13. Lesch C, Uhr K, Vollmer M, Raschidi R, Nessel R, Kallinowski F. Standardized suturing can prevent slackening or bursting suture lines in midline abdominal incisions and defects. *Hernia* 2022;26:1611-23. DOI PubMed PMC
14. Jensen TK, Gögenur I, Tolstrup MB. Standardized surgical primary repair for burst abdomen reduces the risk of fascial redehiscence. *Ann Surg* 2021;274:e1115-8. DOI PubMed
15. Kallinowski F, Ludwig Y, Gutjahr D, et al. Biomechanical influences on mesh-related complications in incisional hernia repair. *Front Surg* 2021;8:763957. DOI PubMed PMC
16. Kallinowski F, Gutjahr D, Harder F, et al. The grip concept of incisional hernia repair-dynamic bench test, CT abdomen with valsalva and 1-year clinical results. *Front Surg* 2021;8:602181. DOI PubMed PMC
17. Turner RD, Bothamley GH. How to count coughs? Counting by ear, the effect of visual data and the evaluation of an automated cough monitor. *Respir Med* 2014;108:1808-15. DOI PubMed
18. Israelsson LA, Millbourn D. Closing midline abdominal incisions. *Langenbecks Arch Surg* 2012;397:1201-7. DOI PubMed
19. Kallinowski F, Harder F, Gutjahr D, et al. Assessing the GRIP of Ventral hernia repair: how to securely fasten DIS classified meshes. *Front Surg* 2017;4:78. DOI PubMed PMC
20. Kallinowski F, Gutjahr D, Vollmer M, Harder F, Nessel R. Increasing hernia size requires higher GRIP values for a biomechanically stable ventral hernia repair. *Ann Med Surg* 2019;42:1-6. DOI PubMed PMC
21. Zucker BE, Simillis C, Tekkis P, Kontovounisios C. Suture choice to reduce occurrence of surgical site infection, hernia, wound dehiscence and sinus/fistula: a network meta-analysis. *Ann R Coll Surg Engl* 2019;101:150-61. DOI PubMed PMC