Safety of laparoscopic graspers with different configurations during liver tissue clamping

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Abstract: Laparoscopic graspers often induce liver damage when large forces are applied during clamping. Here, the safety of graspers with different edge curvature radii, teeth profiles, and jaw windows was evaluated experimentally using a tissue damage assessment method based on in vivo compression tests in a rabbit liver model. The results showed that the degree of damage to liver tissue was associated with the deformation in the tissue and the grasper configuration. Changing the jaw teeth profile from a wedge to a sine, increasing the curvature radius of the jaw edge, reducing the contact coefficient of the square window of the jaw, and increasing the length of the window edge alleviated the damage to liver tissue when a clamping force of 2 N was applied. The results can guide the selection and design of non-traumatic graspers.

1 Introduction
Laparoscopic graspers are widely used in laparoscopic surgery to clamp, pull, and reposition abdominal organs and tissues. To provide sufficient grip strength, the jaws of laparoscopic graspers generally have sharp edges and ridges, as well as windows with different shapes, which can cause an uneven distribution of pinch force over the area of contact between the jaws and the tissue [1, 2]. The high pressure induced by a laparoscopic grasper often leads to tissue damage during tissue manipulation procedures [1, 2]. Tissue damage in laparoscopic surgery can result in a variety of severe complications. An example of a severe complication often induced by liver damage during laparoscopic surgery is liver bleeding, which is associated with high morbidity and mortality rates (up to 29.7%) [3, 4]. To minimise tissue damage, assessing grip safety of laparoscopic graspers with different shapes is crucial. Such an assessment not only helps surgeons select a safe grasper but is also useful to researchers designing new graspers.

Some studies have assessed grip safety of laparoscopic graspers by evaluating the resulting tissue damage. For example, Marucci et al. [5] evaluated the degree of grip-induced trauma by measuring the proportion of sheep stomach tears and found that wave-pattern jaws produced significantly less stomach tissue trauma than jaws with teeth. Chen et al. [6] assessed the safety of different surface patterns in grasper design by calculating the deformation of liver tissue using a laser confocal microscope and demonstrated that the jaws with a hexagonal pillar pattern induced less liver tissue damage than the jaws of a modern surgical grasper with a teeth pattern. Bianchi et al. [7] evaluated grip safety of five commercially available clamps (Geister, Cygnet, Cardiovision [CV] 195.10, CV 195.40, and CV 195.83) using immunohistochemistry and morphologic analysis after thoracic aorta clamping tests and concluded that the amount of intact endothelium in the thoracic aorta of mini pigs was lower when CV 195.10, Cygnet, and Geister were used. Moreover, with regard to the interaction between tissue and graspers with different shapes, Shakhesaft et al. [8] compared the pressure generated at the instrument-tissue interface using two jaws with different edge curvatures and found that rounding of the edge of the jaw reduced the pressure. Heijnsdijk et al. [9] conducted pig caecum clamping experiments using 13 pairs of jaws differing in size and profile and found that jaws with a large contact area could prevent tissue damage, whereas jaws with a slight profile could prevent tissue slip. Vonck et al. [10, 11] tested pig bowel clamping properties of some vacuum grasper prototypes and showed the applicability of the vacuum technique in clamping of soft organs such as the bowel. Brown et al. [12] showed that the force required to pull porcine large bowel tissue was significantly higher for any fenestrated grasper than for non-fenestrated graspers. Cheng and Hannaford analysed the grip safety of graspers with varying radii of curvature and tooth sizes in liver tissue clamping using finite element analysis and found that an increased radius of curvature and a smooth wave pattern of the teeth reduced peak stress and degree of damage to the clamped tissue [13]. Most researchers assessed grip safety of graspers using in vitro animal models. However, tissue properties differ significantly in vivo and in vitro [14]. Histological data on grasper safety obtained using an in vivo model are limited. Therefore, more studies should be conducted using in vivo animal models to simulate real-world surgical conditions.

The aim of this study was to assess grip safety of laparoscopic graspers with different configurations using in vivo compression tests, mechanical characteristics examination, and pathological analysis. The degree of tissue damage was quantified based on a pathological evaluation method for liver tissue presented in our previous report [15]. The results can be useful in designing and testing new graspers to improve patient safety and facilitate surgeon training [6]. They can also guide surgeons when selecting graspers for tissue manipulation.

2 Materials and methods
2.1 Specimen preparation
Compression experiments were performed with the approval of the Institution Animal Care and Use Committee, China. Four male rabbits weighting 2.5–3 kg were obtained from the Experimental Animal Culture Center, Sichuan province. All the animals received humane care in compliance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals (NIH Publication No. 8023, revised in 1978) [16]. Before testing, abdomen hair of each rabbit was cut carefully using medical scissors. Then, the rabbit was fixed on a medical tray by bandaging the limbs and anaesthetised with an auricular vein intravenous injection of 3% sodium pentobarbital at 1 ml/kg (25 mg/kg) of body weight. The abdominal region was rinsed with

ISSN 2405-4518
Received on 29th March 2018
Accepted on 30th April 2018
doi: 10.1049/bsbt.2018.0004
www.ietdl.org

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medical saline, and a 4–5 cm incision was made in the abdominal region using a disposable scalpel. The liver was then gently pulled out of the abdomen for testing. All these procedures were conducted following the regulations for the Administration of Affairs Concerning Experimental Animals, China.

2.2 Experimental set-up

A microcomputer-controlled electronic universal soft tissue mechanical testing machine (HY0580, Shanghai Hengyi Testing Machine Co., Ltd, China) was used in compression experiments, as shown in Fig. 1a. This machine consists of four main devices: a force sensor, a fully digital AC servo motor, a high-precision control actuator, and two sets of clamp devices. The details of the design and testing ranges of this machine are provided in our previous report [15].

The jaws of four different laparoscopic graspers were used to study the effect of tooth and edge shapes on the degree of trauma of liver tissue. These graspers were provided by Tonglu Yida Medical Devices Co., Ltd, China. They are widely used during laparoscopic surgery such as laparoscopic cholecystectomy and laparoscopic resection of liver malignant lesions etc. The jaws of these graspers represented four different shapes: one grasper had wedge-shaped teeth, one had sine-shaped teeth, and the other two were flat with an edge curvature radius of 0.5 or 1.5 mm (0.5 mm flat and 1.5 mm flat, respectively) (see Fig. 1c). The jaws of each grasper were removed from the instrument and embedded into a rectangle block using synthetic resin. Additionally, since commercial fenestrated graspers use relatively few window shapes, four pairs of jaws with different window shapes, such as flat with three round windows (TR), flat with three square windows (TS), flat with a medium square window (MS), and flat with a large square window (LS) (see Fig. 1c), were designed by our research group and manufactured by Tonglu Yida Medical Devices Co., Ltd, China, to study the influence of window size and shape on liver damage. The detailed geometric parameters of the above jaws are shown in Table 1. Before testing, matching jaws were fixed on the upper and lower clamp devices. The liver was pulled out carefully from the abdominal incision and placed on the lower jaw (see Fig. 1b). When testing, the lower jaw was fixed, and the upper jaw indenter was moved down and pressed onto the liver sample with a loading speed of 1 mm/s, a loading force of 2 N and a duration time of 30 s according to the results in our previous study [15]. The average room temperature was 20±2°C and the average relative humidity was 50±5%, which were used to simulate the operation room temperature and humidity. Deformation of liver tissue was measured in terms of compression ratio, the ratio of the displacement of the jaw to the initial tissue thickness.

2.3 Trauma assessment method

After testing, the rabbits were killed by injecting a high dose of 3% sodium pentobarbital. Control and testing samples were immediately obtained for histology using medical scissors. Following the routine

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**Fig. 1** Test set-up  
*a* HY0580 electronic universal soft tissue mechanical testing machine  
*b* Upper and lower clamp devices, grasping jaws, and a rabbit liver  
*c* Shapes of jaws used in clamping experiments
protocol of dermatopathology [17], the harvested samples were rinsed in saline solution, fixed in 4% paraformaldehyde, dehydrated using a gradient of alcohol concentrations, and embedded in paraffin. Afterwards, the samples were cut into 4 μm slices and stained by haematoxylin and eosin to reveal the liver tissue morphology. Then, they were examined under a stereomicroscope (SZX16, Olympus, Japan) (10×) and a biological microscope (BX63, Olympus, Japan) (200×).

Four typical trauma types, that is, inflammatory cell infiltration, hyperaemia, haemorrhage, and hepatic capsule rupture, were observed in the tested livers, which was consistent with our previous report [15]. Thus, the degree of damage to liver tissue was determined using a pathological grading system established in our previous study [15]. The system was created to assess the degree of liver tissue trauma caused by mechanical action of surgical instruments. Briefly, it contains three following steps.

(i) Data quantification. The rupture length of the hepatic capsule was measured at a 10× magnification, while the number of inflammatory cells in a defined area (100 × 100 μm) and the sum of areas with hyperemia and haemorrhage were determined at a 200× magnification using the software analysis systems of the biological microscope and stereomicroscope, respectively.

(ii) Data standardisation. For comparison, two standardised methods were used to determine the Z score and Max–min score. The following equations were used [18]:

\[
Z \text{ score} = \frac{\text{actual value} - \text{median reference value}}{\text{standard deviation}} \tag{1}
\]

\[
\text{Max-min score} = \frac{\text{actual value} - \text{min value}}{\text{max value} - \text{min value}} \tag{2}
\]

(iii) Damage assessment. The degree of damage to liver tissue GI was evaluated based on the following equations:

\[
\text{GI}(Z \text{ score}) = \omega_1 \times Z_1 + \omega_2 \times Z_2 + \omega_3 \times Z_3 \tag{3}
\]

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Table 1: Detailed geometric parameters of the jaws shown in Fig. 1c

| Types of grasppers and surface profiles | Tooth height, mm | Length of window edge, mm | Area covered by the outline A_O, mm² | Surface area A_S, mm² | Contact coefficient A_S/A_O |
|----------------------------------------|-----------------|---------------------------|-------------------------------------|------------------------|---------------------------|
| type I wedge teeth                     | 0.74            | N/A                       | 90                                 | 198.0                  | 2.200                     |
| type II sinusoidal teeth               | 0.52            | N/A                       | 90                                 | 100.5                  | 1.120                     |
| type III 0.5 mm flat                   | N/A             | N/A                       | 90                                 | 72.0                   | 0.800                     |
| type IV 1.5 mm flat                    | N/A             | N/A                       | 90                                 | 36.0                   | 0.400                     |
| type V flat with three round windows (TR) | N/A             | 28.26                     | 90                                 | 68.8                   | 0.764                     |
| type VI flat with three square windows (TS) | N/A             | 29.34                     | 90                                 | 68.8                   | 0.764                     |
| type VII flat with a medium square window (MS) | N/A             | 20.42                     | 90                                 | 68.8                   | 0.764                     |
| type VIII flat with a large square window (LS) | N/A             | 36.00                     | 90                                 | 47.4                   | 0.526                     |

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Fig. 2: Variations of loading force and compression ratio with respect to time

(a) Typical time curves of loading force in compression experiments with jaws with teeth and flat jaws
(b) Variations of compression ratio with time under compression with jaws with teeth and flat jaws
(c) Typical time curves of loading force under compression with fenestrated jaws
(d) Variations of compression ratio with time under compression with fenestrated jaws. MS, flat with a medium square window; LS, flat with a large square window; TS, flat with three square windows; TR, flat with three round windows

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where $\omega_1$, $\omega_2$, and $\omega_3$ represent the weights of inflammatory cell infiltration, hyperaemia and haemorrhage, and hepatic capsule rupture, respectively, $Z_1$, $Z_2$, and $Z_3$ represent the corresponding standardised data obtained using (1) for the above traumas, respectively, and $W_1$, $W_2$, and $W_3$ represent the corresponding standardised data obtained using (2) for the above traumas, respectively.

The weights ($\omega_1$, $\omega_2$, and $\omega_3$) were calculated using the evaluation scale of 1–3–5–7–9 of the AHP method described by Saaty [19].

### 2.4 Statistical analysis

Data are presented as mean ± standard deviation. The experimental data were analysed with SPSS Statistics 18.0 (SPSS Inc., Chicago, IL, USA) using one-way analysis of variance followed by Fisher’s least significant difference test to assess the intergroup differences.
3 Results

3.1 Mechanical characteristics

The mechanical properties of rabbit liver under compression with various jaws are shown in Fig. 2. The typical force and time curves for rabbit liver showed similar trends, that is, as time increased, the loading force increased sharply to a peak value, then quickly returned to the preset value and stayed at this level (see Figs. 2a and c). Fig. 2b shows the changes in compression ratio of rabbit liver with time for jaws with teeth and flat jaws. As shown, the compression ratio increased rapidly in the first 2–4 s and then rose slowly with time. The second time period represented the creep stage. At this stage, the compression ratio in the wedge group was larger than that in the sine group at identical times, while the compression ratio in the 0.5 mm flat group was increased compared to that in the 1.5 mm flat group at identical times. Fig. 2d shows that, at the creep stage, the compression ratios in the MS and TR groups were relatively large compared with those in the other two groups.

3.2 Trauma assessment results

Fig. 3 shows the effects of tooth profile and edge curvature radius of jaws on pathological changes of liver tissue. Typical histological images of liver tissue are given in Figs. 3a–e. In the control group, liver tissue consisted of the hepatic capsule, sinusoid, and vein (see Fig. 3a). In the wedge group, substantial inflammatory cell infiltration and obvious haemorrhage, as well as hepatic capsule rupture, were observed (see Fig. 3b). In the sine group, moderate hyperaemia occurred in the liver tissues (see Fig. 3c). Figs. 3d and e show that, compared to the control group, obvious haemorrhage appeared in the liver tissues in the 0.5 mm flat group, while only slight inflammatory cell infiltration, hyperaemia, and hepatic capsule rupture occurred in the 1.5 mm flat group. According to the statistical analysis of the data presented in Fig. 3f, all these traumas were increased significantly in the test groups compared to those in the control group. In the test groups, the number of inflammatory cells and the rupture length of the hepatic capsule were both significantly higher in the wedge group than in the other groups ($p < 0.05$), while the area of hyperaemia and haemorrhage in the 0.5 mm flat group was increased significantly compared to that in the 1.5 mm flat group ($p < 0.05$). These figures indicate that tooth profile and edge curvature radius have significant effects on liver trauma.

Fig. 4 presents the results of assessment of damage to liver tissue clamped by jaws with teeth and flat jaws. The degree of trauma to liver tissue was significantly higher in the test groups than in the control group ($p < 0.05$) (see Figs. 4a and b). This indicates that jaws with teeth and flat jaws are prone to causing liver tissue trauma during compression. A comparison of Figs. 4a and b suggests similar trends in the max–min and Z scores. The degree of trauma of liver tissue was significantly higher after compression with wedge jaws than after compression with sine jaws ($p < 0.05$), which implies that the sharpness of jaw teeth also has a significant effect on tissue damage during compression. The 0.5 mm flat jaws damaged liver tissue significantly more than the 1.5 mm flat jaws ($p < 0.05$). This indicates that an increase in the radius of curvature of the jaw edge reduces the degree of damage due to compression.

Safety of fenestrated jaws in liver tissue manipulation was also evaluated, as shown in Fig. 5. Figs. 5a–e show typical histological micrographs of rabbit liver after compression with fenestrated jaws. A comparison with the control tissue revealed obvious inflammatory cell infiltration, hyperaemia, and hepatic capsule rupture in the test groups. The results of statistical analysis of these trauma types are shown in Fig. 5f. All the quantified data indicated greater damage to liver tissue in the TR group than in the TS group. The number of inflammatory cells, the sum of area with hyperaemia and haemorrhage, as well as the rupture length of the hepatic capsule were significantly greater in the MS group than in the LS group ($p < 0.05$).

Fig. 6 shows the results of damage assessment for liver tissue compressed with fenestrated jaws following two assessment methods. Both the max–min and Z scores showed that the degree of damage to liver tissue in the TR and MS groups was relatively high compared to that in the other two groups. This suggests that jaws with square windows might be better than jaws with round windows in terms of reduction in liver tissue damage. Furthermore, among jaws with a single window, those with a large window would induce less tissue damage during the clamping process.

4 Discussion

Tissue injury can be caused by high stress concentration during the clamping process [1, 2, 8, 13], resulting in surgical complications. High stress concentration in tissue can be easily induced by graspers with certain profiles [8, 13]. To minimise tissue damage, assessing the safety of graspers used in laparoscopic surgery is necessary. This study improved the method of grasper safety assessment by introducing in vivo compression tests, examining mechanical characteristics, and utilizing pathological analysis. The results indicate that the degree of damage to liver tissue is associated with tissue deformation and grasper configuration; in particular, using jaws with a sine teeth profile instead of a wedge teeth profile, increasing the curvature radius of the jaw edge, reducing the contact coefficient of the square window of the jaw, and increasing the length of the window edge of the jaw, reduced the degree of tissue damage when a clamping force of 2 N was...
applied. The following considerations can be derived from the results.

Among the jaws with teeth, those with a sine profile were safer than those with a wedge profile under the same conditions (see Figs. 3 and 4). The main reason is that wedge jaws have relatively sharp teeth compared with sine jaws, which led to more deformation (see Fig. 2) and stress in liver tissue associated with applying a loading force of 3 N. During the compression process, the liver capsule could be seriously damaged, and large amounts of blood infiltrated the compression site owing to extensive deformation (see Fig. 3). Thus, the degree of damage to liver tissue was greater in the wedge group than in the sine group (see Fig. 3). This result is consistent with the findings of previous studies [5, 9, 13]. Therefore, it can be concluded that reducing sharpness of the teeth of the jaw could help prevent liver tissue damage.

For the flat jaws, the degree of damage to liver tissue increased significantly when the radius of curvature of the jaw edge decreased (see Figs. 3 and 4). This was also related to the deformation of liver tissue. When compressed by flat jaws with a

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**Fig. 5** Typical histological micrographs of rabbit liver clamped by jaws with different fenestrations

- **a** Control group
- **b** TR
- **c** TS
- **d** MS
- **e** LS

/Results of statistical analysis of different trauma types of liver tissue. Error bars indicated standard deviation values. Different letters indicated significant differences at level of 0.05 among groups. TR, flat with three round windows; TS, flat with three square windows; MS, flat with a medium square window; LS, flat with a large square window
radius of curvature of 0.5 mm, liver tissue sustained a relatively high amount of deformation (see Fig. 2). Moreover, the jaw with a smaller edge curvature radius caused greater stress in the liver [13]. Accordingly, the outer pressure on the sinusoid and vein of the liver was relatively high, which might lead to extensive damage to the wall of the sinusoid and the vein. Hence, the sum of area with hyperaemia and haemorrhage was relatively large (see Fig. 3), causing an increase in the degree of liver damage (see Fig. 4). Compression by flat jaws with a curvature radius of 1.5 mm with a loading force of 2 N resulted in less deformation of liver tissue (see Fig. 2), causing less trauma (see Fig. 4). These results are similar to the findings described in the literature [8, 9, 13]. Therefore, the radius of curvature of the jaw edge should be considered during grasper design.

With regard to fenestrated jaws, two factors should be mentioned, including size and shape of fenestration. The effect of size of fenestration on liver trauma was investigated by comparing the MS and LS groups. Liver tissue in the LS group sustained milder injury during compression than liver tissue in the MS group (see Figs. 5 and 6). This could be a consequence of differences in deformation and stress distribution in liver tissue. To achieve a clamp force of 2 N with LS jaws, it is necessary to overcome not only the deformation of liver tissue along the direction of compression, but also the deformation of liver tissue enclosed in the window portion. Compared with the MS jaws, LS jaws had a smaller contact coefficient (see Table 1), that is, the window portion of these jaws covered a larger area. Therefore, more energy was needed to overcome the deformation of tissue enclosed in the window portion, resulting in less energy needed to overcome the deformation of the tissue along the direction of compression. This resulted in less deformation of the tissue along the direction of compression (see Fig. 2) and less stress in the tissue. Consequently, the degree of liver tissue damage was reduced (see Fig. 6). The effect of shape of fenestration on liver trauma was also evaluated using jaws with TS and TR shapes. The jaws with a TS shape induced less tissue trauma than the TR jaws (see Figs. 5 and 6). This was because the length of the window edge of the TS-shaped jaws was greater than that of the TR-shaped jaws (see Table 1). Hence, more tissue could be enclosed in the window of the TS jaws. The energy generated by the TS-shaped jaws during clamping action was spent on deformation of these tissues. Accordingly, less energy was applied towards the deformation of the tissue along the compression direction, which reduced the amount of deformation along this direction (see Fig. 2) and decreased the stress in the tissue. This resulted in less damage to the liver tissue (see Fig. 6).

Noteworthy, pathological scores were obtained based on two standardised methods. There were no significant differences between the corresponding assessment scores. This suggests that both methods are effective in liver damage assessment.

Based on the above results, some suggestions could be provided to help surgeons and researchers choose and design non-traumatic graspers. Among teeth graspers, those with a sine teeth shape were safer than those with wedged teeth in liver tissue manipulation. Among flat graspers, those with greater edge curvature radius of the jaws might induce less trauma during clamping. Among fenestrated graspers, those with square windows in the jaws were better than those with round windows in terms of trauma prevention, while jaws with larger square windows were better in minimising tissue damage.

For simplicity, liver tissue was obtained through an incision in the abdominal area. This method is slightly different from methods typically used in laparoscopic surgery. Thus, the effectiveness of this method of grasper safety evaluation should be verified using actual laparoscopic instruments in future research.

5 Conclusions

The safety of graspers used in laparoscopic surgery was assessed via experimental investigation and pathological damage assessment based on in vivo compression tests in a rabbit liver model. The degree of damage to liver tissue was associated with deformation in the tissue and with grasper configuration. The following measures alleviated the damage to liver tissue when a clamping force of 2 N was used: changing the jaw teeth profile from wedge to sine, increasing the curvature radius of the jaw edge, reducing the contact coefficient of the square window of the jaw, and increasing the length of the window edge.

6 Acknowledgments

This work was supported by National Natural Science Foundation of China (no. 51675447 and no. 51290291).

All procedures performed in studies involving animals were in accordance with the ethical standards of the institution or practice at which the studies were conducted.

7 References

[1] Heijnadjik, E.A.M., Van Der Voort, M., de Visser, H., et al.: ‘Inter-and intraindividual variabilities of perforation forces of human and pig bowel tissue’, Surg. Endosc., 2003, 17, (12), pp. 1923–1926
[2] Cartmill, J.A., Shakhsafi, A.J., Walsh, W.R., et al.: ‘High pressures are generated at the tip of laparoscopic graspers’, Aust. N. Z. J. Surg., 1999, 69, (2), pp. 127–130
[3] Fujikawa, T., Kawamoto, H., Kawamura, Y., et al.: ‘Impact of laparoscopic liver resection on bleeding complications in patients receiving antithrombotics’, World J. Gastrointest. Endosc., 2017, 9, (18), p. 396

Fig. 6 Results of assessment of trauma degrees of liver tissue clamped by jaws with different fenestrations
a Max-min scores
b Z scores. Error bars indicated standard deviation values. Different letters indicated significant differences at level of 0.05 among groups. TR, flat with three round windows; TS, flat with three square windows; MS, flat with a medium square window; LS, flat with a large square window
[4] Gupta, R., Fuks, D., Bourdeaux, C., et al.: ‘Impact of intraoperative blood loss on the short-term outcomes of laparoscopic liver resection’, Surg. Endosc., 2017, 31, (11), pp. 4451–4457

[5] Marucci, D.D., Cartmill, J.A., Walsh, W.R., et al.: ‘Patterns of failure at the instrument–tissue interface’, J. Surg. Res., 2000, 93, (1), pp. 16–20

[6] Chen, H., Zhang, L., Zhang, D., et al.: ‘Bioinspired surface for surgical graspers based on the strong wet friction of tree frog toe pads’, ACS Appl. Mater. Interfaces, 2015, 7, (25), pp. 13987–13995

[7] Bianchi, G., Pucci, A., Matteucci, M., et al.: ‘Mechanical properties and biological interaction of aortic clamps: are these all minimally invasive?’, Innov.: Technol. Cardiotorac. Vasc. Surg., 2013, 8, (1), pp. 42–49

[8] Shakeshaft, A.J., Cartmill, J.A., Walsh, W.R., et al.: ‘A curved edge moderates high pressure generated by a laparoscopic grasper’, Surg. Endosc., 2001, 15, (10), pp. 1232–1234

[9] Heijnsdijk, E.A.M., De Visser, H., Dankelman, J., et al.: ‘Slip and damage properties of jaws of laparoscopic graspers’, Surg. Endosc., 2004, 18, (6), pp. 974–979

[10] Vonck, D., Jakimowicz, J.J., Lopuhaä, H.P., et al.: ‘Grasping soft tissue by means of vacuum technique’, Med. Eng. Phys., 2012, 34, (8), pp. 1088–1094

[11] Vonck, D., Goossens, R.H.M., Van Eijk, D.J., et al.: ‘Vacuum grasping as a manipulation technique for minimally invasive surgery’, Surg. Endosc., 2010, 24, (10), pp. 2418–2423

[12] Brown, A.W., Brown, S.I., Mclean, D., et al.: ‘Impact of fenestrations and surface profiling on the holding of tissue by parallel occlusion laparoscopic graspers’, Surg. Endosc., 2014, 28, (4), pp. 1277–1283

[13] Cheng, L., Hannaford, B.: ‘Evaluation of liver tissue damage and grasp stability using finite element analysis’, Comput. Methods Biomech. Biomed. Eng., 2016, 19, (1), pp. 31–40

[14] Rosen, J., Brown, J.D., De, S., et al.: ‘Biomechanical properties of abdominal organs in vivo and postmortem under compression loads’, J. Biomech. Eng., 2008, 130, (2), p. 021020

[15] Wang, J., Yu, Q.Y., Li, W., et al.: ‘Influence of clamping stress and duration on the trauma of liver tissue during surgery operation’, Clin. Biomech., 2017, 43, pp. 58–66

[16] Institute of Laboratory Animal Resources (US). Committee on Care, Use of Laboratory Animals, National Institutes of Health (US). Division of Research Resources. Guide for the care and use of laboratory animals. National Academies, 1985

[17] Gao, T.W., Sun, J.F.: ‘Current dermatopathology’ (People’s Medical Publishing House, 2001), pp. 443–451

[18] Dibley, M.J., Staehling, N., Nieburg, P., et al.: ‘Interpretation of Z-score anthropometric indicators derived from the international growth reference’, Am. J. Clin. Nutr., 1987, 46, (5), pp. 749–762

[19] Saaty, T.L.: ‘Fundamentals of decision making and priority theory with the analytic hierarchy process’ (Rws Publications, 2000)