Surgical Oncology 31 (2019) 1–6

Contents lists available at ScienceDirect

Surgical Oncology

journal homepage: www.elsevier.com/locate/suronc

Laparoscopic hepatectomy assisted by a flexible 915 MHz microwave antenna: A safe and innovative device for hepatectomy

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ARTICLE INFO

Keywords:
Hepatocellular carcinoma (HCC)
Laparoscopic hepatectomy (LH)
F915 MMA

ABSTRACT

Background: The objective of the present study was to elaborate a flexible 915 MHz microwave antenna (F915 MMA) and to evaluate the safety and feasibility in laparoscopic hepatecyomy (LH).
Methods: The F915 MMA was redesigned based on the experiences in clinical practice. Ten porcine LHs were divided into a 'flexible' group and a control group, with 5 porcine LHs in each group. The F915 MMA was used in the flexible group. The data for 48 patients who underwent LH were analyzed; 12 patients underwent F915 MMA-assisted LH and were regarded as the flexible group, and the others were considered as controls.
Results: The F915 MMA bends freely and rotates flexibly. In the porcine LH *in vivo*, the flexible group had less intraoperative blood loss (54.00 ± 27.02 ml vs 230.00 ± 83.67 ml, $P = 0.002$), and the mean duration of hepatic parenchyma transection in the flexible group was significantly shorter than that in the control group (17.3 ± 7.8min vs 37.9 ± 6.4min). Among th patients, compared to the control group, the flexible group had less intraoperative blood loss (154.17 ± 68.95 ml vs 284.86 ± 294.68 ml, $P = 0.018$), less frequency and duration of the first porta hepatic occlusion (1.50 ± 0.52times vs 2.35 ± 1.14times, $P = 0.021$ and 22.50 ± 7.83min vs 35.95 ± 17.23min, $P = 0.017$, respectively) and lower accumulative complications (33.3% vs 80.5%, $P = 0.008$).
Conclusions: Laparoscopic F915 MMA is an innovative device that can assist LH in a safe, feasible and flexible manner.

1. Introduction

Hepatocellular carcinoma (HCC) ranks as the third leading cause of cancer-related death and the sixth most prevalent cancer worldwide [1], and hepatic resection is considered to be the optimal approach for HCC [2]. With the continuous innovation of laparoscopic techniques and the accumulation of surgical experiences, laparoscopic hepatectomy (LH) has become widely accepted due to its superior proprieties of less invasivness and quick recovery. However, HCC is usually associated with the presence of chronic hepatitis or liver cirrhosis, and LH carries a great risk of hemorrhage. Intraoperative bleeding is associated with higher postoperative hepatic insufficiency and shorter long-term survival. Therefore, sustained improvements in parenchyma transection and hemostatic devices are urgently needed [3]. Previous studies [4] have reported that LH with a radiofrequency ablation (RF) energy (Habib™ 4X), has some deficiencies; it is clumsy and difficult to bend, making it was unusable in the narrow intraperitoneal cavity, especially for right posterior segmental resection. During recent decades, the microwave antenna (MA) has become widely accepted for its safety and higher efficacy [5,6]. However, the RF and MA devices are all straight and rigid designs that make them available only for peripherally located lesions. The objective of the present study was to introduce a self-designed laparoscopic F915 MMA that retains the superior performance of the original design and to further evaluate its safety and feasibility in both live porcine LH and patient LH.

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https://doi.org/10.1016/j.suronc.2019.07.006
Received 27 October 2018; Received in revised form 22 February 2019; Accepted 22 July 2019
Available online 25 July 2019
0960-7404/

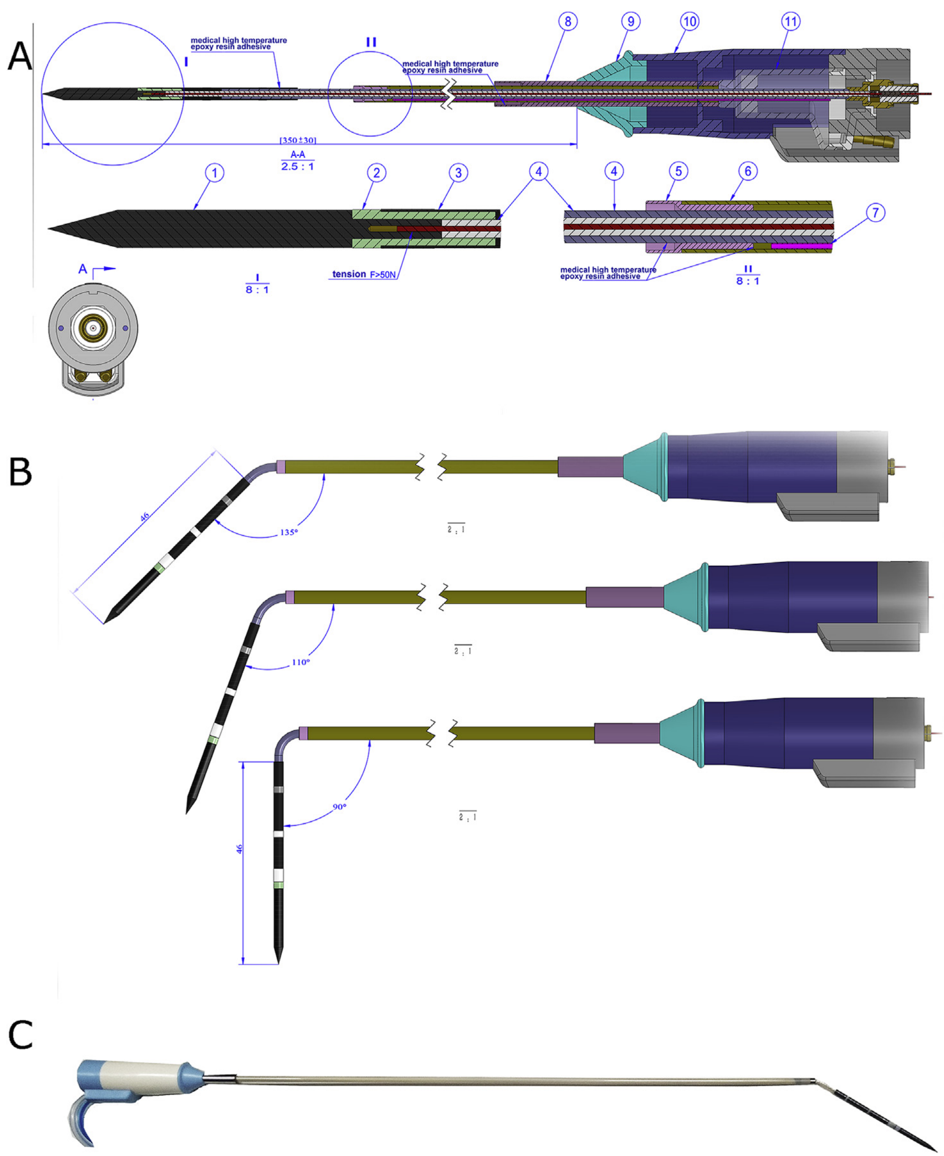

Fig. 1. Schematic diagram of the laparoscopic F915 MMA.

2. Patients and methods

2.1. F915 MMA

The F915 MMA was redesigned with a “flexible joint” and used with a KY-2100 portable microwave generator, and it was produced by Nanjing CANYON Medical Technology Co., Ltd. (Nanjing, China). The power output ranged from 5 to 100 W with the frequency of 915 MHz (± 1%). The device is permitted to be used as medical device by China Food and Drug Administration(CFDA).

2.2. Porcine liver in vivo

Ten Selected shanghai pigs weighing 30–40 kg was obtained from the Shanghai Johnson Academic Center (Shanghai City, China). All animals were housed and fed without exposure to a contaminated environment. The pigs were divided into two groups, the flexible group (n = 5) underwent LH with a F915 MMA, and the control group (n = 5) underwent LH without this device. Left lateral lobectomy was performed. Generally, the F915 MMA was used under with a power of 50 W and a duration of 100 s until a continuous transection plane was achieved. Then, the Cavitron ultrasonic surgical aspirator (Cavitron Ultrasonic Surgical Aspirator; Valleylab, Boulder, CO) was used for parenchymal transection. To avoid hemorrhage in vessels with diameters greater than 5 mm, haemo-lock clip clamps were used. All experiments were completed laparoscopically by the same operating team.

2.3. Patients

Forty-eight patients who underwent LH in the department of hepatobiliary and pancreatic surgery of the first affiliated hospital from September 2016 to December 2018 were included in the study. All patients underwent preoperative assessment, including CT and/or MRI imaging. Baseline characteristics and perioperative outcomes were collected. In brief, during the operation, intraoperative ultrasound was used to evaluate the resectability of the lesions and to reconfirm the radiological findings. The LH procedure included a safety margin of least a 1 cm around the tumor. After marking the liver capsule, the F915 MMA was inserted in the liver perpendicular to the labelled line. After the first coagulation was completed, the antenna was pulled out and inserted into the parenchyma 1.5 cm away from the first site until a continuous coagulation was completed. Then the Cavitron Ultrasonic Surgical Aspirator (CUSA) (Tyco Healthcare, MA, USA) or harmonic scalpel (Ethicon Endo-Surgery, OH, USA) was applied to separate the liver parenchyma.

Written informed consent was obtained from all of the participants. The study was reviewed and approved by the Human Research Ethics Committee of The First Affiliated Hospital, College of Medicine, Zhejiang University and the department of experimental animals of Zhejiang Academy of Medical Sciences.

3. Statistical analysis

The continuous variables of the baseline characteristics of the patients were expressed as the mean ± standard deviation (SD), and differences were assessed using Student's t-test. Enumeration data were expressed as percentages, and differences were assessed using standard χ^2-square or Fisher's exact tests. All statistical analyses were performed using the SPSS statistical software version 25 (IBM SPSS, Chicago, IL, United States). Statistical significance was defined as $P < 0.05$.

4. Results

4.1. F915 MMA

The F915 MMA was designed with a "flexible joint", with which it could orient to any angle and direction easily and flexibly. The specification are as follows: 16G, outer diameter 2.1 ± 0.05 mm; built-in cooled-shaft design; microwave frequency: 915 MHz; output power: 0–120 W; temperature control accuracy: ± 0.1 °C; and bendable angle: 360^0. The middle of the antenna is made of flexible and soft microwave transmission cable material and can be set to arbitrary rotation angles. The structure of the F915 MMA consists of a (1) radiation antenna (915 MHZ microwave needle), (2)PTFE polymer body, (3)stainless steel needle, (4)soft microwave transmission cable, (5)cooling water plug, (6)PEEK outer tube, (7)cooling water pipe, (8)booster tube, (9) a handle assembly, (10) water tank assembly, (11) microwave receiving connector, (12) cooling water inlet, and (13) and water outlet. Detailed information is illustrated in Fig. 1.

4.2. Porcine liver in vivo

All animal experiments were completed successfully. The F915 MMA can bend freely and rotate flexibly to any angle and direction. The mean operation duration in flexible group was 53.3 ± 12.5 min, which was significantly shorter than 87.5 ± 17.8 min in control group ($P < 0.05$). The mean duration of first hepatic portal occlusion in flexible group was 12.9 ± 6.3 min, which was significantly shorter than that in control group (31.5 ± 7.6 min), it has statistical significance ($P < 0.05$). The mean duration of hepatic parenchyma transection in flexible group was 17.3 ± 7.8 min, which was significantly shorter than that in control group (37.9 ± 6.4 min) ($P < 0.05$). The mean intraoperative bleeding volume in flexible group was 54.0 ± 27.0 ml, which was significantly less than 230.0 ± 83.7 ml in control group ($P < 0.05$) (Fig. 2 and Table 1).

4.3. Patients

The baseline characters of the patients were shown in Table 2. A total of 37 (77.1%) patients were male. The mean age was 56.40 ± 9.18 years, and the mean BMI was 23.13 ± 2.64. The proportion of HCC cases was 87.5%. The differences in the baseline characteristics of the 48 patients were not statically significant between the two groups. Compared with the control group, the flexible group had less intraoperative blood loss (154.17 ± 68.95 ml vs 284.86 ± 294.68 ml, $P = 0.018$), a lower frequency of the first porta hepatic occlusion (1.50 ± 0.52times vs 2.35 ± 1.14times, $P = 0.021$), a shorter duration of the first porta hepatic occlusion (22.50 ± 7.83min vs 35.95 ± 17.23min, $P = 0.017$), and fewer accumulative complications (33.3% vs 80.5%, $P = 0.008$). Three patients in the control group required blood cell transfusion. The mean operative duration was 268.75 ± 77.72 min in the flexible group and 272.31 ± 118.08 in the control group, respectively, with no significant difference found ($P = 0.923$) (Table 3 and Fig. 3).

5. Discussion

During the past decades, LH has attracted great attention due to its less invasive and quick recovery proprieties. The benefits over the open procedure include less postoperative adhesions, less analgesic requirement, shorter hospital stay and lower complication rate [7,8]. One previous study [2] reported that LH was associated with a significantly lower comprehensive complication index (CCI), which indicated a lower severity of postoperative complications. With the rapid progression of laparoscopic techniques and facilities, various types of devices for hepatic parenchymal transection have been adopted by hepatobiliary surgeons, such as RF devices. However, intraoperative blood loss remains a life-threatening problem; therefore, minimizing blood loss has been the priority in LH. In the present work, we described, for the first time, an innovative device, the F915 MMA, that retained the superior performance of the original device. To the best of our knowledge, there is currently no such device being used. LH assisted with this device had less frequency and duration of the first porta hepatic occlusion was needed, less intraoperative blood loss was occurred, and fewer accumulative complications.

Liver tissues were less susceptible to charring and desiccation with the F915 MMA device when compared with RF devices [9,10]. Moreover, a temperature of 60 °C was readily achieved using MA, resulting in faster and more complete parenchymal coagulation. In addition, MA has the potential benefits of being less susceptible to 'heat sink' cooling in perivascular tumors, which improves the convection profile [11]. A previous study [4] reported the RF energy (Habib™ 4X) for LH. However, Habib™ 4X has some drawbacks. First, it was unable to overcome the limitations of being accessible only to lesions located at two points along a straight line. Second, its probe is clumsy, especially due to its four-in-one design that makes it sacrifice more normal liver parenchyma in LH. Fortunately, the self-designed laparoscopic F915 MMA overcame these limitations and could orient to any angle and direction freely and flexibly in the narrow abdominal cavity. The surgeons could handle it and insert it into the superior or posterior surfaces of the liver, by which LH could be performed. At the same time, the F915 MMA could also accurately carry out punctures and ablate the tumor by adjusting the required parameters.

In the previous *ex vivo* study, when 50 W/100 s was applied, the 5-cm long axis and 2 cm short axis of the solidification area were the most appropriate for obtaining a sufficient coagulation range, preserving more normal parenchyma and minimizing the injury to the adjacent parenchyma. The geometic shape of the zone in porcine liver *in vivo* was approximately similar to that of the liver *ex vivo*, and it is reasonable to say that blood perfusion has little influence on the thermal field distribution. In fact, the distance measured between antenna tracts was less than 15 mm, which is more likely due to the shrinkage of the liver parenchyma caused by water evaporation during coagulation. In addition, more functional liver parenchyma was retained with less than 7.5 mm of necrosis. The preliminary animal research conducted verified the superior manoeuvrability of the F915 MMA and was suggestive of little or almost no blood loss during the operation process.

There were no significant differences in postoperative liver function, serum albumin, alanine aminotransferase (ALT), alanine aminotransferase (AST), total bilirubin (TBil), direct bilirubin (DBil), prothrombin time (PT), or hemoglobin (Hb) levels between the two groups. The mean postoperative length of hospital stays was no different between the groups.

Most HCC patients had a background of cirrhosis, and cirrhotic liver parenchyma is more susceptible to ischaemia and hypoxia compared

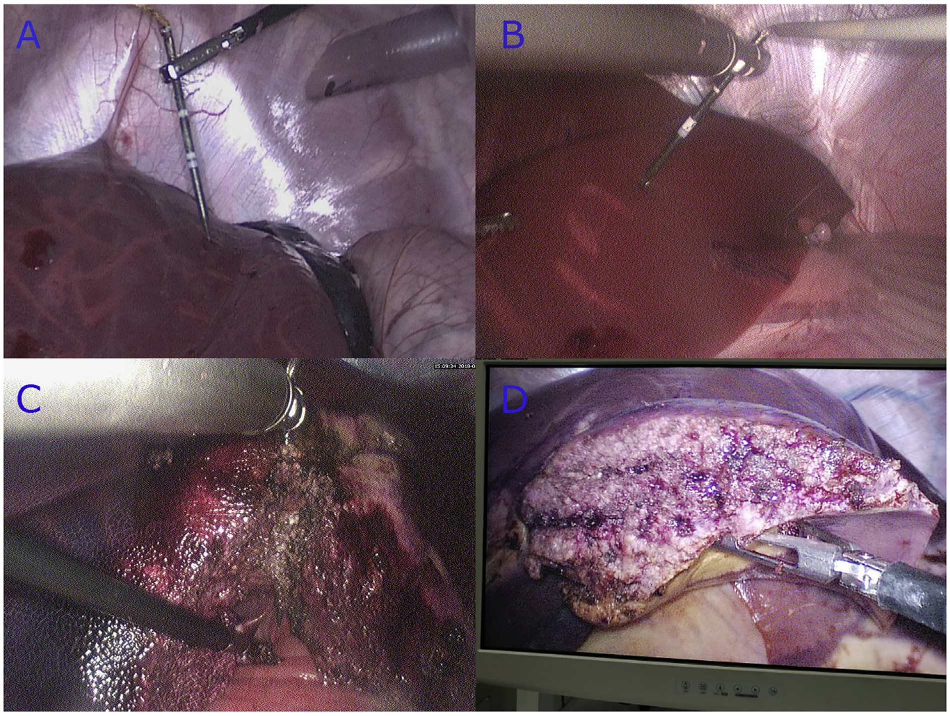

Fig. 2. Porcine liver *in vivo*. A/B. The flexible microwave antenna was inserted into the porcine liver along the diaphragmatic surface. C. The liver was transected along the overlapping necrotic areas along the coagulation surface. D. The coagulation surface was apparently carbonized and bloodless.

Table 1
Outcomes between the flexible group and control group.

	microwave group	control group	*P* Value
Duration of operation (min)	53.3 ± 12.5	87.5 ± 17.8	$P < 0.001$
Duration of the first porta hepatic occlusion (min)	12.9 ± 6.3	31.5 ± 7.6	$P < 0.001$
Duration of transection of liver parenchyma(min)	17.3 ± 7.8	37.9 ± 6.4	$P < 0.001$
Intraoperative blood loss (ml)	54.0 ± 27.0	230.0 ± 83.7	$P < 0.001$

with the noncirrhotic liver parenchyma [12], and bled more easily during the dissection process. The frequency and duration of the first porta hepatic occlusion were of great significance in reducing ischaemia-reperfusion injury and postoperative mortality, especially for cirrhosis patients. In the present study, when F915 MMA precoagulation was performed, vessels below 5 mm were coagulated directly and the liver parenchymal transection process was less likely to bleed, which decreased the frequency and duration of the first porta hepatic occlusion and significantly reduced the ischaemic and anoxic injury. Simultaneously, less blood loss was associated with a lower incidence of recurrence and better long-term survival [13–15]. In the flexible group, small vessels were coagulated, which reduced the probability of tumor

Table 2
Characteristics of patients in flexible group and control group.

	Total patients (n = 36)	Flexible group (n = 12)	Control group (n = 36)	P value
Sex (M)	37 (77.1%)	9 (75.0%)	28 (77.8%)	0.563
BMI	23.13 ± 2.64	22.47 ± 2.28	23.35 ± 2.75	0.323
Mean ages (years)	56.40 ± 9.18	54.17 ± 5.77	57.30 ± 10.18	0.324
Cirrhosis level				0.063
F1–F2	12 (30.0%)	6 (50.0%)	6 (19.0%)	
F3–F4	21 (69.7%)	4 (50.0%)	17 (81.0%)	
Pathologic diagnosis				0.319
HCC	42 (87.5%)	12 (100%)	30 (83.3%)	
ICC	4 (8.3%)	0 (0%)	2 (5.6%)	
Mixed cell carcinoma	2 (4.2%)	0 (0%)	4 (11.1%)	
Preoperative albumin	43.21 ± 4.95	41.19 ± 5.89	43.89 ± 4.48	0.103
Preoperative ALT	33.17 ± 31.42	30.50 ± 11.80	34.06 ± 35.75	0.738
Preoperative AST	30.64 ± 16.36	30.67 ± 9.28	30.62 ± 18.28	0.995
Preoperative TBIL	12.33 ± 5.80	13.91 ± 8.30	11.81 ± 4.73	0.279
Preoperative DBIL	3.96 ± 1.93	4.58 ± 2.97	3.75 ± 1.44	0.199
Preoperative ChE	6808.38 ± 1903.76	5955.83 ± 1718.13	7100.69 ± 1898.40	0.072
Preoperative PT	11.94 ± 1.28	12.29 ± 1.17	11.82 ± 1.31	0.276
Preoperative Hb	138.44 ± 22.09	136.83 ± 22.35	138.97 ± 22.30	0.775
Preoperative HCT	42.75 ± 5.58	40.81 ± 7.14	43.40 ± 4.91	0.167
ICG15 (%)	5.67 ± 6.40	11.25 ± 14.61	4.66 ± 3.35	0.056
ICG plasma clearance	0.22 ± 0.70	0.19 ± 0.08	0.23 ± 0.07	0.248

Data are presented as #: means ± standard deviation.

Table 3
Comparison of operative outcomes between the microwave group and control group.

	Flexible group (n = 12)	Control group (n = 36)	P value
Maximum diameter of the tumor (cm)	7.12 ± 4.07	8.52 ± 3.70	0.272
Type of resection			0.401
Segmental resection	5 (45.5%)	18 (50.0%)	
Biosegmental resection	3 (27.3%)	14 (38.9%)	
Trisegmental or more resection	3 (27.3%)	4 (11.1%)	
Number of the first porta hepatic occlusion	1.50 ± 0.52	2.35 ± 1.14	0.021
Duration of the first porta hepatic occlusion (min)	22.50 ± 7.83	35.95 ± 17.23	0.017
Duration of operation (min)	268.75 ± 77.72	272.31 ± 118.08	0.923
Intraoperative blood loss (ml)	154.17 ± 68.95	284.86 ± 294.68	0.018
Cumulative complications (%)			0.008
Clavien-Dindo I complications	4 (33.3%)	26 (72.2%)	
Clavien-Dindo II complications	0 (0%)	0 (0%)	
Clavien-Dindo III complications	0 (0%)	3 (8.3%)	
Transfusion (%)	0 (0%)	3 (8.3%)	0.302
Length of postoperative stay (days)	8.17 ± 3.71	7.47 ± 2.67	0.484
Postoperative day7 albumin	35.82 ± 4.41	34.56 ± 3.61	0.373
Postoperative day7 ALT	98.60 ± 66.47	72.04 ± 41.78	0.163
Postoperative day7 AST	48.91 ± 29.43	37.36 ± 21.12	0.190
Postoperative day7 TBIL	27.00 ± 12.93	17.79 ± 10.15	0.052
Postoperative day7 DBIL	12.27 ± 8.84	7.64 ± 4.68	0.126
Postoperative day7 PT	13.72 ± 1.17	13.61 ± 1.91	0.871
Postoperative day7 Hb	118.45 ± 19.56	107.63 ± 27.70	0.250

Data are presented as means ± standard deviation or as numerical value (percentage).

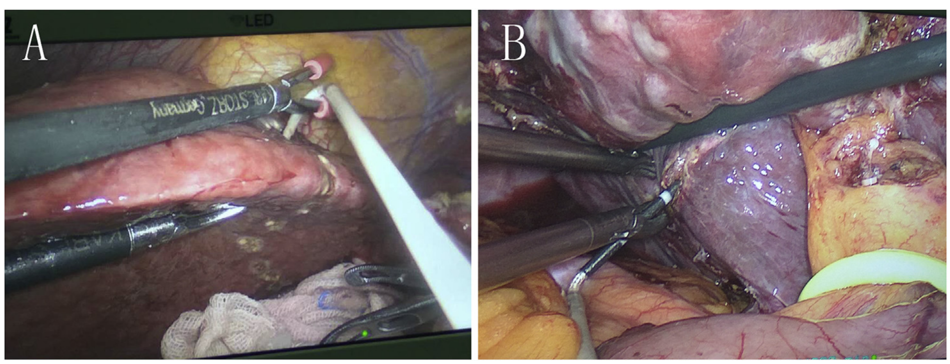

Fig. 3. In laparoscopic hepatectomy, F915 MMA can be bent and rotated at different angles.

haematogenous metastasis when the liver parenchyma was compressed. Interestingly, the operation time did not differ between the groups, and the most likely reason to accounted for this phenomenon may be that the precoagulation time compromised the liver parenchyma transection duration.

Although the short-term results were encouraging, some drawbacks exist. This is a preliminary study with a relatively small sample size. Further, more experience is necessary, the performance parameters should be continuously improved, and more analysis should be performed when survival data become available.

6. Conclusions

In conclusion, the self-designed laparoscopic F915 MMA is an innovative device by which LH can be performed in a safe, feasible and flexible manner. Based on accumulated experience and unremitting efforts, we have reason to believe that the device can be used successfully in liver parenchymal transections.

Funding

This work was supported by National Natural Science Foundation of China (No.81372626, No.81572975), Key Research and Development Project of Science and Technology Department of Zhejiang, China (No.2015C03053), and Zhejiang Provincial Program for the Cultivation of High-Level Innovative Health Talents (2016).

Conflicts of interest

None.

Acknowledgments

None.

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