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# An Ex Situ Cadaver Liver Training Model Continuously Pressurized to Simulate Specific Skills Involved in Laparoscopic Liver Resection: the Lap-Liver Trainer

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Abstract      *Background:*  
Laparoscopic liver resection (LLR) requires delicate skills. The aim of the study was to develop a training model mimicking as much as possible intraoperative bleeding and bile leakage during LLR. We also assessed the educational value of the training model.  
*Methods:*  
The Lap-liver trainer (LLT) combined a continuously pressurized ex situ cadaver liver and a customized mannequin. The customized mannequin was designed by computer-aided design and manufactured by 3D printing. The left lateral sectionectomy (LLS) was chosen to assess the feasibility of a LLR with the LLT. Eighteen volunteers were recruited to perform LLS and to assess the educational value of the LLT using a Likert scale.  
*Results:*  
The customized mannequin consisted of a close laparoscopic training device based on a simplified reconstruction of the abdominal cavity in laparoscopic conditions. Ex situ cadaver livers were pressurized to simulate blood and bile supplies. Each expert surgeon ( $n = 3$ ) performed two LLS. They were highly satisfied of simulation conditions ( $4.80 \pm 0.45$ ) and strongly recommended that the LLT should be incorporated into a teaching program ( $5.00 \pm 0.0$ ). Eight novice and 4 intermediate surgeons completed a teaching program and performed a LLS. Overall, the level of satisfaction was high ( $4.92 \pm 0.29$ ), and performing such a procedure under simulation conditions benefited their learning and clinical practice ( $4.92 \pm 0.29$ ).  
*Conclusions:*  
The LLT could provide better opportunities for trainees to acquire and practice LLR skills in a more realistic environment and to improve their ability to deal with specific events related to LLR.

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Keywords (separated by '-')      Laparoscopic liver surgery - Simulation education - Ex situ pressurized liver - Cadaver liver - Specific events


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# An Ex Situ Cadaver Liver Training Model Continuously Pressurized to Simulate Specific Skills Involved in Laparoscopic Liver Resection: the Lap-Liver Trainer

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## Abstract

**Background** Laparoscopic liver resection (LLR) requires delicate skills. The aim of the study was to develop a training model mimicking as much as possible intraoperative bleeding and bile leakage during LLR. We also assessed the educational value of the training model.

**Methods** The Lap-liver trainer (LLT) combined a continuously pressurized ex situ cadaver liver and a customized mannequin. The customized mannequin was designed by computer-aided design and manufactured by 3D printing. The left lateral sectionectomy (LLS) was chosen to assess the feasibility of a LLR with the LLT. Eighteen volunteers were recruited to perform LLS and to assess the educational value of the LLT using a Likert scale.

**Results** The customized mannequin consisted of a close laparoscopic training device based on a simplified reconstruction of the abdominal cavity in laparoscopic conditions. Ex situ cadaver livers were pressurized to simulate blood and bile supplies. Each expert surgeon ( $n=3$ ) performed two LLS. They were highly satisfied of simulation conditions ( $4.80 \pm 0.45$ ) and strongly recommended that the LLT should be incorporated into a teaching program ( $5.00 \pm 0.0$ ). Eight novice and 4 intermediate surgeons completed a teaching program and performed a LLS. Overall, the level of satisfaction was high ( $4.92 \pm 0.29$ ), and performing such a procedure under simulation conditions benefited their learning and clinical practice ( $4.92 \pm 0.29$ ).

**Conclusions** The LLT could provide better opportunities for trainees to acquire and practice LLR skills in a more realistic environment and to improve their ability to deal with specific events related to LLR.

**Keywords** Laparoscopic liver surgery · Simulation education · Ex situ pressurized liver · Cadaver liver · Specific events

## Introduction

Laparoscopic procedures have significantly progressed in the past decades and have become the standard approach in most surgical specialties, driven by the desire for less surgical

trauma, faster postoperative recovery, shorter hospital stay, and better cosmetic results.<sup>1-3</sup>

Laparoscopic liver resection (LLR) has been progressively developed and gained worldwide acceptance during the past decade.<sup>4</sup> Resections of lesions in the anterior liver segments or the left lateral segments can now be safely performed by laparoscopic approach.<sup>5</sup> However, LLR requires delicate skills in both liver and laparoscopic surgery, and experts believe that only surgeons who do both advanced laparoscopic procedures and liver surgeries during daily practice should perform LLR.<sup>5</sup> Although a steep learning curve (LC) exists for LLR, the postoperative outcomes should be improved by stepwise progression in skills.<sup>6-8</sup> Because only few studies evaluated the educational value of LLR training programs,<sup>8</sup> the Southampton meeting has recently emphasized the lack of evidence-based studies focusing on LLR education.<sup>5</sup>

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47 Unlike open surgery, several technical challenges such  
 48 as limited tactile feedback, fulcrum effect, reliance on two-  
 49 dimensional vision, and difficult hand-eye-coordination have  
 50 contributed to the extended LC in acquiring laparoscopic  
 51 skills.<sup>9,10</sup> In the specific area of LLR, bleeding and bile leak-  
 52 age are the two major intraoperative risks and require sophis-  
 53 ticated skills for hemostasis and suturing.<sup>11</sup> Learning and  
 54 building these skills in the operating room is not ideal.<sup>12</sup> In  
 55 addition, there is a shift in idea on the suitability of devel-  
 56 oping such skills during clinical practice regarding patient  
 57 safety. Training outside of the operating room has proven its  
 58 positive impact on surgical training because it eliminates the  
 59 ethical concerns of learning laparoscopic skills on patients in  
 60 clinical practice.<sup>13,14</sup> A training model mimicking as much  
 61 as possible a real liver organ and simulating intraoperative  
 62 bleeding and bile leakage could greatly enhance the acquisi-  
 63 tion of specific skills in LLR.

64 We therefore hypothesized that an ex situ cadaver liver  
 65 with simulated intraoperative bleeding and bile leakage  
 66 should be anatomic, helpful, and practicable in LLR skill  
 67 training. In the present study, we describe the development  
 68 of the Lap-liver trainer, which combines a continuously pres-  
 69 surized ex situ cadaver liver training model and a customized  
 70 mannequin. We also intended to assess the feasibility of a  
 71 LLR using the Lap-liver trainer and the educational value of  
 72 this training model to provide a more holistic and realistic  
 73 environment for trainees to learn specific skills in LLR.

## 74 Materials and Methods

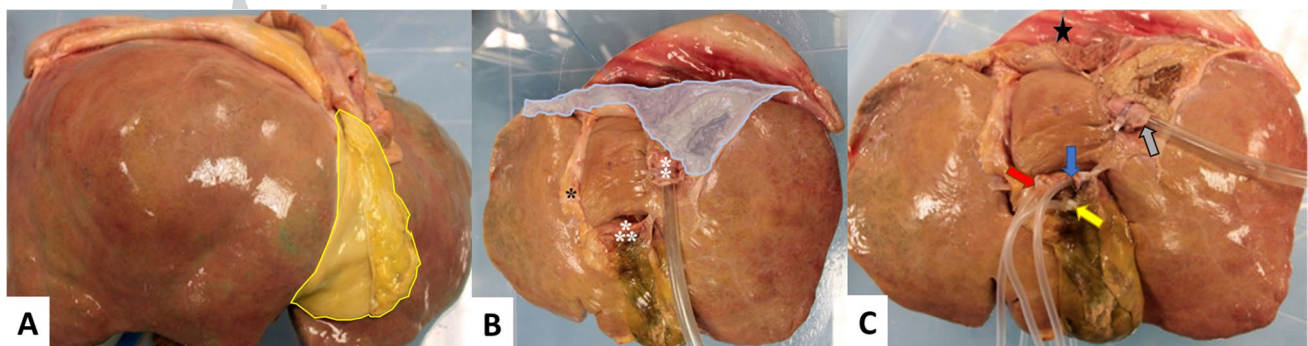
75 Experimentations were performed at the Laboratoire de Bio-  
 76 mécanique Appliquée (LBA) and at the Center for Surgical  
 77 Teaching and Research (CERC), Aix-Marseille Université,  
 78 France. The study was approved by both center's institu-  
 79 tional review board. Written consent was not required.

## Procurement and Preparation of Ex Situ Cadaver Livers

80  
81  
82 The cadaver livers used in this study were from formalin-  
 83 fixed cadavers preserved at the LBA, Aix-Marseille Uni-  
 84 versité, France. Experimental activity on cadavers at the  
 85 LBA is carried out within a strict, rigorous framework that  
 86 respects the rules of ethics, quality, hygiene, and safety  
 87 dictated by the French bioethics law (<https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000043884384>).  
 88

89 The removal of the cadaver liver was standardized. A  
 90 large thoraco-phreno-laparotomy allowed easy access to  
 91 the liver, to its arterial and portal inflow, to the hepatic  
 92 veins and inferior vena cava, to the biliary tract, and to  
 93 its anatomical attachments (Fig. 1A and B). The ex situ  
 94 cadaver liver was thus pressurized by 4 systems of dedi-  
 95 cated tanks and tubing by cannulation of the hepatic  
 96 artery, the portal vein, the common biliary duct, and the  
 97 inferior vena cava to simulate blood and bile supplies  
 98 (Fig. 1C). Arterial pressure was maintained continu-  
 99 ously at 65 mmHg (90 cmH<sub>2</sub>O), comparable to a mean  
 100 arterial pressure of 65 mmHg. Portal and hepatic venous  
 101 pressures were maintained at 15 mmHg (20 cmH<sub>2</sub>O) and  
 102 7.5 mmHg (10 cmH<sub>2</sub>O) respectively.<sup>15</sup> The main bile duct  
 103 was pressurized with continuous pressure of 7.5 mmHg  
 104 (10 cmH<sub>2</sub>O) to simulate possible bile leakage during LLR.  
 105 The hepatic model was pressurized with a fluid that best  
 106 approximated the dynamic viscosity of blood. For this  
 107 purpose, we used a colored preparation combining saline  
 108 (70% saline) and liquid glycerin (30%) to obtain a dynamic  
 109 viscosity of  $3.73 \times 10$  to 3 Pa.S close to that of human  
 110 blood.<sup>16</sup>

111 The first part of the study was to assess the usability of  
 112 the ex situ pressurized cadaver liver as a training model for  
 113 LLR. Two expert surgeons were asked to perform wedge



**Fig. 10** Ex situ cadaver liver preparation. **A** Anterior aspect of the ex situ cadaver liver showing the falciform and round ligaments (yellow area). **B** Posterior aspect of ex situ cadaver liver. The hepatic pedicle (\*\*), the cannulated inferior vena cava (‡), the Arantius ligament (\*), and diaphragmatic attachments of the liver (blue area) are visualized.

**C** The hepatic artery (red arrow), the portal vein (blue arrow), the common biliary duct (yellow arrow), and the inferior vena cava (gray arrow) were cannulated. The supra-diaphragmatic end of the inferior vena cava was closed with running sutures (black star)

114 resections in anterior segments and a LLS to assess the  
115 surgical relevance of the model, the vascular permeability  
116 of the liver, and the efficacy of surgical devices during  
117 liver resections.

## 118 Customized Mannequin Design

119 The customized mannequin should be able to host the ex situ  
120 cadaver liver continuously pressurized model, whatever its  
121 size or anatomy, and to provide laparoscopic conditions of  
122 surgical training. Namely, the mannequin was designed to  
123 maintain in a realistic and anatomical position for human  
124 livers of different dimensions, in order to facilitate both the  
125 reproducibility and scalability of the teaching model. These  
126 included a working space obtained through the pneumop-  
127 eritoneum in the operating room, a realistic insertion and  
128 manipulation of laparoscopic devices through the anterior  
129 abdominal wall, and the caudal approach of the liver model  
130 during LLR.<sup>17,18</sup> For a satisfying educational potential,  
131 trocar placement should be free for each operator, to teach  
132 novice surgeons how to correctly place them. To enhance  
133 the simulation realism, the simulator and the liver should  
134 be placed in an anatomical position (i.e., suspended by its  
135 anatomical attachments, especially to the diaphragm), as in  
136 the operating room where the operating table is placed in a  
137 slightly sloping position.

138 Other specifications had to be met to facilitate the use of  
139 the customized mannequin. It had to be liquid proof to han-  
140 dle pressurization fluids losses and to be properly cleaned.  
141 Pressurization fluid losses and smokes due to electrical or  
142 ultrasonic instruments had to be drained from the custom-  
143 ized mannequin for good visibility during the simulation.

144 The customized mannequin was designed by computer-  
145 aided design on Rhinoceros 6 software (Robert McNeel &  
146 Associates, Barcelona, Spain) based on a numerical finite  
147 element model of the abdominal cavity.

## 148 Prototype Manufacturing

149 The main large prototype parts were manufactured by 3D  
150 printing by the company INITIAL (Chavanod, Haute-Savoie,  
151 France). The smallest parts were 3D printed thanks to the  
152 Markforged® Mark Two printer (Watertown, Massachusetts,  
153 USA) of the LBA.

154 A 10-mm thick RS Pro neoprene rubber plate (Corby,  
155 UK) was used to simulate the skin space of the abdominal  
156 anterior wall.

157 To be able to play with the orientation of the customized  
158 mannequin and to allow the connection of the pressuriza-  
159 tion liquid evacuations, four adjustable feet from Nu-Tech  
160 Engineering (Poole, UK) were used.

## Identification of LLR

162 The Southampton Guidelines advocated that the laparo-  
163 scopic approach should be considered the standard practice  
164 for the lesions of the left lateral and anterior segments at  
165 the beginning of the LC.<sup>5</sup> Indeed, laparoscopy has become  
166 the standard surgical approach for left lateral sectionectomy  
167 (LLS) (i.e., en-bloc resection of segments 2 and 3) due to its  
168 anatomical accessibility.<sup>19–21</sup> The LLS was the LLR chosen  
169 to assess the educational value of the Lap-liver trainer. All  
170 simulated procedures were done at the CERC, Aix-Marseille  
171 Université, France. The CERC has the necessary laparo-  
172 scopic surgical equipment (i.e., grasp, bipolar coagulation,  
173 laparoscopic thunderbeat™ or LigaSure™ devices, liver  
174 retractor, laparoscopic vacuum device, laparoscopic cam-  
175 era, light source, and monitor) to perform a LLR with the  
176 Lap-liver trainer (Supplementary Fig. 1).

## Selection of Participants

178 Fifteen volunteers were recruited through personal commu-  
179 nication as participants of the present study from a teaching  
180 hospital (Hôpital Nord, Aix-Marseille Université, Marseille,  
181 France). Among them, 3 were experts (surgeons experienced  
182 both in laparoscopic and hepatobiliary surgery and with  
183 prior experiences in LLR), 4 were intermediates (young  
184 surgeons who had performed more than 30 laparoscopic  
185 procedures but no LLR independently), and 8 were novices  
186 (postgraduates who had little laparoscopic exposure).

## Educational Value Assessment of the Lap-Liver Trainer

189 Expert surgeons were asked to each perform two LLS with  
190 the Lap-liver trainer. A questionnaire designed to assess lap-  
191 liver trainer was completed by all experts after each proce-  
192 dure. The lap-liver trainer was evaluated using a Likert scale  
193 (1 = strongly disagree/dissatisfied/constrained; 2 = disagree/  
194 dissatisfied/constrained; 3 = indifferent; 4 = agree/satisfied/  
195 not constrained; and 5 = strongly agree/satisfied/absolutely  
196 not constrained) in terms of overall satisfaction, realism of  
197 laparoscopic condition, realism of anatomical condition of  
198 the model, realism of operative tactile properties, realism  
199 of intraoperative bleeding and bile leakage, realism of suc-  
200 cessive procedure steps, and in terms of gestural constraints  
201 encountered during LLS with the lap-liver trainer (Table 1).

202 Prior to LLS with the lap-liver trainer, a standardized  
203 teaching program with video was shown to instruct step by  
204 step all novices and intermediates on techniques of LLR  
205 and specific steps of the surgery<sup>11</sup>. Then, novice and inter-  
206 mediate surgeons were asked to each perform a LLS with  
207 the lap-liver trainer and were supervised by one expert sur-  
208 geon during the procedure. Similarly, the lap-liver trainer

**Table 1** Criteria for evaluations of the lap-liver trainer by expert surgeons

## Section 1. Satisfaction

- 1- Overall, were you satisfied with such a procedure in simulation condition on the lap-liver trainer?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 2- Does the educational value of the lap-liver trainer seem satisfactory to you?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 3- Do you think that the lap-liver trainer has its place in a practical teaching program of laparoscopic liver surgery?  
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree

## Section 2. Realism

- 4- Is the overall realism proposed by the lap-liver trainer satisfactory?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 5- Are the laparoscopic conditions proposed by the lap-liver trainer satisfactory?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 6- Is the pressurized ex situ liver model used by the lap-liver trainer realistic and relevant?  
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 7- Does the positioning of the pressurized ex situ liver model within the lap-liver trainer seem appropriate for the performance of laparoscopic liver surgery?  
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 8- Does the lap-liver trainer allow a realistic and satisfactory laparoscopic mobilization of the anatomical attachments of the left lateral lobe?  
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 9- Is the realization of the parenchymal transection plan on the lap-liver trainer realistic?  
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 10- Is the dissection of the Glissonian pedicle of segments 3 and 2 on the lap-liver trainer realistic?  
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 11- Is the dissection of the left hepatic vein on the lap-liver trainer realistic?  
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 12- Is the bleeding on the Lap-liver trainer, if it has occurred, realistic?  
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 13- Is the leakage of bile on the Lap-liver trainer, if it has occurred, realistic?  
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 14- Is the analysis of the parenchymal transection plan on the Lap-liver trainer at the end of the procedure realistic and satisfactory under laparoscopy conditions?  
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree

## Section 3. Procedure

- 15- Does the implementation and positioning of the trocars on the Lap-liver trainer seem satisfactory and appropriate to perform a left lateral sectionectomy?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 16- Is the available laparoscopic instrumentation suitable for performing a left lateral sectionectomy on the lap-liver trainer?  
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 17- Is the operating view and the positioning of the operative aid satisfactory?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 18- Is the realization of the parenchymal transection plan on the lap-liver trainer satisfactory with the available laparoscopy equipment?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 19- Is the control and section of the Glissonian pedicle of segment 3 and 2 on the lap-liver trainer satisfactory with the available laparoscopy equipment?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 20- Is the control and section of the left hepatic vein on the lap-liver trainer satisfactory with the available laparoscopy equipment?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 21- Is the control of bleeding and/or biliary leakage on the Lap-liver trainer, if it has occurred, satisfactory with the available laparoscopy equipment?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied

## Section 4. Gesture

- 22- Overall, were you constrained in your gestures during the procedure?  
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained



**Table 1** (continued)

- 23- Were you forced into setting up the trocars?  
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 24- Have you been constrained in your vision of the operating field?  
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 25- Have you been constrained in your gestures for the mobilization of the left lateral lobe of its anatomical attachments?  
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 26- Were you constrained in your gestures during parenchymal transection?  
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 27- Have you been constrained in your gestures for the control and section of the vascular structures of the left lateral lobe?  
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained

**Table 2** Criteria for evaluations of the Lap-Liver trainer by residents and novice surgeons

## Section 1. Satisfaction

- 1- Overall, were you satisfied with the directed teaching and such a procedure in simulation condition on the lap-liver trainer?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 2- Has the realization of a laparoscopic left lateral sectionectomy on the lap-liver trainer brought you a benefit for your clinical practice or your learning?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied

## Section 2. Realism

- 3- Is the overall realism proposed by the Lap-liver trainer satisfactory?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 4- Are the laparoscopic conditions proposed by the Lap-liver trainer satisfactory?  
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied

## Section 3. Gesture

- 5- Overall, were you constrained in your actions during the procedure?  
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 6- Were you forced into setting up the trocars?  
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 7- Have you been constrained in your vision of the operating field?  
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 8- Have you been constrained in your gestures for the mobilization of the left lateral lobe of its anatomical attachments?  
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 9- Were you constrained in your gestures during parenchymal transection?  
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 10- Have you been constrained in your gestures for the control and section of the vascular structures of the left lateral lobe?  
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained

209 was evaluated by novice and intermediate surgeons using  
210 a Likert scale in terms of overall satisfaction, realism of  
211 laparoscopic condition, and in terms of gestural constraints  
212 encountered during LLS with the lap-liver trainer (Table 2).

## 213 Results

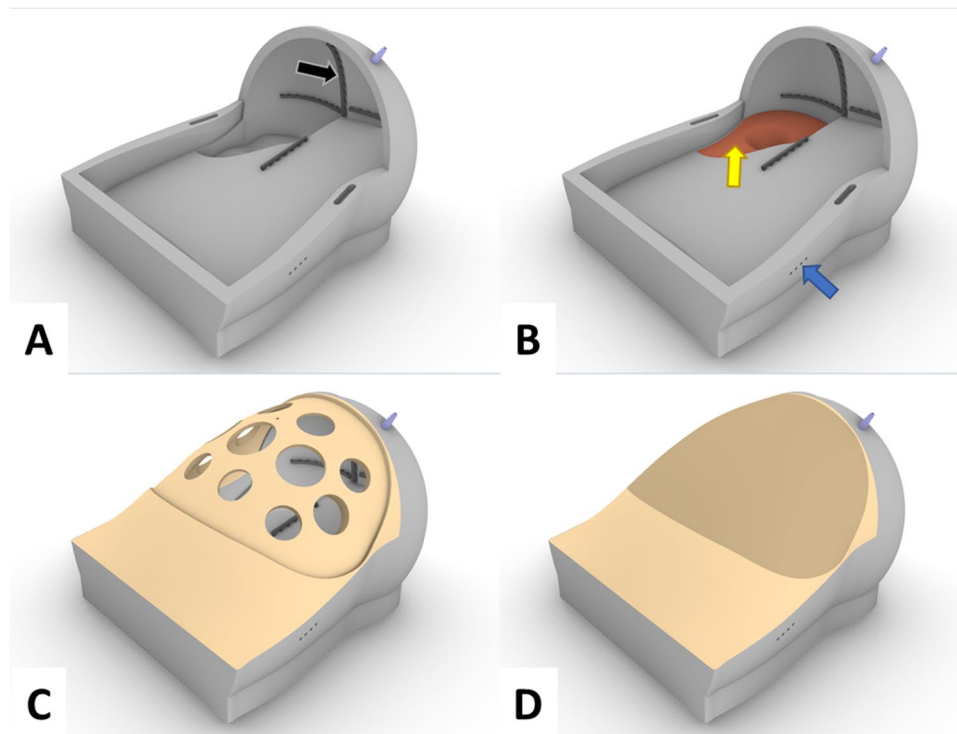
### 214 Usability of the Ex Situ Pressurized Cadaver Liver 215 Model for Surgical Training

216 On a back table, 10 ex situ pressurized cadaver liver models  
217 could be prepared for experimentation. The preparation of  
218 the liver model took an average of 35 min. A wedge resection  
219 of segment 6 and an LLS was done by two expert surgeons

on each liver model (Supplementary Fig. 2). Peripheral and 220  
deep vascular and biliary permeability of the model were 221  
observed for the 10 ex situ pressurized livers. The texture 222  
of the liver parenchyma was judged suitable for dissection, 223  
parenchymal transection, and control of intra-parenchymal 224  
vascular and biliary structures during the different proce- 225  
dures. The laparoscopic instrumentation used allowed con- 226  
trol of the occurrence of bleeding. 227

### Customized Mannequin Conception 228

The customized mannequin consisted of a close laparoscopic 229  
training device. To host the ex situ pressurized cadaver liver 230  
model, the customized mannequin was based on a simpli- 231  
fied reconstruction of the abdominal cavity in laparoscopic 232



**Fig. 2** Customized mannequin was designed by computer-aided design. **A** The base reconstructed, in a simplified way, the posterior abdominal wall and the diaphragm. The Liver model can be suspended by its anatomical attachments thanks to small bridges positioned at the corresponding locations on the base (black arrow). **B** To accommodate any liver size, three retroperitoneal wedges were developed to be placed in the right hypochondrium cavity (yellow area).

Four holes located on the right side allowed the passage of dedicated tubes for cannulation (blue arrow). **C** The cover was designed as a dome to simulate the pneumoperitoneum and to mimic the anterior abdominal wall in laparoscopic conditions. It was pierced with holes designed for the passage of trocars. **D** A recess was designed to receive a flexible neoprene-type material reproducing the skin space of the anterior abdominal wall

233 conditions. It consisted of two parts: a base and a cover  
234 (Fig. 2).

235 The base rested on adjustable feet, allowing to adjust the  
236 customized mannequin positioning. It reconstructed, in a  
237 simplified way, the posterior abdominal wall and the dia-  
238 phragm (Fig. 2A). The latter was designed by a hemisphere  
239 shape. A cavity corresponding to the right hypochondrium  
240 was dug to host the liver, and three funnel-shaped drain holes  
241 for fluids and smoke losses were placed at the lowest points  
242 of the base and at the diaphragm top. The liver model could  
243 be suspended by its anatomical attachments (i.e., falciform,  
244 round, and triangular ligaments) thanks to small bridges  
245 positioned at the corresponding locations on the base. To  
246 accommodate any liver size, three retroperitoneal wedges  
247 were developed to be placed in the right hypochondrium  
248 cavity (Fig. 2B). To pressurize the ex situ liver model, four  
249 holes located on the right side allowed the passage of dedi-  
250 cated tubes for cannulation. The latter could be hooked up  
251 to a bridge to avoid unintentional movement.

252 The cover was developed to mimic the anterior abdominal  
253 wall in laparoscopic conditions (Fig. 2C). Because real pneu-  
254 moperitoneum is difficult to achieve, as it would require the

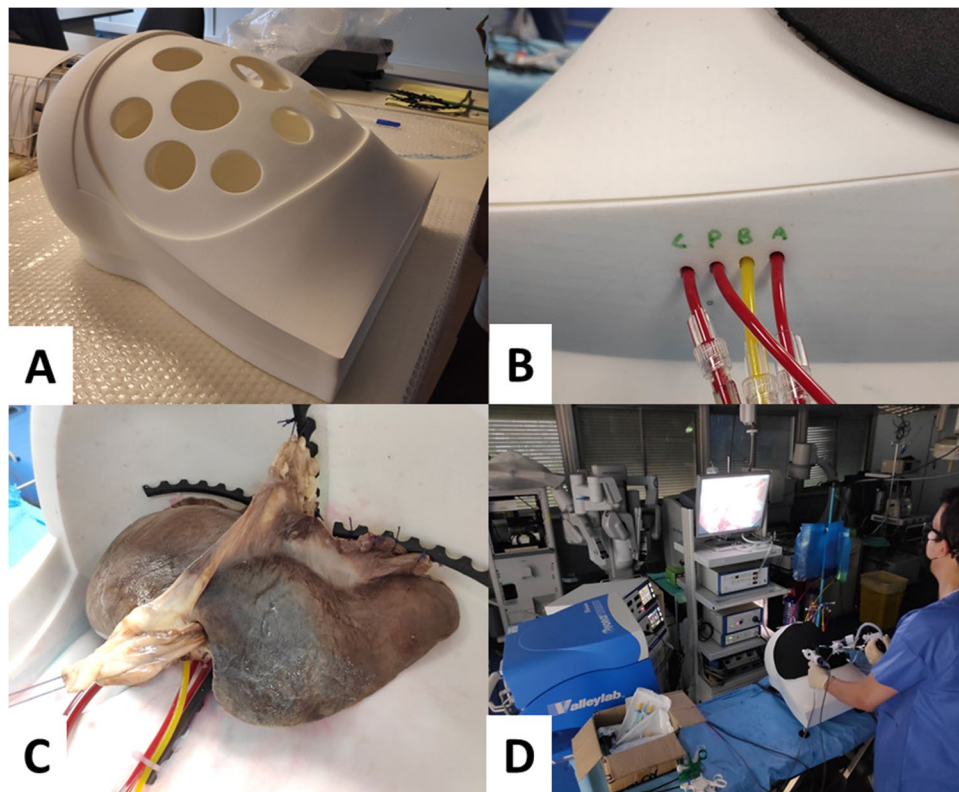
use of a CO<sub>2</sub> insufflator and related instruments, the cover  
255 was designed as a dome to simulate the pneumoperitoneum.  
256 It was pierced with holes designed in a honeycomb pattern,  
257 respecting the triangulation principle, for the passage of  
258 trocars and the free use of laparoscopic devices. The diam-  
259 eters of the holes were determined to avoid any mechanical  
260 stress between the trocars and the cover and between hands.  
261 Another hole, smaller, allows the suspension of the liver  
262 round ligament, as it would be to the umbilicus in humans.  
263 A recess was designed to receive a flexible neoprene-type  
264 material reproducing the skin space of the anterior abdomi-  
265 nal wall (Fig. 2D).  
266

### 267 Prototype Manufacturing

268 The 3D printing technology by powder sintering using poly-  
269 amide PA2200 was chosen for the base and the cover manu-  
270 facturing (Fig. 3A). A waterproofing varnish was applied  
271 afterwards. The material used for the small bridges' manu-  
272 facturing was Onyx, a nylon filled with carbon microfibers.

273 Prototype dimensions were 429 × 417 × 304 mm (height,  
274 width, depth), allowing it to be moved and used easily on a

**Fig. 3** The Lap-liver trainer. **A** Customized mannequin prototype. **B** The 5.2 mm diameter holes on the right side of the base let the dedicated tubes pass perfectly for cannulation. **C** After cannulation, the small bridges easily allowed suspension of the ex situ pressurized cadaver liver with interrupted sutures. **D** A novice surgeon performing a laparoscopic left lateral sectionectomy with the lap-liver trainer



275 surgical training table. The basal simulator proclivity is 15°,  
 276 and adjustable feet could increase or reduce it. The flexible  
 277 neoprene-type material was placed over the cover and held  
 278 in place with a self-adhesive hook and loop tape. Magnets  
 279 placed on both parts of the prototype satisfyingly held the  
 280 base and the cover together.

281 The 5.2 mm diameter holes on the right side of the  
 282 base let the dedicated tubes pass perfectly for cannulation  
 283 (Fig. 3B). Drainage holes for fluids and smoke losses were  
 284 linked to a basin and a suction system respectively. Small  
 285 bridges easily allowed suspension of the ex situ pressurized  
 286 cadaver liver with interrupted sutures (Fig. 3C). Thus, the  
 287 liver was positioned realistically and could be mobilized like  
 288 in the operating room.

289 On the cover, trocar holes had a diameter between 40 and  
 290 80 mm to give the operator freedom for trocar placement and  
 291 to avoid any mechanical stress. The flexible neoprene-type  
 292 material allowed to hold the trocars in place and to learn  
 293 trocar positioning with force feedback.

### 294 Feasibility of a Laparoscopic LLS with the Lap-Liver 295 Trainer and Educational Value

296 Each expert surgeon performed completely two LLS with  
 297 the lap-liver trainer. All the experts gave positive scores  
 298 in their questionnaire answers (Table 3). Expert surgeons  
 299 were highly satisfied of the simulation conditions proposed

by the lap-liver trainer ( $4.80 \pm 0.45$ ), and they all strongly  
 recommended that the lap-liver trainer should be incorporated  
 into a teaching program of laparoscopic liver surgery  
 ( $5.00 \pm 0.0$ ). The experts gave a positive evaluation of the  
 laparoscopic condition and anatomic structures, in that the  
 abdominal cavity had been well reproduced.

Furthermore, experts found that the overall realism proposed  
 by the lap-liver trainer was satisfactory ( $4.60 \pm 0.55$ )  
 with a caudal approach of the liver during simulation.  
 Although haptic feedback was slightly different from operations  
 performed in the operating room, the usage of pressurized  
 cadaver tissues made the experience realistic. Experts  
 highlighted that blood and bile supplies made the surgical  
 view identical to a real procedure (Fig. 4) and that demonstration  
 of bleeding control and bile leakage was analogous  
 to that of real surgery (Supplementary Fig. 3).

A total of 12 participants, including 8 novice and 4 intermediate  
 surgeons, completed the teaching program and performed a  
 LLS with the lap-liver trainer.

Overall, the level of satisfaction was high ( $4.92 \pm 0.29$ ),  
 with 100% of the participants scoring 4/5 or 5/5 on question  
 1 (Table 4). In addition, 100% of the participants found that  
 performing such a procedure under simulation conditions benefited  
 their learning and clinical practice ( $4.92 \pm 0.29$ ). Regarding  
 the realism proposed by the lap-liver trainer, all the participants  
 gave positive scores in their questionnaire answers ( $4.42 \pm 0.51$ ).  
 Finally,

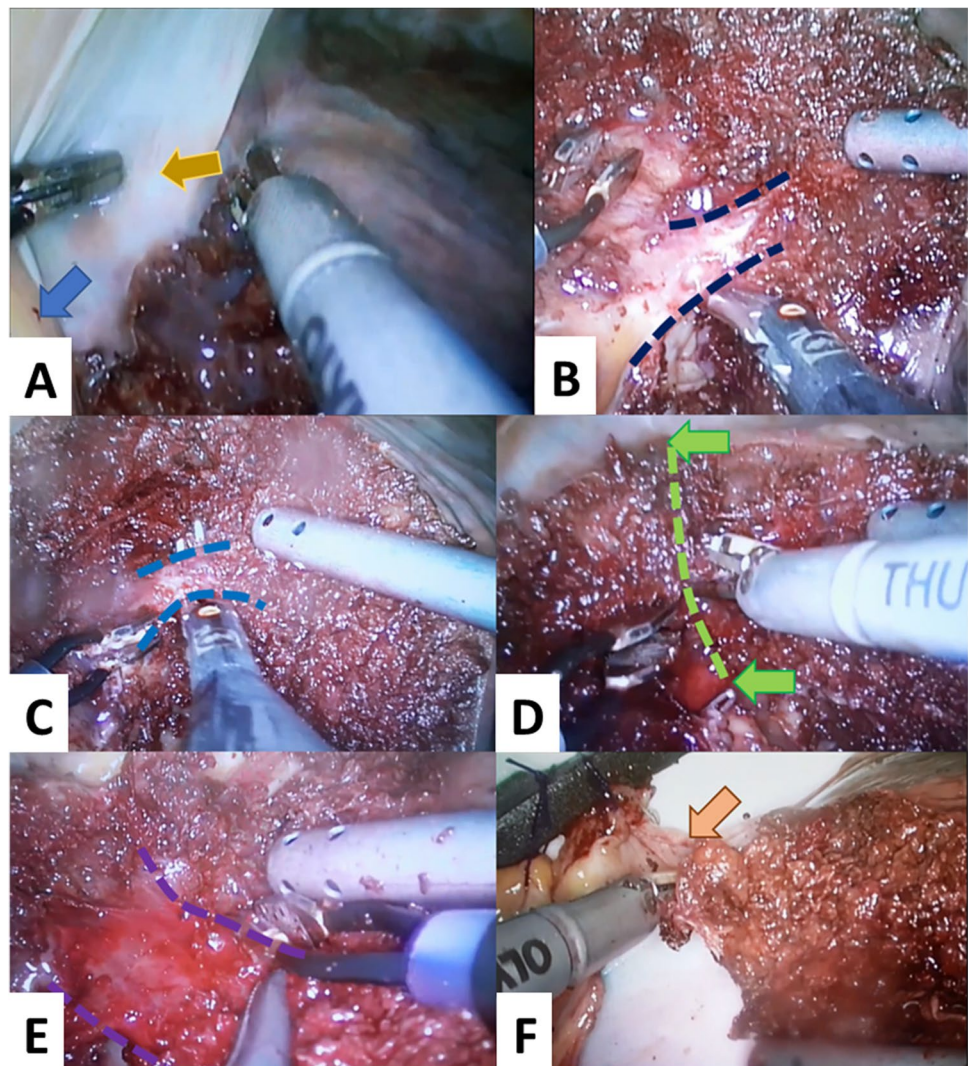
**Table 3** Scores given by experts to the lap-liver trainer on a 5-point Likert scale

Items	Mean $\pm$ SD
Section 1. Satisfaction	
1- Overall, were you satisfied with such a procedure in simulation condition on the Lap-liver trainer?	4.80 $\pm$ 0.45
2- Does the educational value of the Lap-liver trainer seem satisfactory to you?	4.60 $\pm$ 0.55
3- Do you think that the Lap-liver trainer has its place in a practical teaching program of laparoscopic liver surgery?	5.00 $\pm$ 0.0
Section 2. Realism	
4- Is the overall realism proposed by the Lap-liver trainer satisfactory?	4.60 $\pm$ 0.55
5- Are the laparoscopic conditions proposed by the Lap-liver trainer satisfactory?	4.60 $\pm$ 0.55
6- Is the pressurized ex situ liver model used by the Lap-liver trainer realistic and relevant?	4.80 $\pm$ 0.45
7- Does the positioning of the pressurized ex situ liver model within the Lap-liver trainer seem appropriate for the performance of laparoscopic liver surgery?	4.80 $\pm$ 0.45
8- Does the Lap-liver trainer allow a realistic and satisfactory laparoscopic mobilization of the anatomical attachments of the left lateral lobe?	5.00 $\pm$ 0.0
9- Is the realization of the parenchymal transection plan on the Lap-liver trainer realistic?	4.20 $\pm$ 0.45
10- Is the dissection of the hepatic pedicle of segment 3 and 2 on the Lap-liver trainer realistic?	4.00 $\pm$ 0.71
11- Is the dissection of the left hepatic vein on the Lap-liver trainer realistic?	4.40 $\pm$ 0.55
12- Is the bleeding on the Lap-liver trainer, if it has occurred, realistic?	4.20 $\pm$ 0.45
13- Is the leakage of bile on the Lap-liver trainer, if it has occurred, realistic?	4.20 $\pm$ 0.45
14- Is the analysis of the parenchymal transection plan on the Lap-liver trainer at the end of the procedure realistic and satisfactory under laparoscopy conditions?	4.40 $\pm$ 0.55
Section 3. Procedure	
15- Does the implementation and positioning of the trocars on the Lap-liver trainer seem satisfactory and appropriate to perform a left lateral sectionectomy?	4.40 $\pm$ 0.55
16- Is the available laparoscopic instrumentation suitable for performing a left lateral sectionectomy on the Lap-liver trainer?	4.40 $\pm$ 0.55
17- Is the operating view and the positioning of the operative aid satisfactory?	4.40 $\pm$ 0.55
18- Is the realization of the parenchymal transection plan on the Lap-liver trainer satisfactory with the available laparoscopy equipment?	4.20 $\pm$ 0.45
19- Is the control and section of the segment 3 and 2 hepatic pedicles on the Lap-liver trainer satisfactory with the available laparoscopy equipment?	4.60 $\pm$ 0.55
20- Is the control and section of the left hepatic vein on the Lap-liver trainer satisfactory with the available laparoscopy equipment?	4.40 $\pm$ 0.55
21- Is the control of bleeding and/or biliary leakage on the Lap-liver trainer, if it has occurred, satisfactory with the available laparoscopy equipment?	4.80 $\pm$ 0.45
Section 4. Gesture	
22- Overall, were you constrained in your gestures during the procedure?	4.40 $\pm$ 0.55
23- Were you forced into setting up the trocars?	4.80 $\pm$ 0.45
24- Have you been constrained in your vision of the operating field?	4.40 $\pm$ 0.45
25- Have you been constrained in your gestures for the mobilization of the left lateral lobe of its anatomical attachments?	4.60 $\pm$ 0.55
26- Were you constrained in your gestures during parenchymal transection?	4.80 $\pm$ 0.45
27- Have you been constrained in your gestures for the control and section of the vascular structures of the left lateral lobe?	4.00 $\pm$ 1.00

327 concerning the gestures and possible constraints encountered during the simulation, none of the participants were 328  
 329 constrained in the placement of the trocars (4.58  $\pm$  0.51) 330  
 331 and the vision of the operating field (4.67  $\pm$  0.49). Two 332  
 333 of the novice surgeons were constrained at the end of the 334  
 335 parenchymal transection as well as for the dissection and 336  
 336 control of the left hepatic vein. The macroscopic multinodular cirrhotic and fibrous aspect of the two liver models on which the procedure was performed explains the exposure difficulties encountered by these two participants.

At the end of the teaching program and the simulation, 337  
 participants expressed the wish to be able to repeat this 338  
 experience to become more familiar with this approach 339  
 in liver surgery. All emphasized the value of this training 340  
 outside the operating room. Moreover, they highlighted the 341  
 way that it allowed them to become aware of the anatomical 342  
 proximity of the vascular elements of the liver and of 343  
 their orientation in space. 344

**Fig. 4** Laparoscopic left lateral sectionectomy with the Lap-liver trainer. **A** The parenchymal transection plan was begun at the left side of the round (blue arrow) and falciform (yellow arrow) ligaments. **B** Dissection and control of the Glissonian pedicle of segment 3 (dark blue lines). **C** Dissection and control of the Glissonian pedicle of segment 2 (light blue lines). **D** The parenchymal transection plan continued along the falciform and Arantius ligaments (green line and arrows). **E** Dissection and control of the left hepatic vein (purple lines). **F** Final mobilization of the left lateral lobe (orange arrow)



**Table 4** Scores given by residents and novice surgeons to the Lap-liver trainer on a 5-point Likert scale

Items	Mean $\pm$ SD
<b>Section 1. Satisfaction</b>	
1- Overall, were you satisfied with the directed teaching and such a procedure in simulation condition on the Lap-liver trainer?	4.92 $\pm$ 0.29
2- Has the realization of a laparoscopic left lateral sectionectomy on the Lap-liver trainer brought you a benefit for your clinical practice or your learning?	4.92 $\pm$ 0.29
<b>Section 2. Realism</b>	
3- Is the overall realism proposed by the Lap-liver trainer satisfactory?	4.42 $\pm$ 0.51
4- Are the laparoscopic conditions proposed by the Lap-liver trainer satisfactory?	4.42 $\pm$ 0.51
<b>Section 3. Gesture</b>	
5- Overall, were you constrained in your actions during the procedure?	4.33 $\pm$ 0.49
6- Were you forced into setting up the trocars?	4.58 $\pm$ 0.51
7- Have you been constrained in your vision of the operating field?	4.67 $\pm$ 0.49
8- Have you been constrained in your gestures for the mobilization of the left lateral lobe of its anatomical attachments?	4.50 $\pm$ 0.52
9- Were you constrained in your gestures during parenchymal transection?	4.33 $\pm$ 0.98
10- Have you been constrained in your gestures for the control and section of the vascular structures of the left lateral lobe?	4.25 $\pm$ 0.87

## Discussion

Laparoscopic liver surgery has a steep LC, and safe implementation of it requires stepwise training.<sup>6–8</sup> Competency in minor LLR is acquired after 15 to 60 cases, whereas 20 to 60 cases are needed to reach proficiency in major LLR, provided proficiency has been already reached for minor LLR.<sup>5,8</sup> However, LC is a “moving target,” where, on the one hand, surgeons take on more difficult cases with increasing experience, and on the other hand, the LC may change from the self-taught pioneer to the master/apprentice timeline. This LC could be dramatically reduced with specific training and increased exposure of trainees to LLR.<sup>7</sup> Indeed, the Southampton consensus guideline recommends fellowships in high-volume centers, proctored programs, and courses to facilitate training.<sup>5</sup>

This study presents a novel innovation using *ex situ* cadaver liver continually pressurized in a customized mannequin. The lap-liver trainer uses several sources to create a more holistic and realistic clinical scenario for laparoscopic liver surgery education at the beginning of the LC.<sup>5</sup> Haptic feedback is an essential part of laparoscopic training.<sup>22,23</sup> In our study, most of the participants spoke highly of the system, regarding it as a new, effective laparoscopic liver training model and considering the real tactile feedback to be one of the most attractive features. Furthermore, the caudal approach of the liver<sup>17,18</sup> and specific events of LLR were successfully demonstrated including intraprocedural bleeding and bile leakage which were unattainable in other training models like human cadaver, conventional training simulators, or virtual reality. In addition, in comparison to animal models, the lap-liver trainer is free from specific logistic and ethical demands for managing animals and is easy to transport. Our system was patented under application number FR2200286 on 2022/01/14. The next step for us is to find a partnership with a manufacturer to disseminate our model in France first, then possibly internationally.

Human cadaveric livers are harvested from bodies donated for medical research that are used for other research purposes in the meantime. Hence, the mean cost for a cadaveric liver can only be estimated, around 1000€, and their availability relies on body donation regulatory aspects and necessitates the facilities of an anatomy lab. When it comes to the manufacturing of our model, its entire cost is estimated at around 3431€. Moreover, liver collection from bodies donated for medical research constitutes a potential educational session in itself. As for LLR, apart from LLS, only wedge resection of the anterior segments (WRAS) has been taught to novices with this model. Indeed, until now, the purpose was to train novices in laparoscopic liver surgery. Forthcoming studies should assess our model for more complex LLR, such as right hepatic lobectomy.

The rapid expansion and acceptance of laparoscopic surgery have increased the demand of laparoscopic training for advanced surgeries. Many new techniques for laparoscopic training have been explored and have demonstrated the positive impact of simulation on technical skills for basic laparoscopic procedures.<sup>24–28</sup> Moreover, simulation-based training programs have shown benefits in shortening the LC of young surgeons and reducing the number of adverse events in the operating room.<sup>29,30</sup> However, simulation for complex laparoscopic procedures has been assessed to a lesser extent.<sup>8,31</sup> These procedures are associated with a longer LC and are not easily accessible by young surgeons. In hepatobiliary surgery, the average number of hepatic resections performed by postgraduates at the completion of their general surgery training is estimated to be five cases (range 0–20), which are predominantly open surgery.<sup>32,33</sup> A training model mimicking as much as possible a real organ and simulating intraoperative bleeding and bile leakage could greatly enhance the acquisition of specific skills in LLR.

Systematic reviews on laparoscopic training curriculums found that the use of live animal models or *ex vivo* simulators was preferred because other modalities cannot realistically reproduce the specific events.<sup>31,34–38</sup> In LLR, the main training models used were live animal models, *ex vivo* simulators, and human cadavers.<sup>8</sup> LLR requires surgeons to be trained in managing hemostasis and bile leakage control during parenchymal transection. Recently, efforts have been made to improve the experience of *ex vivo* simulators to overcome organizational constraints rendered by animal-based training curriculums.<sup>38–41</sup> Red fluid<sup>14,38,41</sup> or porcine blood<sup>40</sup> was used to simulate bleeding control during LLR, but data regarding bile leakage simulation are lacking. However, bile leakage is a specific event in LLR that requires special attention during parenchymal transection plan assessment at the end of the procedure to optimize patient outcomes.<sup>11</sup> Moreover, *ex vivo* simulator models using animal organs demonstrate one crucial drawback: animal organs cannot resemble human anatomy in its entirety which is necessary in advanced surgery to identify anatomical landmarks.

Our augmented reality simulator combines a continuously pressurized *ex situ* cadaver liver training model and a customized mannequin to improve laparoscopic surgical skills and to help participants to climb the inherent LC of LLR in a more realistic environment without the restrictions of anatomical differences, exorbitant expenses, and ethical issues of animal models. Our study showed that our system can be reproducibly used in laparoscopic training and that wedge resection and LLS are feasible with the lap-liver trainer. The educational value of the lap-liver trainer was highlighted by all participants and provides a more holistic and realistic environment for trainees to learn specific skills in both laparoscopy surgery and LLR. Most importantly,

449 participants can improve their ability to deal with unex-  
 450 pected events intraoperatively using the lap-liver trainer, as it  
 451 is currently unattainable in other inanimate training models.  
 452 Specific events (such as bleeding and bile leakage) initiated  
 453 during simulation serves to further refine the scenarios and  
 454 techniques involved to optimize patient outcome in clinical  
 455 practice. In addition, our system can be used in an open liver  
 456 resection training program thanks to the removable capaci-  
 457 ty of the customized mannequin's cover. In case of ethical  
 458 restrictions on the use of cadaver organs, an animal liver can  
 459 be used for simulation.

460 Despite the potential advantages of the lap-liver trainer  
 461 and the contributions of our study, there are some limita-  
 462 tions. First, anatomical features around the liver such as dia-  
 463 phragmatic movements cannot be reproduced completely.  
 464 Second, the macroscopic aspect of the cadaver liver is dif-  
 465 ficult to predict before procurement and could impair the  
 466 reproducibility of LLR simulation between participants.  
 467 Before training, the procurement and preparation of cadaver  
 468 livers were standardized. Some techniques relevant to liver  
 469 transplantation could involve a specific transplantation train-  
 470 ing program and should benefit young surgeons. Third, the  
 471 study's aim was to assess the feasibility of a LLR on the  
 472 lap-liver trainer and its educational value but did not pro-  
 473 vide a robust evaluation of trainees' skill acquisition. In this  
 474 prospective and the will to determine objective data related  
 475 to the acquisition of skills, the lap-liver trainer seems to be  
 476 a suitable platform for the motion analysis of psychomo-  
 477 tor skills in LLR. To recognize and assess each instrument  
 478 individually irrespective of instrument exchanges, which  
 479 allows the characterization of the motions of multiple surgi-  
 480 cal instruments simultaneously in complex training tasks, it  
 481 seems better than basic procedures data to digitize the level  
 482 of surgical competency and to provide a clear feedback of  
 483 motion parameters to trainees.<sup>42</sup> Finally, for now, our model  
 484 has only been developed to host a liver. Other organs could  
 485 be implemented in this simulator in the future, provided that  
 486 the same method is used to design its anatomical attaches  
 487 and to prove its educational value.

488 In summary, the lap-liver trainer developed in the pre-  
 489 sent study could provide better opportunities for trainees to  
 490 acquire and practice LLR skills in a more realistic environ-  
 491 ment. Most importantly, trainees can improve their ability  
 492 to deal with unexpected specific events related to LLR. The  
 493 lap-liver trainer is a feasible and effective training system  
 494 and could be used efficiently to improve skill teaching and  
 495 learning in laparoscopic liver surgery. We are currently  
 496 working to improve our novel system and for a better under-  
 497 standing of motion parameters of psychomotor skills related  
 498 to the inherent LC. Furthermore, a subsequent step in our  
 499 research will be to demonstrate improvement following a  
 500 training session on the lap-liver trainer in the junior surgeons  
 501 and transfer of skills in the operating room setting.

**Supplementary Information** The online version contains supplemen- 502  
 tary material available at <https://doi.org/10.1007/s11605-022-05566-9>. 503

**Author Contribution** Pierre-Guillaume Champavir: Conception 504  
 and design of the work and acquisition of data. Drafted and revised 505  
 the work. Final approval of the version to be published. Agreed to 506  
 be accountable for all aspects of the work in ensuring that questions 507  
 related to the accuracy or integrity of any part of the work are appro- 508  
 priately investigated and resolved. 509

Laura Beyer-Berjot: Conception and design of the work, analysis, 510  
 and interpretation of data. Drafted and revised the work. Final approval 511  
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 of the work in ensuring that questions related to the accuracy or integ- 513  
 rity of any part of the work are appropriately investigated and resolved. 514

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 be accountable for all aspects of the work in ensuring that questions 517  
 related to the accuracy or integrity of any part of the work are appro- 518  
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 the accuracy or integrity of any part of the work are appropriately 523  
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 all aspects of the work in ensuring that questions related to the accuracy 527  
 or integrity of any part of the work are appropriately investigated and 528  
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 related to the accuracy or integrity of any part of the work are appro- 533  
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David Jérémie Birnbaum: Conception and design of the work, 535  
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Théophile Guilbaud: Conception and design of the work, analysis, 540  
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 rity of any part of the work are appropriately investigated and resolved. 544

**Declarations** 545

The present liver training model named lap-liver trainer was patented 546  
 under application number FR2200286 on 2022/01/14. 547

**Competing Interests** The authors declare no competing interests. 548

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