

Basic Study

Miniature magnetically anchored and controlled camera system for trocar-less laparoscopy

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Author contributions: Dong DH, Wu RQ and Lv Y conceived and designed the experiments; Dong DH contributed to miniature magnetically anchored and controlled camera system supplement; Dong DH, Zhu HY, Luo Y, Zhang HK and Xue F perform the surgery; Dong DH and Xiang JX collected data; Xiang JX analyzed tissue sample; Dong DH, Wu RQ and Lv Y contributed to manuscript writing.

Supported by National Natural Science Foundation of China (Major Instrumental Program), No. 81127005; and the Science and Technology Innovation Project of Shaanxi Province, China, No. S2016TNGY0119.

Institutional review board statement: The entire study was carried out in strict accordance with protocols approved by the Ethics Committee of the First Affiliated Hospital of Xi'an Jiaotong University (Approval No. 2016-55).

Institutional animal care and use committee statement: All procedures involving animals were reviewed and approved by the Institutional Animal Care and Use Committee of the Experimental Animal Center, School of Medicine, Xi'an Jiaotong University, and performed according to the Guidelines for Animal Experimentation of Xi'an Jiaotong University (SYXK-SHAN 2014-003) and the Guide for the Care and Use of Laboratory Animals Published by the US National Institutes of Health.

Conflict-of-interest statement: The authors report no conflicts of interest related to this study.

Data sharing statement: The technical appendix, statistical code, and dataset are available from the corresponding author at luyi169@126.com. Participants gave informed consent for data sharing.

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Manuscript source: Unsolicited manuscript

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Received: November 28, 2016
Peer-review started: December 1, 2016
First decision: January 10, 2017
Revised: January 17, 2017
Accepted: February 17, 2017
Article in press: February 17, 2017
Published online: March 28, 2017

Abstract**AIM**

To design a miniature magnetically anchored and controlled camera system to reduce the number of trocars which are required for laparoscopy.

METHODS

The system consists of a miniature magnetically anchored camera with a 30° downward angle, an external magnetically anchored unit, and a vision output device. The camera weighs 12 g, measures $\Phi 10.5 \text{ mm} \times 55 \text{ mm}$ and has two magnets, a vision model, a light source, and a metal hexagonal nut. To test the prototype, the camera was inserted through a 12-mm conventional trocar in an *ex vivo* real liver laparoscopic training system. A trocar-less laparoscopic cholecystectomy was performed 6 times using a 12-mm

and a 5-mm conventional trocar. In addition, the same procedure was performed in four canine models.

RESULTS

Both procedures were successfully performed using only two conventional laparoscopic trocars. The cholecystectomy was completed without any major complication in 42 min (38-45 min) *in vitro* and in 50 min (45-53 min) using an animal model. This camera was anchored and controlled by an external unit magnetically anchored on the abdominal wall. The camera could generate excellent image, with no instrument collisions.

CONCLUSION

The camera system we designed provides excellent optics and can be easily maneuvered. The number of conventional trocars is reduced without adding technical difficulties.

Key words: Trocar-less laparoscopy; Magnetically anchored and controlled camera; Minimally invasive surgery

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Core tip: This study introduced a miniature magnetically anchored and controlled camera system. The miniature magnetically anchored camera is among the smallest size, and it can pass through a conventional 12-mm trocar. Magnetically anchored instruments are positioned intra-abdominally and stabilized through a coupling force to external magnets on the abdominal skin. In this way, the instruments do not share space with the trocar during surgery. By using this camera system, the number of trocars required for conventional laparoscopy could be reduced without adding technical difficulties.

Dong DH, Zhu HY, Luo Y, Zhang HK, Xiang JX, Xue F, Wu RQ, Lv Y. Miniature magnetically anchored and controlled camera system for trocar-less laparoscopy. *World J Gastroenterol* 2017; 23(12): 2168-2174 Available from: URL: <http://www.wjgnet.com/1007-9327/full/v23/i12/2168.htm> DOI: <http://dx.doi.org/10.3748/wjg.v23.i12.2168>

INTRODUCTION

Laparoscopic surgery has significantly evolved as a conventional surgical procedure for smaller incisions and faster recovery since its emergence in the late 1980s^[1,2]. It is a standard alternative practice to the traditional open operation in cholecystectomy, nephrectomy, and other procedures^[3-5]. Conventional laparoscopic surgery requires 3 or more 5-10 mm trocars. The number of trocars is associated with postoperative pain, cosmesis, and the risk of bleeding

or organ damage^[6,7]. Minimizing the invasiveness of surgery is a fundamental driving force for surgeons and patients seeking new procedures with fewer trocars.

Single-site laparoscopy (SSL), represented by laparoendoscopic single-site (LESS) surgery and natural orifice transluminal endoscopic surgery, has recently gained more interest among minimally invasive laparoscopic surgeons^[8-10]. SSL is superior to conventional multiport laparoscopy for cosmesis because the new procedure relies on a single port site that is limited to an inconspicuous position. In theory, the number of trocars is reduced in SSL. However, in reality, the incision length of the single port in SSL is much greater than that used in conventional multiport laparoscopy (approximately 25-30 mm vs 5-12 mm), which increases the risk of post-operative inflammation^[11,12]. Moreover, because all of the instruments are restricted to a single trocar, SSL is also technically demanding, and the technical challenges are intrinsically linked to loss of triangulation and instrument conflicts^[13-15]. As a result, the widespread adoption of SSL is limited.

In the hands of laparoscopic surgeons, laparoscopic surgery has relied on fewer conventional trocars and multiple instruments constrained in a single trocar to overcome the challenges faced by SSL. Therefore, our team attempted to perform trocar-less laparoscopy by developing a miniature magnetically anchored camera that can pass through a conventional laparoscopic trocar. The magnetically anchored and controlled instruments were first introduced by Cadeddu in 2007 and were called magnetically anchored and guided systems^[16]. Such instruments are positioned intra-abdominally and stabilized through a coupling force to external magnets on the abdominal skin. In this way, the instruments do not share space with the trocar during surgery.

In the present study, we present the initial development of an MMAC weighing 12 g and measuring $\phi 10.5 \text{ mm} \times 55 \text{ mm}$. It has a 30° downward angle and can be inserted into the abdomen through a conventional 12 mm trocar. By using this miniature camera, the number of conventional trocars is reduced without adding more demanding techniques. This camera provides excellent optics of the surgical space and can easily be maneuvered in the abdomen. With this camera, a trocar-less laparoscopic cholecystectomy using two conventional trocars was performed in an animal model.

MATERIALS AND METHODS

System composition

Similar to our previous work, the miniature magnetically anchored and controlled camera system consists of an MMAC with a 30° downward angle, an external magnetically anchored unit, and a vision output device.

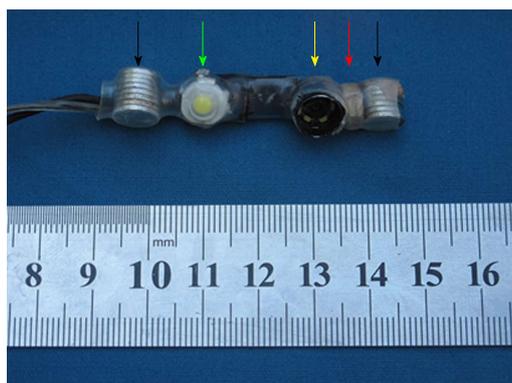


Figure 1 The miniature magnetically anchored camera with a 30° downward angle. It consists of inner magnets (black arrow), a light source (green arrow), a vision model (yellow arrow), and a metal hexagonal nut (red arrow).

The camera is the internal component and is inserted into the abdominal cavity through a conventional trocar. Its position in the abdomen is controlled by the external magnetically anchored unit *via* a magnetic force through the abdominal wall. On the basis of previous work, the external magnetically anchored unit is composed of 15 magnets (60 mm × 10 mm × 4 mm, NdFeB N50 permanent magnet). The external magnetically anchored unit regulates the magnetic force according to abdominal wall thickness. The vision output device displays an image captured by the miniature camera and supports power for the system.

Miniature magnetically anchored camera

The size of the camera is the most important part for trocar-less laparoscopy surgery. The MMAC measures $\phi 10.5$ mm × 55 mm and is composed of two magnets ($\phi 8$ mm × 7 mm, NdFeB N50 permanent magnet), a vision model, a metal hexagonal nut, and a light source (Figure 1). The vision model is produced by Audenson Technology Corporation (Shenzhen, China) and consists of a 1/5" 1024 × 768 pixel color CMOS camera and a 720-line TV contained in an 8 mm × 6 mm × 2.5 mm cuboid. The focal length of the camera lens is 6-8 cm. The metal hexagonal nut is fixed on the lateral surface of the vision model. The nut is used to achieve the 30° downward angle of the vision model. A 3 W hemispherical light-emitting diode (LED) (Juli Industrial Development Corporation, Shenzhen, China) is the light source. It provides high-color temperature (6000-6500 K) and luminous flux (200-220 LM) equal to that of xenon lamps used in conventional laparoscopy. The MMAC weighs approximately 12 g.

In vitro test

A laparoscopy training platform, called the *ex vivo* real-liver laparoscopic training system, was used as the bench test in this study (Figure 2A). It was composed of a special dummy and a laparoscope. The abdominal wall of the dummy was made of a material

and a nonmagnetic metal support that mimics the elasticity and shape of a human pneumoperitoneum. A partial porcine liver was placed in the dummy for the laparoscopic cholecystectomy model.

In the bench test, a laparoscope was inserted through an umbilical trocar when necessary to visualize the camera performance. The trocar-less laparoscopic cholecystectomy was performed using a 12-mm trocar and a 5-mm conventional trocar. The 12-mm trocar was placed below the xiphoid, and the 5-mm trocar was placed at the right mid-clavicular line. The MMAC was inserted into the abdomen through the 12-mm conventional trocar and then coupled to the external magnetically anchored unit by gently depressing it. The camera was maneuvered into position using the external magnet. The conventional laparoscopic instruments (Hangzhou Kangji Medical Instrument Co., Ltd., Zhejiang, China) were inserted through the 12- and 5-mm trocars as needed during the cholecystectomy. The gallbladder was freed from its hepatic attachments, and the cystic duct was transected. After completing the procedure, the gallbladder was extracted from the xiphoid defect. The camera was removed by pulling cables after decoupling the external magnet. The procedure was performed 6 times. The performance of the MMAC was evaluated by manipulation, operative time, and the achievement of critical views.

In vivo test

After obtaining approval from the institutional animal care and use committee of our institution, the trocar-less laparoscopic cholecystectomy was performed in 4 male canines weighing a mean of 15 kg. The surgical instruments and techniques used were the same as for the *in vitro* test. Additionally, the abdominal cavity was insufflated with carbon dioxide to a pressure of 15 mm Hg. The surgeon manipulated the external magnet during the procedure to adjust the view of the MMAC. After the operation, the surgeon closed the incision with an interrupted absorbable suture. In addition to the indicators mentioned above, estimated blood loss, adverse events, and biosafety were used to assess the camera. Biosafety was evaluated by peritoneal specimens in the active area of the magnetic camera. They were harvested after the operation and examined using HE staining.

RESULTS

The trocar-less laparoscopic cholecystectomy using 12- and 5-mm conventional trocars was successfully performed *in vitro* in all 6 cases. The MMAC easily passed through the 12-mm conventional trocar, and only thin wires for powering and imaging were left in the trocar, which provided sufficient space for conventional laparoscopic instruments and did not cause instrument conflicts. The camera was anchored and controlled well by the external magnetically

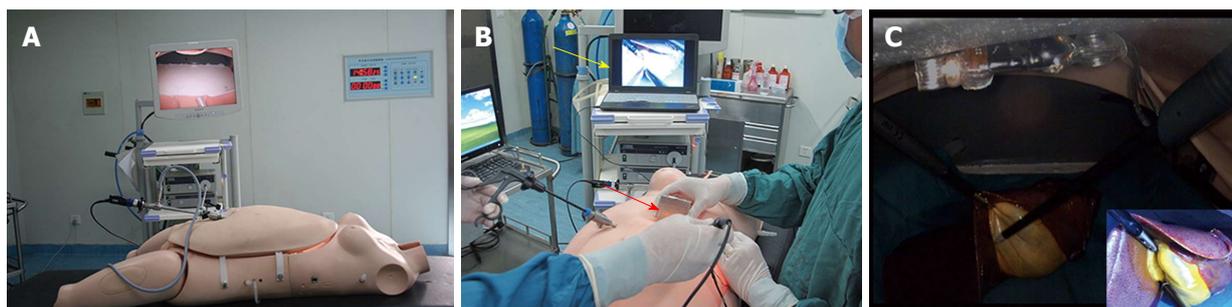


Figure 2 *In vitro* test. A: The bench test consists of a special mannequin and a laparoscope; B: External view image for trocar-less laparoscopic cholecystectomy *in vitro*: the external magnetically anchored unit (red arrow) and the vision output device (yellow arrow); C: Critical view image for trocar-less laparoscopic cholecystectomy *in vitro* (the picture-in-picture view is the image captured by the miniature magnetically anchored camera with its own light source).

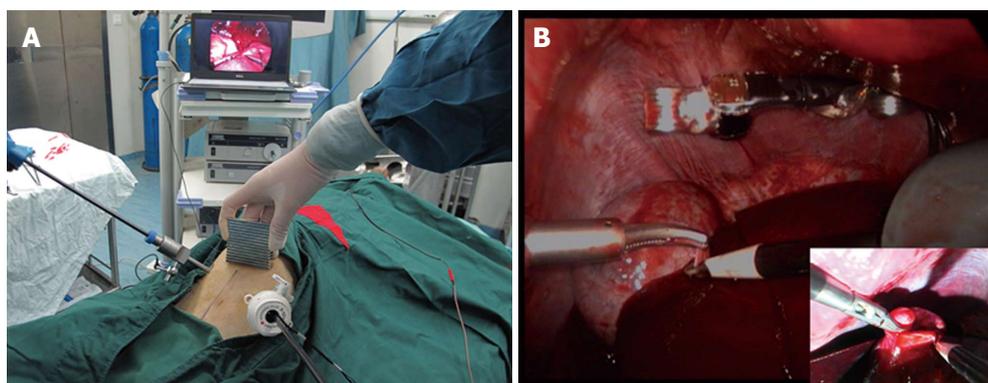


Figure 3 *In vivo* test. A: External view image for trocar-less laparoscopic cholecystectomy in a canine model; B: Critical view image for trocar-less laparoscopic cholecystectomy in a canine model (the picture-in-picture view is the image captured by the miniature magnetically anchored camera with its own light source).

anchored unit on the dummy skin surface. Decoupling did not occur during the operation, even when the wires were used to pull out the camera. The camera's 30° downward angle enabled critical views of the procedure. The image generated by the camera was excellent because it was equipped with the high-color temperature LED and the focal length of the camera lens was appropriate for the height of the pneumoperitoneum. The mean operative time was 42 min (38-45 min) (Figure 2B and C).

After confirming the camera's feasibility for trocar-less laparoscopic cholecystectomy *in vitro*, similar procedures were also completed in 4 canines without adverse events, such as bile spillage. The mean estimated blood loss was 6 mL (3-10 mL). In the canine model, the camera was also inserted into the abdomen through a 12-mm conventional trocar and was easily "pulled up" to the thin abdominal wall (approximately 1 cm according to the preoperative ultrasound). The camera was manipulated into position by smoothly sliding the external magnetically anchored unit. Because of the 30° downward angle, the critical views were achieved well, and the image quality was as excellent as it was *in vitro*, with high resolution and sufficient lighting (Figure 3). Approximately once per operation, the camera had to be pulled out by the wires to clean fog off of the lens. There were no instrument collisions. The mean operative time was 50

min (45-53 min) *in vivo*. Hematoxylin-eosin staining showed no significant tissue damage at the muscle layer in the camera's active area, thus supporting its biosafety *in vivo* (Figure 4).

DISCUSSION

SSL was once considered a promising alternative approach to conventional laparoscopic surgery^[9]. Unfortunately, all instruments were constrained in a single port, which was technically demanding, and the incision length impeded the widespread adoption of SSL for laparoscopic surgery^[11-15]. The new approach must maintain the ergonomics of traditional laparoscopy and reduce the incision length. We have therefore investigated trocar-less laparoscopy, which relies on conventional laparoscopic trocars. For example, a laparoscopic cholecystectomy was performed using 2 conventional trocars in this study. Because trocar-less laparoscopy is predicated on conventional trocars, the surgical instruments for the new approach, such as the retractor and cautery device, are the same as those used for conventional laparoscopy. Trocar-less laparoscopy addresses the dilemma of SSL while offering additional benefits. It saves money and training time compared with SSL, which encourages its clinical adoption.

The new instrument's special positioning technology

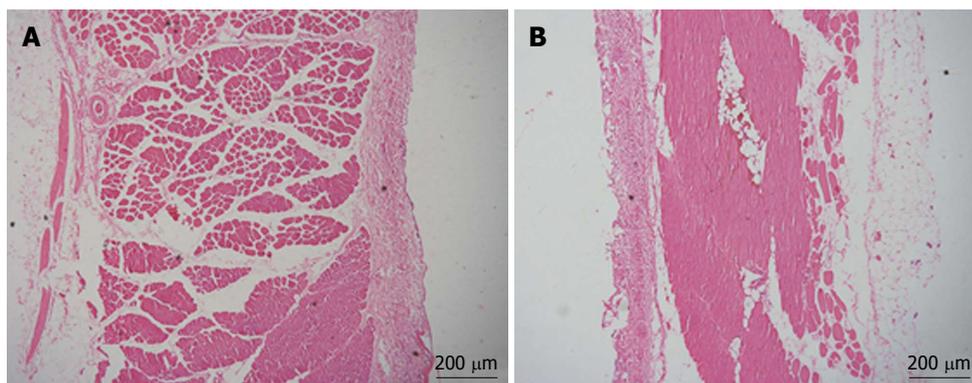


Figure 4 Pathologic assessment of abdominal wall. A: Hematoxylin-eosin (HE) staining of normal area; B: HE staining of active area.

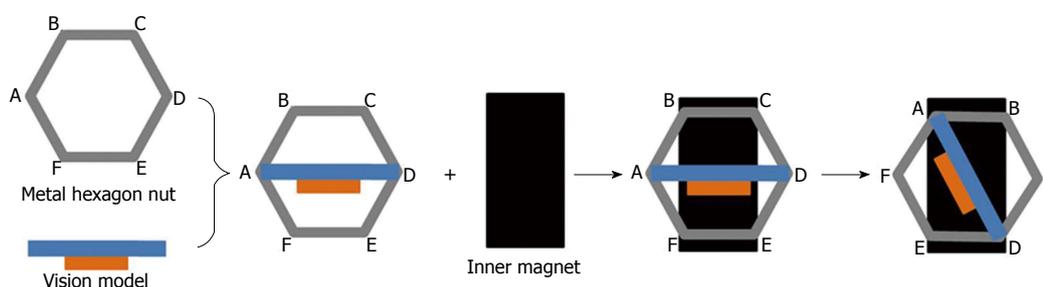


Figure 5 The method of achieving a 30° downward angle using the miniature magnetically anchored camera.

is the key to trocar-less laparoscopy and should address the following requirements: First, the new instrument should not occupy space in the trocar during surgery to avoid instrument conflicts. Second, the new instrument should use the entire insufflated abdomen to accommodate the required changes in position. Many positioning technologies have been attempted in trocar-less surgery, such as vacuum positioning, needle anchoring, and magnetic anchoring^[16-18]. Magnetically anchoring is the most promising positioning technology because the coupling force is generated by internal and outer components without direct contact, thus allowing the instrument to be free from the trocar and enabling the full use of the insufflated abdomen. Other positioning technologies have deficiencies in reliable anchoring and convenient guidance.

Surgeons who perform minimally invasive laparoscopic procedures have significant interests in developing magnetically anchored and controlled instruments. Numerous instruments have been developed, such as cameras, retractors, dissectors, and even surgical robots^[19-25]. Most of these instruments are above $\Phi 20$ mm because they aim to address instrument collisions in SSL, which are not suitable for trocar-less surgery that relies on conventional trocars. Our team has strongly advocated this promising technology in the hope of further advancing minimally invasive surgery. Our team previously developed a deployable magnetically anchored retractor that could pass through a conventional 12 mm trocar^[26]. We also developed an MMAC measuring $\Phi 11$ mm \times 50 mm aimed at reducing

the incision of SSL (unpublished data). However, the view angle of this camera is 90° downward, whereas conventional laparoscopy has a 30° downward angle. In our current work, we refined the camera's internal magnets and vision model to minimize its size. More significantly, the latest generation of the magnetically anchored camera achieves a 30° downward angle using a metal hexagonal nut, thus making the new camera suitable for trocar-less surgery. The 30° downward angle was achieved as follows: (1) the bottom of the vision model was fixed to point A and point D of the metal hexagonal nut; (2) the metal nut was attracted by an inner magnet (the inner magnet was vertical to the long axis of the camera) so the vision model would achieve a different downward angle by turning the nut; and (3) when L_{AE} was parallel to the long axis of the inner magnet, the vision model had a 30° downward angle (Figure 5). This is a simple but reliable method to achieve the 30° downward angle because the nut is hexagonal.

This is a small pilot study limited to a canine model. The new generation of cameras will be a vital advance only if the following problems are addressed: First, if the new camera can cooperate with other magnetically anchored and controlled instruments (such as the magnetically anchored retractor that we developed previously), the trocar-less laparoscopy performed with a single conventional trocar will be possible. Unfortunately, in our experience, multiple outer magnets cause magnet-to-magnet interference and operator hand-to-magnet collisions. The minimum

separation distance of outer magnets is considered to be 3 cm^[16]. Future studies should focus on developing an external magnet platform to reconcile the collisions by keeping the outer magnets at an appropriate separation distance. Second, kinematic safety is still a blind area in magnetically anchored and controlled instruments. Although decoupling rarely occurs in current research because the latest camera is light and the outer magnet is sufficiently large, it is necessary to resolve the cause of decoupling to operate magnetically anchored and controlled instruments safely. Abdominal wall thickness has been regarded as a relative factor^[27]. However, more issues need to be explored for the further development of magnetically anchored and controlled instruments.

In conclusion, we have successfully designed, manufactured, and implemented a new magnetically anchored and controlled camera system to perform trocar-less laparoscopy. The system consists of an MMAC with a 30° downward angle, a vision output device, and an external magnetically anchored unit. The miniature camera measures $\Phi 10.5 \text{ mm} \times 55 \text{ mm}$ and weighs 12 g. It can be inserted into a 12-mm conventional trocar and easily maneuvered in the abdomen. The image generated by the camera is excellent and sufficient to perform cholecystectomy. Pilot studies in canine models have demonstrated the feasibility of canine laparoscopic cholecystectomy using the MMAC with a 30° downward angle and only 2 conventional trocars. Future studies will aim to modify the current device and develop new magnetically anchored and controlled instruments to minimize the invasiveness of laparoscopic surgery further.

COMMENTS

Background

Laparoscopy is a promising minimally invasive method that is based on multiple trocars. Decreasing the number of trocars necessary for laparoscopy could further reduce surgical trauma and achieve a better cosmetic outcome. Cadeddu first introduced magnetically anchored and controlled instruments in 2007. Such instruments could not share space with the trocar during surgery. However, previous magnetically anchored instruments were greater than $\Phi 20 \text{ mm}$ to address instrument collisions in single-site laparoscopy (SSL). This would not be suitable for conventional laparoscopy. Therefore, the authors designed a miniature magnetically anchored and controlled camera system that could pass through the conventional laparoscopic trocar. By using this camera system, the number of trocars required for conventional laparoscopy could be reduced without adding technical difficulties.

Research frontiers

A magnetically anchored instrument is the most promising positioning method for trocar-less laparoscopy because the coupling force is generated by internal and outer components without direct contact, thus allowing the instrument to be free from the trocar and enabling full use of the insufflated abdomen. However, previous magnetically anchored instruments are too large to pass through a conventional laparoscopic trocar.

Innovations and breakthroughs

In this study, the authors provided a miniature magnetically anchored camera measuring $\Phi 10.5 \text{ mm} \times 55 \text{ mm}$, which was the first able to pass through the conventional 12 mm trocar. A trocar-less laparoscopic cholecystectomy

using 2 conventional trocars was performed using this camera system. The authors developed an artful method to achieve the 30° downward angle of the camera by simply using a metal hexagon, which is crucial to obtain excellent intraoperative optics.

Applications

The miniature magnetically anchored and controlled camera system provided in this study could realize trocar-less laparoscopy by replacing the trocar used for the laparoscopy. Combined with other instruments, a laparoscopic cholecystectomy based on only one conventional trocar could be achieved in the future by using the camera system, which would be much less invasive than current SSL.

Terminology

Magnetically anchored instruments are positioned intra-abdominally and stabilized through a coupling force to external magnets on the abdominal skin. In this way, the instruments do not share space with the trocar during surgery. The miniature magnetically anchored camera is a type of magnetically anchored instrument used for providing intraoperative optics.

Peer-review

The research group presented an interesting concept. The miniature magnetically anchored and controlled camera system has drawn the interest of surgeons to conduct further research and make a judgment about it. It may be a promising method for trocar-less laparoscopy. This is a very interesting work.

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P- Reviewer: Azodi M S- Editor: Yu J L- Editor: Ma JY
E- Editor: Zhang FF





Published by **Baishideng Publishing Group Inc**
8226 Regency Drive, Pleasanton, CA 94588, USA
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ISSN 1007-9327

