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REVIEW

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The development and application of magnetic surgery in clinical treatment

Long Liu[1†], Shuqin Xu[1†], Shuang Bai[2,3,4], Jiaru Xu[5], Yan Li[2,3,4], Luigi Bonavina[6], DongKi Lee[7], Linbiao Xiang[1], Dinghui Dong[1,2,3,4], Jiahong Dong[8*] and Yi Lyu[1,2,3,4*]

[†] Long Liu and Shuqin Xu have contributed equally to this work and share first authorship.

*Correspondence:
dongjiahong@mail.tsinghua.edu.cn; luyi169@126.com

[1] Department of Hepatobiliary Surgery, the First Affiliated Hospital of Xi'an Jiaotong University, Xi'an 710061, Shaanxi, China
[8] Hepatopancreatobiliary Center, Beijing Tsinghua Changgung Hospital, School of Clinical Medicine, Tsinghua University, Beijing 100084, China
Full list of author information is available at the end of the article

Abstract

In the twenty-first century, increasing studies suggest that magnetic devices are employed for technical innovation and solving clinical bottleneck problems. Magnetic surgery technology uses specially designed magnetic medical instruments or equipment to transform the "non-contact" magnetic force into a particular force. This could play a specific function in clinical diagnosis and treatment, such as vascular anastomosis, tissue compression, instrument anchoring, surgical navigation, space expansion, and controlled tracing. According to different application methods and principles, magnetic surgery technology can be divided into the following five core categories: magnetic compression technique (MCT), magnetic anchor technology (MAT), magnetic navigation technology (MNT), magnetic levitation technology (MLT), and magnetic tracer technology (MTT). Some of these technologies present great superiority and tend to replace traditional approaches, which are widely used in multiple diseases, including digestive, gynecological, breast, and urinary. From this perspective of multidisciplinary, magnetism could be utilized in clinical practice well, and magnetic surgery has tremendous potential in clinical treatment. The application of magnetic surgery makes operation greatly simplified and the postoperative complications reduced. Meanwhile, the biological security of magnetic surgery is assessed, and a uniform standard needs to be established. Despite some challenges that still exist in the development of magnetic surgery, it is necessary to investigate and explore more novel technologies, which bring clinical benefits to patients.

Keywords: Magnetic surgery, Magnetic compression technique, Minimally invasive, Clinical treatment, Biocompatibility

Background

Surgery serves as an important approach for the prevention and treatment of human diseases and performs a pivotal role in facilitating people's quality of life [1, 2]. With advances in science and technology, surgery is gradually evolving to solve clinical problems more effectively. Milestone events such as aseptic techniques, anesthesia, and transfusion have laid the foundation for the development of modern surgery [3, 4]. Since then, various surgical methods are emerging and booming. The optimization of surgery technologies is exploring and discussing in globally [5]. In recent years, laparoscopic technique, and robot technology push for minimally invasive surgery, making operations more precise and safer [6]. For example, laparoscopic major liver resection produces favorable efficacy in terms of lesser blood loss, fewer operative morbidities, and faster recovery [7]. Although minimally invasive surgery has improved clinical outcomes of patients, there are lots of room for progress. Multidisciplinary support and integration might accelerate the innovation and development of surgery. Currently, the telesurgery using 5G technology has favored feasible treatment option for patients, reducing health care costs [8]. The nanomaterials are employed to precision imaging-guided surgery, which assisted surgical therapy [9]. Magnetic surgery (MS) is a new comprehensive clinical technology integrating clinical medicine, materials science, and biomechanics, performing significant advantages in many aspects, such as vascular anastomosis, stricture recanalization, and surgical anchoring [10]. The medicine and other disciplines crosses, penetrates, and integrates, promoting surgical technologies and delivering substantial benefits to human health. Meanwhile, surgical procedures require continual focus and advancement to address diseases more effectively.

As we known, many surgical treatments involve major trauma and lack of minimally invasive surgery [11]. With scientific progress and economic development, people have growing concerns about health and beauty. The large incisions unsightly sutures and residual scars bother people striving for beauty [12]. Meanwhile, the occurrence of postoperative complications is also an important concern in surgery [13]. More explorations for new technologies might solve these problems, reducing complications, making a beautiful appearance, and minor trauma. Magnetic surgery technology uses specially designed magnetic medical instruments or equipment to transform the “non-contact” magnetic force between magnetic substances into a particular force. This can play a specific function in clinical diagnosis and treatment, including vascular anastomosis, tissue compression, instrument anchoring, surgical navigation, space expansion, controllable tracer, and other functions [14, 15]. It has important application value in the minimally invasive diagnosis and treatment of digestive, gynecological, mammary, and urinary diseases [16]. Over the past 40 years, magnetic medicine has achieved fruitful results, both solving some clinical bottlenecks and optimizing some treatment approaches. According to different application methods and principles, magnetic surgery technology can be divided into the following five core categories: magnetic compression technique (MCT), magnetic anchor technology (MAT), magnetic navigation technology (MNT), magnetic levitation technology (MLT), and magnetic tracer technology (MTT).

Along with multidisciplinary concepts and innovations in medical technology, many more patients get benefits and prolong survival. In this context, we delve into the theoretical cornerstone of magnetism in clinical practice. We focus on the development and application of magnetic surgery technologies. Additionally, we summarized the biological security of magnetic fields, magnetic materials, and magnetic surgery technologies. This review identifies the latest advances and tremendous potential of magnetic surgery in clinical treatment.

The theoretical cornerstone of magnetism in multidisciplinary knowledge

Magnetic field and magnetic force

The magnetic field exists in the space around magnets, currents, and moving charges [17]. All magnetic fields are generated by electric charges in motion. Magnetic force is generated when a magnet and an electric current are placed in a magnetic field. The application of magnetic forces has been explored and practiced for a long time. For instance, using large magnetic fields and superconducting magnets, magnetic resonance imaging (MRI) is employed for medical diagnosis [18]. Relying on the natural diamagnetism of specific materials, the magnetic force on magnets could be utilized to levitate biological samples [19]. The superparamagnetic iron oxide nanoparticles (SPIONs) could be labeled on immune cells for immunoimaging and be linked with cationic liposomes for concentration and delivery [20]. Moreover, the magnetic property is the properties of the interaction between matter and magnetic fields. In other words, it is the magnetic property of the matter itself in response to the magnetic field [21]. Magnetism means that paramagnetic substances attracted by magnetic fields tend to move toward areas with strong magnetic fields. While diamagnetic materials tend to move towards areas with weaker magnetic fields, repelling magnetic fields [22]. The progress of a substance that does not originally harbor magnetic properties but obtains magnetic properties is characterized as magnetization. In conversely, the process is defined as demagnetization [23, 24]. Generally, according to the magnetization characteristics of magnetic materials, they can be divided into three categories, such as superparamagnetic, soft magnetic, and hard magnetic. Compared with paramagnetic materials, the paramagnetic susceptibility of superparamagnetic materials is several orders of magnitude higher [21]. Iron, chromium, and iron oxide as common superparamagnetic materials are widely used in MRI and magnetic separation [25]. Soft magnetic materials have typical characteristics, harboring high permeability and low coercivity, and good reversibility of magnetization [26]. These materials are commonly used in electronic equipment such as transformers, inductors, and motors. Hard magnetic material is a kind of magnetic material with high coercivity, high remanence, and low permeability [27]. The difficulty in magnetizing and demagnetizing is a typical characteristic. Among these hard magnetic materials, rare earth NdFeB is popularly employed in biomedical fields such as medical robots, artificial hearts, and targeted drug delivery [28]. The application of magnetism and magnetic materials in clinical therapy is mainly based on three properties: (a). Non-contact without direct contact between the magnets can produce a strong interaction force in the space; (b). Negative correlation between the magnetic force size and the distance, the closer the distance between the magnetic poles, the greater the magnetic force. This makes it especially suitable for scenes with small spaces so that magnetic surgical instruments can be compact. (c). Strong directivity of the force between the magnetic poles. When there is a dislocation between the magnets relative to the predetermined suction position, the magnetic force can make the magnets themselves correct the dislocation and return to the pre-set alignment suction position.

The biological effect of steady-state magnetic field

A steady-state magnetic field refers to the strength and direction of the magnetic field that has no changes in a certain time and space, which are mainly involved in magnetic surgery. In contrast, a magnetic field whose strength changes with time is called a dynamic magnetic field, which is usually employed for magnetic particle imaging (MPI) and magnetic hyperthermia [29]. Controlled magnetic fields are characterized by their adjustable magnitude, orientation, and gradient, which are deliberately manipulated in real-time or in a stepwise manner to perform specific tasks, such as those in magnetic anchoring and magnetic navigation [30, 31]. For instance, during procedures like magnetic navigation of a capsule endoscope, the external magnetic field is adjusted at low frequencies to guide the device along a desired path or to anchor it at a specific location [32]. The rate of change of these fields is slow enough that, for the purpose of calculating the forces and torques on the magnetic device, they can be considered static at any given instant. This "quasi-static" nature is fundamental to the precise spatial and angular control required for these applications. Steady-state magnetic fields Much scientific research also suggests that the steady-state magnetic field plays crucial roles on multiple levels, encompassing regulating blood flow, promoting bone metabolism, inhibiting tumor growth, and regulating blood sugar levels [33]. The steady-state magnetic field with diverse parameters can differently regulate the body's blood flow. Inconsistent results might be generated from many aspects, such as the state of the research object, the period of magnetic field processing, the processing time, the object of observation, and the magnetic field gradient [34]. Generally, the steady-state magnetic field might balance the circulatory system and become an effective alternative for improving vascular disease, such as excessive or insufficient blood flow [34]. The steady-state magnetic field is also associated with regulating the proliferation and differentiation of bone tissue cells. These biological characteristics improve osteoporosis, promote fracture healing, and relieve osteoarthritis effects [35]. Meanwhile, a steady-state magnetic field reveals clinical treatment potential in tumors [36]. Using magnetic nanorobots could deliver both chemotherapy drugs and targeted drugs specifically to tumor blood vessels, promoting the efficacy and development of drug therapy. Apart from the steady-state magnetic field, the dynamic magnetic field also displays therapeutic significance. The high-frequency alternating magnetic field acts on magnetic nanoparticles generating heat energy and then inducing tumor cell death [37]. The electromagnet-generated steady-state magnetic field further combined with an electric field could effectively ameliorate the insulin action deficiency in Type 2 diabetes mellitus (T2DM) mice [38]. The biological effect of steady-state magnetic field harbors therapeutic prospects and potential in cancer theranostics and might overcome some limitations of conventional cancer treatments.

The NdFeB permanent magnet materials with high-performance

Currently, the magnetic materials related to magnetic surgery mainly include rare earth permanent magnet materials (e.g., samarium cobalt and NdFeB), magnetic ferro-trioxide nanoparticles, and electromagnetism. The magnetic properties of rare earth permanent magnet materials are superior to others in medical applications [39]. The development of rare earth permanent magnets has experienced three generations, the first generation SmCo5, the second generation Sm2Co17, and the third generation NdFeB. The NdFeB permanent magnet material has excellent magnetic properties, including high coercivity, high remanence, and high magnetic energy products [40]. Owing to the outstanding performance and low cost of NdFeB, this material has been widely used in many fields. Meanwhile, NdFeB harbors good histocompatibility, thus it is also an ideal choice for magnetic materials in magnetic surgery technologies. The disadvantage of NdFeB is poor corrosion resistance, so there is an urgent need to improve the corrosion resistance and promote surface protection technology. The commonly used industrial NdFeB surface treatment methods include electroplating, electroless plating, physical vapor deposition, spraying, composite surface modification, and so on. Although these methods can meet most industrial and daily life needs, whether can also meet the requirements of magnetic surgery. Many experimental studies are performed to explore and evaluate the optimal NdFeB magnet surface modification scheme suitable for human implantation.

NdFeB permanent magnet materials were first used in oral orthodontics [41]. With the birth and expansion of magnetic surgery-related technologies in the past 40 years, the scope of in-body implantation of NdFeB magnets has increased significantly, basically covering the cavity organs and tissue spaces of the entire human body. Furthermore, different magnetic surgical techniques require that the magnets be retained in the body for different times, from a few minutes to a lifetime. We summarized the external environment of the magnets related to the magnetic surgery in Table 1. The research on surface modification is relatively backward, and no unified standard has been formed at home and abroad. Most foreign scholars use polymer material as the surface treatment scheme, while domestic scholars mostly employ titanium nitride coating treatment. Here, we collected some NdFeB surface modification schemes in the literature as shown in Table 2.

Table 1 The external environment of the magnets related to the magnetic surgery

Magnetic surgery-related techniques	Suitable application fields	Magnets exposed to external environment
Magnetic compression technique (MCT)	Side-to-side anastomosis [42], gastroenterostomy [43], small bowel anastomosis [44], colic anastomosis [45], vesicostomy [46], esophageal stenosis/atresia recanalization [47], biliary stenosis/atresia recanalization [48], hepatoenterostmoy [49], pancreaticojejunostomy, gastrointestinal fistulas [50], gastrointestinal fistula repair [51], end-to-end anastomosis [52], and so on	Vessel lumen[IV], gastric cavity[II], enteric cavity[II], ureter/bladder[II], esophagus[II], biliary tract[II/III], pancreatic duct[II/III], abdominal cavity[II/IV], thorax[IV], tissue space[IV], and so on
Magnetic anchor technology (MAT)	Orthodontics clinic, stamp reduction card surgery [53], correction of skeletal deformities [54], magnetic anchoring assisted endoscopic mucosal resection [55], and so on	Oral cavity[IV], abdominal cavity[I], thorax[I], tissue space[II], digestive tract[I], and so on
Magnetic navigation technology (MNT)	magnetic navigation magnetic catheter and magnetic capsule endoscopy [56], magnetic navigation bronchoscope [57], and so on	vessel lomen[I], respiratory tract[I], digestive tract[I], and so on
Magnetic levitation technology (MLT)	Cervical space expansion device, artificial joint, and so on	Tissue space[II/IV], articular cavity[II/IV], and so on
Magnetic tracer technology (MTT)	Lymphatic tracing [58], digestive tract radiography, and so on	Tissue space[I], gastrointestinal tract[I], and so on

[I] Temporary implant: the retention time is usually less than 72 h; [II]Short-term implant: the retention time is usually less than 30 days; [III]Medium- and long-term implant: the retention time is usually between 30 to 90 days; [IV]Long-term implant: the retention time is usually greater than 90 days or permanent implant

Table 2 The surface modification of medical NdFeB

Authors	Application object	Implanting position	Surface modification	Retention time
Avaliani et al. [49]	Human	Biliary tract and duodenum	Polyurethane	7–10 days
Graves et al. [44]	Human	Small intestine	Polycarbonate	17–85 days
Matsuzaki et al. [55]	Dog	Stomach	Polyamide	< 1 days
Yan et al. [51]	Human	Vagina	Titanium nitride	16 days
Klima et al. [42]	Human	Blood vessel	Titanium nitride	Permanent time
Ganz et al. [59]	Human	Abdominal cavity	Titanium shell	Permanent time
Bonavina et al. [60]	Human	Abdominal cavity	Titanium shell	Permanent time
Wang et al. [52]	Dog	Abdominal cavity	Titanium nitride and shell	180 days
Liu et al. [61]	Dog	Abdominal cavity	Titanium nitride and polypropylene shell	180 days
Fan et al. [62]	Dog	Biliary tract and jejunum	Titanium nitride and metal shell	14 days
Uygun et al. [50]	Rat	Stomach and extraperitoneal	Chrome plating	20 days
Jamshidi et al. [43]	Pig	Small intestine	Polytetrafluoroethylene (PTFE)	7–14 days

The history and development of magnetic surgery

In 1978, Obora et al. first provided a new surgical anastomosis, magnetic compression anastomosis, which was used for femoral artery anastomosis in dogs and neck vascular anastomosis in rats [63]. During the same year, Kanshin et al. achieved suture-free anastomosis in gastrointestinal surgery for dogs, harnessing the mechanical squeezing effect generated by magnetic attraction [64]. Then, Jansen et al. also utilized magnetic rings to achieve distal colonic anastomosis and completed favorable anastomosis outcomes in 1980 [65]. In this stage, Japanese research is in a relatively leading position, especially the Yamanouchi's team. They achieved great success and initially formed a "magnetic compression anastomosis (MCA)". The advent of NdFeB permanent magnetic materials in 1984, pioneered by M. Sagawa, further unlocked the immense potential of magnetic medicine, captivating the interest of researchers worldwide. Based on magnetic medicine, the operation of surgery displayed a great prospect of development. Although various magnetic surgical techniques emerged such as artery anastomosis and gastrointestinal anastomosis, most research is mainly concentrated in the animal experimental demonstration stage, and the clinical application is limited.

With the exploration of biological mechanisms and the progress of animal experiments and clinical research, the concept of "magnetic anastomosis" was first proposed by Professor Harrison in 2009 [43]. Then, this technology is popularly used in the fields of general surgery, obstetrics and gynecology, and vascular surgery. Meanwhile, magnetic-related research is blooming everywhere in China. Our team guided by Professor Yi Lyu did a lot of basic and clinical work in magnetic materials and surgical fusion, then first proposed the concept of "magnetic surgery" in 2010. Magnetic surgery technology is summarized into the following five categories: MCT, MAT, MNT, MLT, and MTT. Encouragingly, the "First International Conference on Magnetic Surgery" initiated by Professor Yi Lyu was successfully held in Xi'an from June 1 to 3, 2018.

These technologies were widely used in the domestic and overseas. For example, using the MCT, Professor Yi Lyu successfully carried out the first magnetic squeeze dredging operation for children with benign esophageal stenosis in China. Harrison et al. employed MAT and reported the application of a magnetic mini-mover device (3MP device) in the correction of the funnel chest [66]. The electromagnetic navigation bronchoscopy (ENB) achieved clinical utility in the diagnosis and treatment of lung cancer. The magnetic tracer technology is mainly used for sentinel lymph node tracing in breast cancer at present [58]. The Corheart 6 is a newly developed levitated continuous flow left ventricular assist device based on magnetic suspension technology currently undergoing multicenter clinical trials in China [67]. We summarize the important novel findings in the research history of magnetic surgery and illustrate Fig. 1.

The concept and application of five core magnetic surgery technologies

Magnetic compression technique (MCT)

Magnetic compression technique (MCT) uses the special properties of magnetic force to complete some specific clinical operations, such as the connection of organs, tissue pressing closure, and flow limiting of lumen contents. Magnetic compression anastomosis (MCA) as an important branch of MCT refers to a comprehensive approach to restore lumen continuity. This process is achieved through laparotomy, endoscopic

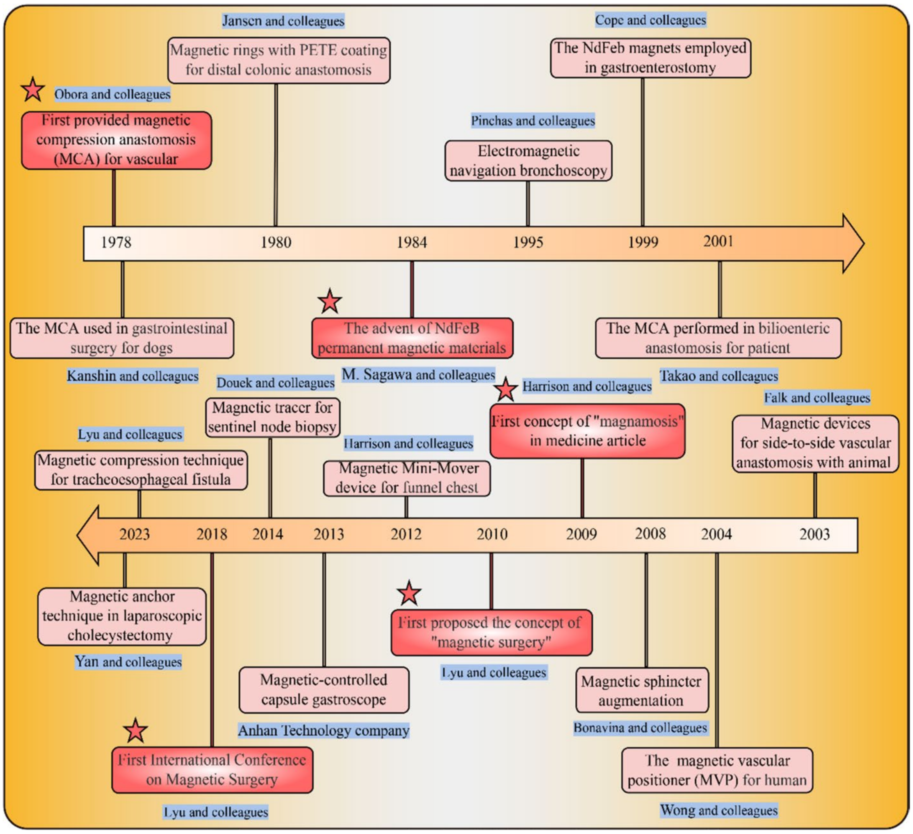

Fig. 1 A timeline of key events in the research history of magnetic surgery. Here, we summarize the historic context, the breakthrough discovery of magnetic surgery, and significant contributed researchers

operation, or interventional technology with the help of "non-contact" magnetic force between magnets. Currently, MCA changes the traditional lumen anastomosis and lumen occlusion/stenosis recanalization and is mainly used in the following three clinical areas: gastrointestinal lumen anastomosis, digestive tract occlusion/stenosis recanalization, and vascular anastomosis [68]. The MCA achieves sutures-free anastomosis and has many advantages, such as little tissue damage, no foreign body remaining at the anastomotic site, and good anastomosis healing [68].

Alimentary canal lumen anastomosis is the most common operation in digestive surgery. Currently, the commonly used methods of alimentary canal lumen anastomosis include manual suture and mechanical anastomotic anastomosis. The manual suture is complicated and has a high incidence of postoperative complications, especially laparoscopic surgery. Mechanical staplers are often used for lumen diameters larger gastrointestinal anastomosis rather than small gastrointestinal anastomosis. The MCA comes into being in this situation for better clinical operation and many pathophysiological changes occur during anastomosis [69]. Firstly, the tissue between magnets is squeezed by magnetic force and ischemia gradually begins to appear. Secondly, necrosis occurred, and the anastomotic tissue located around the magnet generated adhesiveness. Finally, anastomotic tissue healed with each other and completed lumen anastomosis. The MCA could be used in gastroenteric anastomosis, biliary-enteric anastomosis, pancreatic-intestinal anastomosis, and other small lumen reconstructions of the digestive tract, improving anastomosis efficiency and quality. From 2012 to 2015, Liu et al. performed MCA to carry out clinical biliary-enteric anastomosis in 41 patients [70]. The average anastomosis time of 10.5 min and the median follow-up time was 547.5 days. Notably, no anastomose-related complications were found during the follow-up period.

Gastrointestinal stenosis/occlusion is also a common surgical disease. The traditional treatment is to restore the continuity of the digestive tract under laparotomy or thoracotomy. This kind of surgery is traumatic, has a high incidence of postoperative recurrence and a high recurrence rate, and usually requires multiple operations [71]. For surgical intolerance, patients are only treated with external permanent drainage or fistula to maintain life [71]. The MCA provides a novel treatment strategy the magnet is placed on both sides of the stenosis/occlusion site by natural lumen or interventional means. Then, the obstruction can be removed, and the lumen continuity can be restored by mutual attraction between magnetic forces promoting tissue necrosis and shedding [72]. In 2014, Russell et al. successfully used MCA to treat a child with congenital anorectal malformation [73]. Zaritzky et al. also reported that MCA was successfully employed to treat 17 patients with digestive tract obstruction, stenosis, or atresia [74]. Moreover, the MCA also can safely and effectively resolve complete biliary obstruction that is not feasible using endoscopic or percutaneous treatment approaches. Lee et al. recently substantiated MCA is a useful alternative method to treat biliary stricture in post-living donor liver transplantation (LDLT) and post-cholecystectomy patients [75]. The MCA is an effective solution for lumen stenosis, promoting clinical outcome.

Vascular anastomosis is a common operation in plastic surgery and organ transplantation, and the speed and quality of vascular anastomosis are also the key factors affecting the postoperative outcome. Traditional vascular anastomosis is mainly completed by manual suture, which is complicated, time-consuming, and laborious, giving the target organ a long period of ischemia or bruising time, and the postoperative complications are high. The MCA can serve as a rapid method for vascular anastomosis because of its unique characteristics [76]. Liu et al. used this method to perform rapid anastomosis of blood vessels in canine liver transplantation, and the results indicated that MCA significantly shortened the time of the liver-free stage [77]. In 2019, Yi Lyu et al. carried out magnetic-assisted rapid vascular anastomotic technology to clinical liver transplant patients for the first time, reducing the "hopeless period" from 30 to 40 min reported internationally to 9 min and 50 s, creating a new world record. In conclusion, MCA as a new type of lumen anastomosis technique, has presented good results in clinical practice.

Magnetic anchor technology (MAT)

Magnetic anchor technology (MAT) is the magnetic attraction between magnets and magnets or between magnets and paramagnetic substances, making anchored magnets perform non-contact spatial anchoring on the target magnets [78]. The core principle of MAT involves using an external magnet, positioned outside the body, to control an internal magnet placed within the body. By manipulating the external magnet, an operator can adjust the position and the direction of force on the internal magnet in real-time, thereby enabling surgical tasks such as traction, fixation, or manipulation of tissues and organs. The MAT could use magnetic force to perform non-invasive or minimally invasive treatment in the body cavity which is difficult to achieve with traditional approaches. The internal magnet can produce forces in different directions with the control movement of the external magnet, providing an "operation triangle" for the operator. This new technology can effectively solve the entanglement defect of main and auxiliary instruments and illumination camera instruments in endoscopic surgery, reduce the number of puncture holes in the abdominal wall, and shorten the operation time [79]. In 2007, the University of Texas Southwestern Medical Center performed MAT to complete single-hole laparoscopic nephrectomy and natural duct cholecystectomy in pigs. The operations were successful, and no skin and abdominal wall necrosis occurred in the animal model [80]. With the progress of MAT, the magnetic anchoring and guidance system (MAGS) is proposed, further driving clinical application. Cadeddu and Dominguez et al. applied MAGS devices in clinical practice and successfully assisted in many laparoscopic surgeries, resulting in less trauma, and more intelligent and individual, minimally invasive surgery. In 2018, RIVAS et al. reported the results of the first prospective clinical trial of magnetic surgery, which evaluated the use of MAGS in laparoscopic cholecystectomy and concluded it safe and effective [81]. MAGS also began to emerge in more surgical operations such as video-assisted thoracoscopy and endoscopic submucosal dissection. The MAT and MAGS have broad scientific research and application space, promoting clinical technology progress.

Magnetic navigation technology (MNT)

Magnetic navigation technique (MNT) driving and targeting traction on response magnet (RM) or paramagnetic substance using targeting navigation magnet (NM). In the magnetic field along the destination path to the target location, thereby helping to inspect or carry equipment to the desired location [82]. In 2013, Rodrigues et al. inserted a catheter with an electromagnetic tracking sensor into the desired puncture site, during the ureteroscopy of six pigs [83]. A tracking needle with a similar electromagnetic tracking sensor was then used to locate the kidney and ureter, and all renal pelvis punctures were successful. More successful experience of MNT was successfully applied to cardiovascular surgery and gastrointestinal capsule endoscopic navigation [84]. The MNT has been employed in various electrophysiological procedures, encompassing catheter ablation of ventricular tachycardia (VT) and atrial fibrillation (AF) ablation. Capsule endoscopy is an emerging technology, at the forefront of digestive endoscopy technology development, it has the advantages of being painless, non-invasive, convenient, and fast, and has been widely used in the examination of gastrointestinal diseases [85]. In 2010, Swain and Keller et al. added NdFeB permanent magnet materials to the traditional capsule endoscope and used a magnetic handle to control the direction [86, 87]. Compared with the traditional method, this capsule endoscopy with MNT could control the time of capsule endoscopy passing through the esophagus, adjust the direction in the stomach, fix point movement, long-term retention, and examine any part of the stomach. In the future, it is expected to expand the application practice of the MNT in more medical fields.

Magnetic levitation technology (MLT)

The magnetic levitation technique (MLT) applies the basic characteristics of the same pole repulsion between magnets to achieve special medical purposes [88]. Heart failure is the final stage of the development of various heart diseases and is also one of the main death factors in patients with heart disease. Ventricular assist devices also known as artificial hearts, provide cardiac replacement support and prolong prognosis survival [89]. An artificial heart is a complex and precise medical device that has undergone three major transformations, including the first generation of large-volume pulsating blood flow device in the 1990s, the second generation of axial flow device in the early twenty-first century and the latest third generation of magnetic levitation device [89]. The artificial heart based on MLT is called the "third generation of magnetic levitation artificial heart implantation", which is characterized by magnetic levitation non-contact bearing, small size, and belongs to the world's most advanced artificial heart. This technology solves the oversize of the first-generation pulsating blood flow device and significantly decreases thrombosis of the second-generation axial flow device [90]. Artificial joint replacement is an effective treatment for bone and joint diseases, which can effectively reduce the pain caused by joint deformation and restore joint function [91]. However, long-term wear greatly limits its service life, the application of MLT might enhance joint stability by reducing friction. The detailed mechanism is that a NdFeB permanent magnet is placed in the prosthesis, with the help of the magnetic repulsion of the concave and convex surfaces, reducing the burden on the joint-bearing surface. In 2018, our team proposed an MLT cervical traction device, which harbors the functions and effects of axial traction, horizontal rotation, and magnetic therapy. This MLT cervical traction device improves the existing technology, breaks through the limitations of the patient's head movement, and promotes the patient's treatment experience. With the development of clinical traits, the MLT would solve more clinical problems and play a greater role in clinical medicine.

Magnetic tracer technology (MTT)

The magnetic tracer technique (MTT) injects liquid magnetic-related substances into the lumen of the human body, or the organs connected with the lumen. The magnetic substances diffuse along the lumen or metabolic pathway and are monitored and tracked by magnetic detection equipment in vitro [92]. The gastric tumor is a common tumor of the digestive system and the combination of two mirrors (laparoscopy combined with gastroscopy) is often used in clinical practice to accurately locate tumor lesions [93]. Although it can achieve accurate location, it limits the flexibility of surgical arrangements owing to the need for endoscopists. Our team made some attempts for better clinical practice using MTT and successfully used MTT to locate gastric tumor markers. In this experimental study, all 6 Beagle dogs were successfully implanted with trace magnets under gastroscopy. After gastroscopy 24 h, the tracking magnet was successfully implanted under laparoscopic surgery, and then the tracking magnet and the tracing magnet automatically attracted each other to form a sandwich structure of "tracer magnet—stomach wall—tracing magnet". This progress completed the localization and identification of gastric tumors under laparoscopy. In addition, the MTT is also employed to conduct laparoscopic radical NOSES treatment of rectal cancer. The surgical application of MTT needs further development and more clinical experiments.

In conclusion, the innovative technology of magnetic surgery can simplify current surgical procedures, reduce the difficulty of operation, shorten operation time, and improve the therapeutic effects. We summarized the characteristics of these technologies in Fig. 2.

The extended application of magnetic surgery technology

Magnetic surgery techniques are numerous and developing rapidly. Although five core classifications have summarized as MCT, MAT, MNT, MLT, and MTT, some expanded application of magnetic surgery technologies are emerging and solving clinical problems. For example, the Magnetic sphincter augmentation (MSA) is an ingenious and laparoscopically implantable device, which is created to restore Lower Esophageal Sphincter (LES) barrier based on magnetic force. The MSA can be classified as MCT with flow limiting of lumen contents. Moreover, the MSA also can be defined as Magnetic sphincter technology (MST) owing to this idea could perform on multiple sphincters, such as esophagus, urethral, and rectum.

Gastroesophageal reflux disease (GERD) is a very prevalent condition affecting up to 30% of the population in western countries [94]. Magnetic sphincter augmentation (Linx™) is an innovative laparoscopic procedure for GERD that provides a more standardized surgical option for patients dissatisfied with medical therapy and for those with early stage disease who would not usually be considered ideal candidates for fundoplication [60]. The Linx is a mechanical device manufactured in different sizes and designed to augment the physiologic barrier to reflux by magnetic force. The device consists of a series of titanium beads containing a magnetic core and interlinked with independent titanium wires to form an expandable ring. Magnetic sphincter augmentation is effective in (a) reducing typical reflux symptoms and use of proton-pump inhibitors, (b) decreasing esophageal acid exposure, and (c) improving patients' quality of life. Safety issues

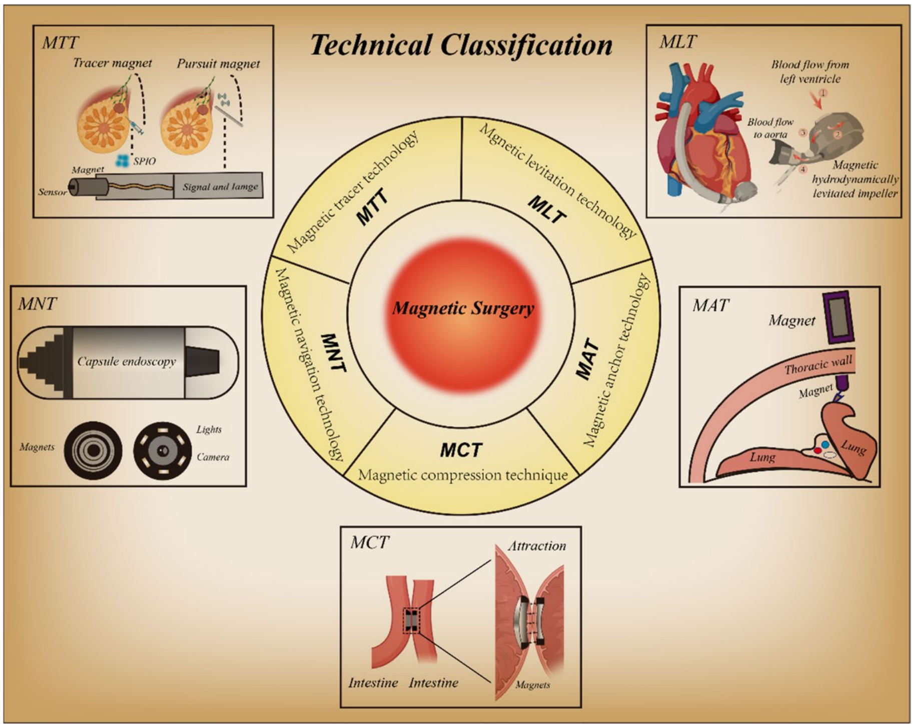

Fig. 2 The five core magnetic surgery technologies. After systematic investigation and summary, magnetic surgery technologies could mainly be classified into the following five core categories: magnetic compression technique (MCT), magnetic anchor technology (MAT), magnetic navigation technology (MNT), magnetic levitation technology (MLT), and magnetic tracer technology (MTT). The representative clinical application of each technology was displayed

such as device erosions or migrations have been rare and not associated with mortality. The device can be easily removed laparoscopically, if necessary, thereby preserving the option of fundoplication or other therapies in the future. A potential limitation of the Linx procedure is the contraindication to undergo scanning in > 1.5 Tesla magnetic resonance systems. Ganz et al. reported a similar MSA device is prospectively assessed in 100 patients with GERD. This MSA device is also making siginicant clinical benefits.

Using MST might also treat stress urinary incontinence that affecting humans' health and quality of life. The female stress urinary incontinence harbored high morbidity is mainly caused by urethral hypermobility and intrinsic sphincter deficiency [95]. Solving the relaxation of pelvic-floor musculature and promoting poor urethral closure might make clinical cure. Our team developed a magnetic control device, including permanent magnet and magnetic hydrogel. The first, permanent magnet, is fixed to the medial part of the inferior end of the pubis.The second, magnetic hydrogel, is injected into the horizontal urethrovaginal septum where the permanent magnet is located. In the non-voiding state, the magnetic hydrogel is attracted to the permanent magnet and the urethra is closed. While, the increasing urethral pressure overcomes the magnetic force between the magnetic hydrogel and the permanent magnet, and the urethra opens in urinating. Similarly, using magnetic force designs the corresponding device might also resolve faecal incontinence. Here, the magnetic devices for treating GERD and female stress urinary incontinence are shown in Fig. 3.

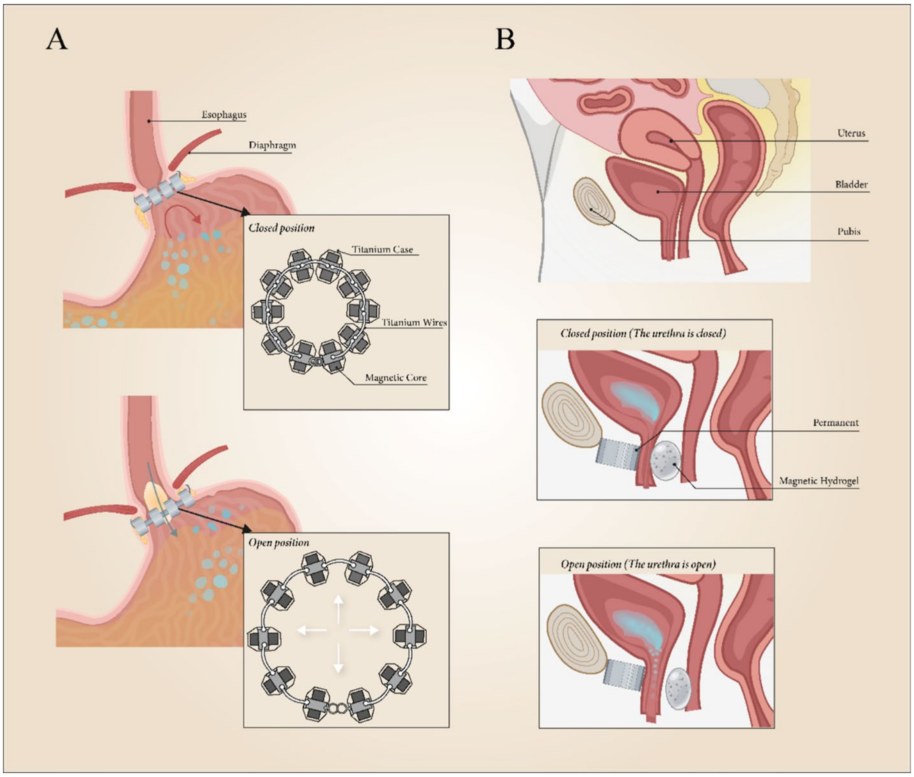

Fig. 3 Magnetic device for solving gastroesophageal reflux disease and stress urinary incontinence. The principle is using magnetic force to complete flow limiting of organ contents. The diseases are caused by the functional deficiency of sphincter and magnetic devices could perform sphincter augmentation. The panel A exhibits the magnetic device in closed position prevents food reflux by augmentation of the lower esophageal sphincter. In the open position, it allows normal physiological function, such as transport of food, belching, and vomiting. The panel B displays the magnetic device in closed postion prevents urine passing as urethral pressure less than magnetic force, while the magnetic device in open postion allows urine passing as urethral pressure over magnetic force

The assessment of biological security

Biological security is a key issue that needs more consideration. For the safety of magnetic field, some studies proved that researchers placed tumor-bearing mice at 9.4 T 88 h, and no harmful effects were found [96]. Moderate liver injury was observed at 24.5 T 9 h. The biological security of a magnetic field is mainly dependent on magnetic flux intensity and exposure time. Meanwhile, the US FDA has increased the safe strength limit of the steady-state magnetic field to 8 T, further promoting the clinical application of magnetic surgery.

Major international bodies have defined clear exposure limits. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommends an occupational exposure limit of 2 T for the head and trunk, and 8 T for the limbs, which are regarded as spatial peak values [97]. A crucial caveat is the significantly lower limit for personnel with Active Implantable Medical Devices (AIMDs), such as pacemakers or defibrillators. For these individuals, the recommended ceiling is much lower, typically 0.5 mT, to prevent device interference [98]. It is important to contextualize these limits with the actual magnetic field strengths of current surgical systems. The external magnets used for technologies like magnetic navigation bronchoscopy or catheter ablation typically generate fields in the range of 50–100 mT in the immediate operational area [99–101]. This operational magnetic field strength is approximately 20–40 times lower than the general occupational exposure limits established by the ICNIRP. Furthermore, due to the rapid decay of magnetic field strength with distance, personnel standing even a short distance from the magnetic source are exposed to a much weaker field. Therefore, the screening of personnel for AIMDs and the clear demarcation of the 0.5 mT safety line are suitable. The magnetic fields generated by current adjustable systems are well within established safety parameters for operating room staff.

Many experiments also demonstrated the biological security of magnetic materials implanted in vivo [102]. The structural planning of magnetic surgical instruments should follow the four design principles; including magnetic force meets functional needs, safety and no damage, volume minimization, and shape optimization. Excessive magnetic force may cause safety hazards to patients, while too small a magnetic force does not meet the functional requirements. Firstly, according to different application scenarios, the functional requirements for magnetic instruments are different. These magnetic materials should meet the clinical application situation, such as compression, anchor, and navigation. Secondly, the excessive magnetic force reduces the movement sensitivity of the working unit and weakens the advantages of MAT. Meanwhile, an excessive magnetic anchoring force acts on the tissue between internal and external magnets for a long time, resulting in tissue ischemic necrosis [103]. Thirdly, the volume of the magnet should be minimized, so that the magnetic energy can be used with maximum efficiency. A bigger magnet performs a greater risk of infection, mechanical damage, and rejection in clinical practice. Finally, the magnetic field distribution is directly affected by the shape of the magnet. In the same space, different magnetic field distributions produce different magnetic field effects. The optimal shape of the magnet could promote better clinical application [104]. Overall, the biological security of magnetic surgery is very important in the process of exploration and development.

Design principles for magnets in clinical applications

The design of magnets for clinical applications is governed by four key principles: (1) functional adequacy of magnetic force; (2) safety and prevention of tissue injury; (3) volume minimization; (4) shape optimization. A delicate balance must be struck, as an excessive magnetic force can pose safety risks to the patient, whereas an insufficient force will fail to meet the functional requirements for procedures such as anastomotic reconstruction.

Functional needs also dictate the magnet's geometry. In the treatment of biliary strictures, a cylindrical magnet is required to match the circular lumen of the bile duct. This design must also be equipped with a tail-end fixation structure to facilitate connection and placement via a delivery system. From a clinical perspective, magnet design must pursue volume minimization and shape optimization to reduce the risk of tissue damage and simplify surgical manipulation. However, a significant design conflict arises, as creating a larger anastomosis to promote tissue reconstruction and lower complication risks often necessitates the use of larger magnets. The ideal size is frequently unachievable due to constraints imposed by anatomical space and the limited maneuverability of endoscopic or laparoscopic instruments. Moreover, the clinical use of larger magnets increases the risks of infection, mechanical injury, and immune rejection. Future advancements will require innovative designs and structural optimization. The goal of such innovations is to reconcile the demands of clinical maneuverability with the need for effective anastomotic reconstruction within confined anatomical spaces.

Limitations

While magnetic surgery performs immense potential, its continued development and widespread clinical adoption hinge on addressing several critical challenges. These limitations primarily involve the material properties of the magnets, the long-term biological effects of exposure to strong magnetic fields, and the need for application-specific device design.

Surface modification and biocompatibility of magnetic materials

A significant hurdle lies in the inherent material properties of some high-performance magnets, which can be brittle and exhibit poor corrosion resistance. Within the complex biochemical environment of the human body, inadequately surface-treated magnetic devices may degrade over time [105, 106]. This degradation can lead to a decay in magnetic force, compromising the therapeutic efficacy of the device. Furthermore, the disintegration of the magnet could release potentially harmful metallic ions, raising concerns about long-term systemic toxicity and biocompatibility. Therefore, optimizing the surface modification strategies for these devices, in close collaboration with materials science experts, is crucial to ensure their stability and safety following implantation.

Biological safety of magnetic fields

The Earth's natural magnetic field is approximately 50 μT, whereas tissues and cells surrounding an implanted surgical magnet are exposed to a field that can be hundreds or even thousands of times stronger. A critical question is whether this prolonged, localized exposure significantly impacts the physiological activity of normal cells. A growing body of research has begun to investigate the biology effects of magnetic fields, suggesting beneficial outcomes such as improved cellular oxidative stress, enhanced pancreatic cell viability, and promotion of hepatocyte regeneration after injury [38, 107, 108]. However, a comprehensive understanding is still lacking. Clarifying biological effects of magnetic fields have on cells and tissues is essential for safety assessment and is a prerequisite for the broader clinical translation of magnetic surgery technologies.

Optimization of magnetic device design

The clinical effectiveness of a magnetic device is highly dependent on its physical design, including its size, shape, and magnetic force, which must be tailored to specific applications. In the treatment of gastrointestinal strictures, the magnets must have a precise geometry and force profile to ensure accurate apposition of tissues and to prevent postoperative complications such as anastomotic leaks or restenosis. Consequently, the design of magnetic devices requires a sophisticated approach that integrates anatomical considerations with the intrinsic properties of the magnetic materials. Future efforts must focus on optimizing these designs to meet the diverse and demanding needs of various clinical scenarios.

Conclusions and further perspectives

The development of magnetic surgery has attracted increasing attention, with remarkable breakthroughs in theoretical innovation, technological advancement, and clinical practice. The five core magnetic surgery technologies have been employed in solving more clinical challenges. There are also some problems become increasingly clear to researchers. It is urgent to establish the clinical application operation standard and clinical quality control standard to guide clinical practice. Randomized controlled clinical trials are required to further evaluate the safety and clinical superiority of magnetic surgical technologies, thereby improving the level of clinical evidence. Integrating the advantages of materials science, magnetism, biomechanics, and other related disciplines further solves the interdisciplinary problems faced in the development of magnetic surgery. People interested in magnetic surgery should encourage and attract medical device companies to participate in the design, development, and processing of new techniques, further accelerating clinical application.

Future breakthroughs in magnetic surgery will be deeply dependent on interdisciplinary convergence. The cross-pollination of mechanical engineering and minimally invasive surgery will expand the applications of magnetic technologies, enabling more flexible and sophisticated operational maneuvers in complex surgical scenarios. Concurrently, the synergy between medical imaging and artificial intelligence (AI) is set to redefine the paradigm of precision therapy in magnetic surgery. The development of a closed-loop control system integrating "imaging, magnetic fields, and instrument motion" will dramatically enhance surgical accuracy. Furthermore, the fusion of materials science and biomedical engineering will continue to push the performance boundaries of magnetic instruments, leading to the development of advanced, composite implantable devices that possess both magnetic control functions and active biological therapeutic effects. Magnetic surgery is expected to continue flourishing through continuous innovation, ultimately benefiting a broader range of patients.

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Author contributions
Yi Lyu and Long Liu made the conceptualization, data curation, investigation, and writing—original draft. Yi Lyu, Jiahong Dong made the conceptualization, funding acquisition, and writing—review and editing. Shuqin Xu, Shuang Bai, Jiaru Xu, Yan Li, Luigi Bonavina, DongKi Lee, Linbiao Xiang, and Dinghui Dong made the writing review and editing. Yi Lyu, Long Liu, and Shuqin Xu have verified the underlying data. All authors read and approved the final version of the manuscript.

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Declarations

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The authors declare no competing interests.

Author details
[1]Department of Hepatobiliary Surgery, the First Affiliated Hospital of Xi'an Jiaotong University, Xi'an 710061, Shaanxi, China. [2]National Local Joint Engineering Research Center for Precision Surgery & Regenerative Medicine, the First Affiliated Hospital of Xi'an Jiaotong University, Xi'an 710061, Shaanxi, China. [3]Shaanxi Province Center for Regenerative Medicine and Surgery Engineering Research, the First Affiliated Hospital of Xi'an Jiaotong University, Xi'an 710061, Shaanxi, China. [4]Shaanxi Provincial Key Laboratory of Magnetic Medicine, the First Affiliated Hospital of Xi'an Jiaotong University, Xi'an 710061, Shaanxi, China. [5]Xi'an Jiaotong University Health Science Center, Xi'an Jiaotong University, Xi'an 710061, Shaanxi, China. [6]Department of Biomedical Sciences for Health, Division of General Surgery, University of Milan, IRCCS Policlinico San Donato, Milan, Italy. [7]Department of Internal Medicine, Gangnam Severance Hospital, Yonsei University College of Medicine, Seoul 06273, Korea. [8]Hepatopancreatobiliary Center, Beijing Tsinghua Changgung Hospital, School of Clinical Medicine, Tsinghua University, Beijing 100084, China.

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