



# Totally Obstructed Biliary Stricture I: Concept and Methods of Magnetic Compression Anastomosis

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## History

The concept of compression articulation was originally proposed in 1826 by Denan, who described a newly formed anastomotic fistula caused by ischemic compression of tissue [1]. Denan's spring-loaded device was further developed by Murphy in 1892 and became known as the Murphy button [2–5]. This technique allows for the formation of a circular anastomosis of the intestinal tract by ischemic compression of the tissues between the two buttons and is used to prepare a sutureless connection through end-to-end or side-to-side ischemic compression. It was the first surgical device made for such a purpose [6]. In 1991, an attempt was made to compress an anastomosis using a compression button and an improved Murphy button in an animal study [7]. This device was used to create a compression anastomosis by contacting two screws. The physical contact can be replaced by a magnetic force mediated by a magnetic field. The effects of magnetic force in the intestinal tract were analyzed after swallowing a magnet in some children who had natural perforation or fistulas [8–11]. In 1980, Jansen et al. [12] con-

ducted the first human experiment to achieve tissue compression with magnetic force compression. Magnetic compression-induced mucosal anastomosis was successfully performed in five patients undergoing colonic resection. In 1993, Saveliev et al. [13] conducted clinical and laboratory studies on mongrel dogs, and cholecystoenteric, enteroenteric, and magnetic cholecystogastric anastomoses were successful. In addition, data from four patients who underwent cholecystogastric anastomosis and one patient who underwent cholecystoduodenal anastomosis indicated the possibility of endoscopic magnetic cholecystoenteric anastomosis [14]. Attempts have been made to evaluate the concept and clinical utility of magnetic resonance [15]. In 1998, Yamanouchi et al. [16] introduced the magnetic compression anastomosis (MCA) method and successfully established a bile duct-small intestinal fistula. Other clinical results have also been reported [17–32].

## Magnets

Magnetic force is very important for the success of MCA. Rare earth magnets are classified as neodymium-iron-boron magnets and samarium-cobalt (Sm-Co) magnets. Both types are suitable for MCA because of their high flux density and retention. However, the retention of Sm-Co magnets is stronger than that of neodymium-iron-boron

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magnets, and they are used more frequently [17–20, 26, 33]. A magnetic force determination algorithm (MAGDA) is used to calculate the magnetic force of a magnet [14, 33]. It has been assumed that calculating magnetic forces will help predict the success of MCA. Several variables, such as the shape of the magnet, diameter, nature of the material, magnetic grades, strength, and experimentally estimated or derived strength between *in vivo* magnets, are inputted into the MAGDA.

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## Animal Studies

In the 1990s, efforts were made to induce compression anastomosis through magnetic attraction between strong rare earth magnets. In 1995, Cope et al. [34, 35] demonstrated the feasibility and safety of MCA by creating bilioenteric and enteroenteric anastomoses in pigs. Cope used neodymium-iron fluoride or rare earth Sm-Co magnets to perform cholecystogastric and cholecystojejunal anastomoses in pigs, and a bilioenteric anastomosis formed as a result of MCA after 9–16 weeks [34]. Preliminary studies have shown that magnets can be used to make enteroenteric anastomoses without a short-term leak in pigs [35]. The shape of the magnet used in subsequent MCA studies was modified to amplify the magnetic effect, and further animal studies were performed. Jamshidi et al. [21] performed MCA using a uniform and tapered suture method compared with an additional hand-stapled anastomosis. In addition, gross appearance, histology, and mechanical stability were evaluated, and functional radiological evaluation was performed. No severe complications or stenoses were observed. The rupture pressures of the anastomosis formed by MCA and the anastomosis formed by surgery did not differ. On pathological examination, the anastomosis formed by MCA demonstrated continuity of serous, submucosal, and mucosal layers, and no ischemia or necrosis was observed. Thus, the MCA was safe and similar, or even superior, to anastomosis made with conventional sutures or a stapler [21]. In addition, the same team showed that MCA-assisted enteroenteros-

tomy is feasible using modified magnets in the form of convex-concave radial symmetry [36]. Achieving a reliable enteric anastomosis requires the design and development of a controlled MCA system (magnamosis) that optimizes magnetic coupling, distance between magnets, and surface matching [37]. A magnamosis device has three main features: (1) two convex-concave radial symmetrical rings that self-align magnetically, (2) ring-shaped magnets allowing immediate opening, and (3) radial terrain specially designed to facilitate necrosis at the center and to heal nearby. This ensures that the anastomosis will not be punctured.

In addition to modifications to the magnets, animal studies were performed to optimize the endoscopic magnet supply [38]. A modular soft magnetic anastomosis device was developed without leakage. One study used a partially covered stent to improve the modular shape of the magnet and the opening of the MCA fistula [39]. Inserting a partially covered stent into the gastroenteric anastomosis formed by the MCA maintained the opening for more than 7 weeks. A compression anastomosis using magnets has been experimentally tested in blood vessels and the biliary and gastrointestinal tracts [40].

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## Human Studies

In 1998, Yamanouchi et al. [16] successfully introduced the MCA method and successfully established a bile duct-small intestinal fistula. Other clinical results have also been reported [17–32]. Thereafter, MCA has been successfully used for biliobiliary anastomoses and bilioenteric anastomoses. Long-term follow-up data on side effects and restenosis after the procedure are still lacking. However, some results have demonstrated the stability and effectiveness of the method. Jang et al. studied 39 patients who underwent MCA, and recanalization was successful in 35 patients [41]. One patient had mild cholangitis, and none died. The average follow-up period was 41.9 months, and restenosis was confirmed in one patient.

## Indication of MCA

The development of nonsurgical treatments, including endoscopic and percutaneous approaches, enables reperfusion of benign or malignant postoperative severe biliary strictures [25, 42–45]. However, non-operative treatment has limited effectiveness for severe biliary strictures or complete occlusion, and inserting and maintaining a drain catheter is necessary in patients who fail to respond to stricture treatment using conventional methods. Therefore, the indications of MCA are severe biliary stricture or a complete obstruction that cannot be treated using endoscopic or percutaneous treatment (Fig. 2.1) [17–24].

## Methods

### Outline of the Procedure

The magnets used in MCA are cylindrical Sm-Co rare earth magnets that can be delivered in a variety of ways [33]. The most common delivery pathways are percutaneous and peroral. The

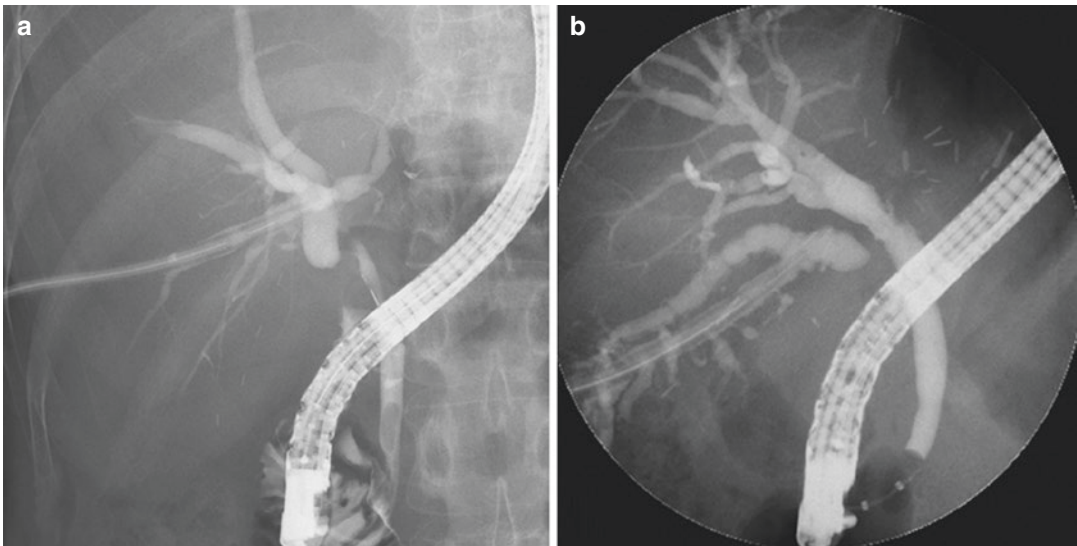
MCA procedure is divided into four steps: (1) delineating the track to deliver the magnet, (2) magnet approximation, (3) magnet removal, and (4) maintenance and removal of the internal catheter.

### Step 1: Track Formation for Magnet Delivery

The percutaneous transhepatic biliary drainage (PTBD) route is formed using a PTBD catheter to deliver the magnet. The PTBD catheter is exchanged with an 18-Fr sheath prior to MCA approximation, allowing for convenient insertion of the magnet through the PTBD catheter, which reduces intrahepatic duct damage. After a full endoscopic sphincterotomy (EST) and balloon dilatation or retrieval, a fully covered self-expandable metal stent (FCSEMS) is temporarily inserted into the common bile duct (CBD) to facilitate delivery of the magnet via the oral route (Fig. 2.2).

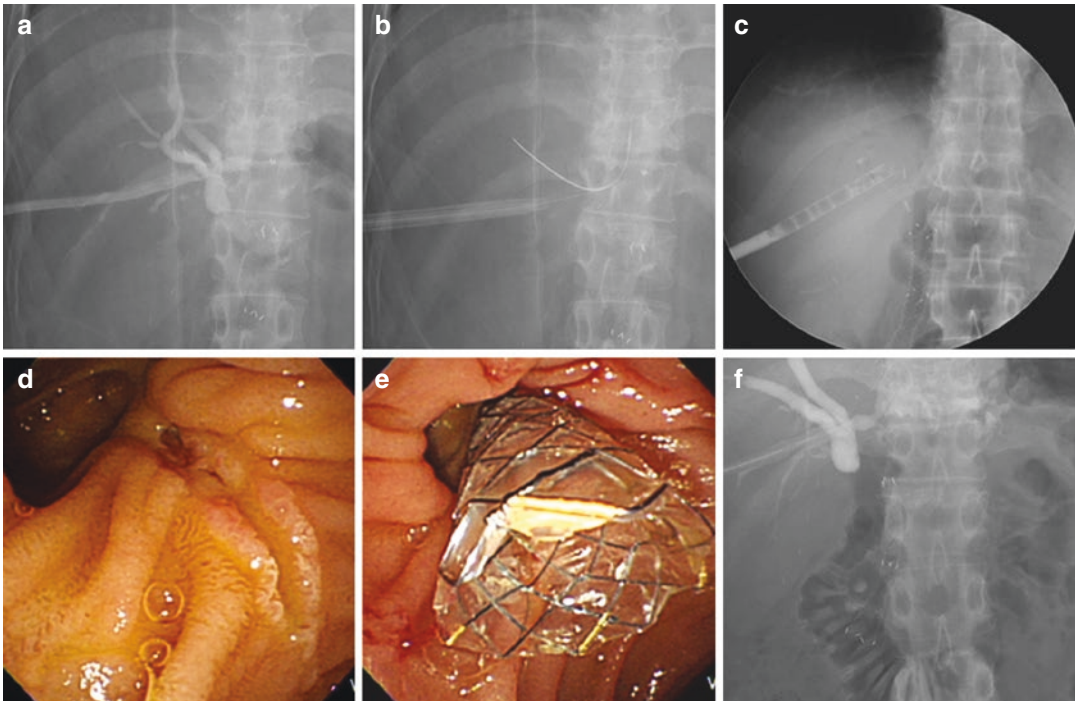
### Step 2: Magnet Approximation

A screw attached to one magnet is fixed to a polypectomy snare and the magnet is moved to the anastomosis site via the 18-Fr PTBD



**Fig. 2.1** Indications for magnetic compression anastomosis (MCA). MCA was performed for a refractory benign biliary stricture that could not be treated using con-

ventional endoscopic and/or percutaneous methods because of a complete obstruction through which the (a) guide wire or (b) dye was unable to pass



**Fig. 2.2** Magnet delivery routes. (a) A percutaneous transhepatic biliary drainage (PTBD) tract was formed and dilated to 16-Fr size. (b) The PTBD catheter was changed to an 18-Fr sheath to deliver the magnet without injuring the duct. (c) The location of the 18-Fr sheath was confirmed using contrast dye under fluoroscopy. (d) The orifice of the ampulla was opened after endoscopic

sphincterotomy using endoscopic retrograde cholangiopancreatography (ERCP). (e) A retrievable fully converted self-expandable metal stent (FCSEMS) was inserted into the common bile duct to facilitate delivery of the magnet. (f) The location of FCSEMS was confirmed using contrast dye under fluoroscopy

sheath. The polypectomy snare passes through the channel of an endoscopic retrograde cholangiopancreatography (ERCP) scope, and the other magnet is fixed in front of the scope. The magnets are moved to the anastomosis site via FCSEMS, and MCA approximation is possible owing to the attraction between the two magnets. The magnet is advanced through the PTBD and ERCP tracks using a balloon catheter to better approximate the magnet. The approximation of the two magnets is confirmed by radiography. Next, the long sheath tube is removed, and an indwelling PTBD catheter is inserted. The FCSEMS inserted in the CBD is removed immediately after the magnets are approximated (Fig. 2.3).

### Step 3: Magnet Removal

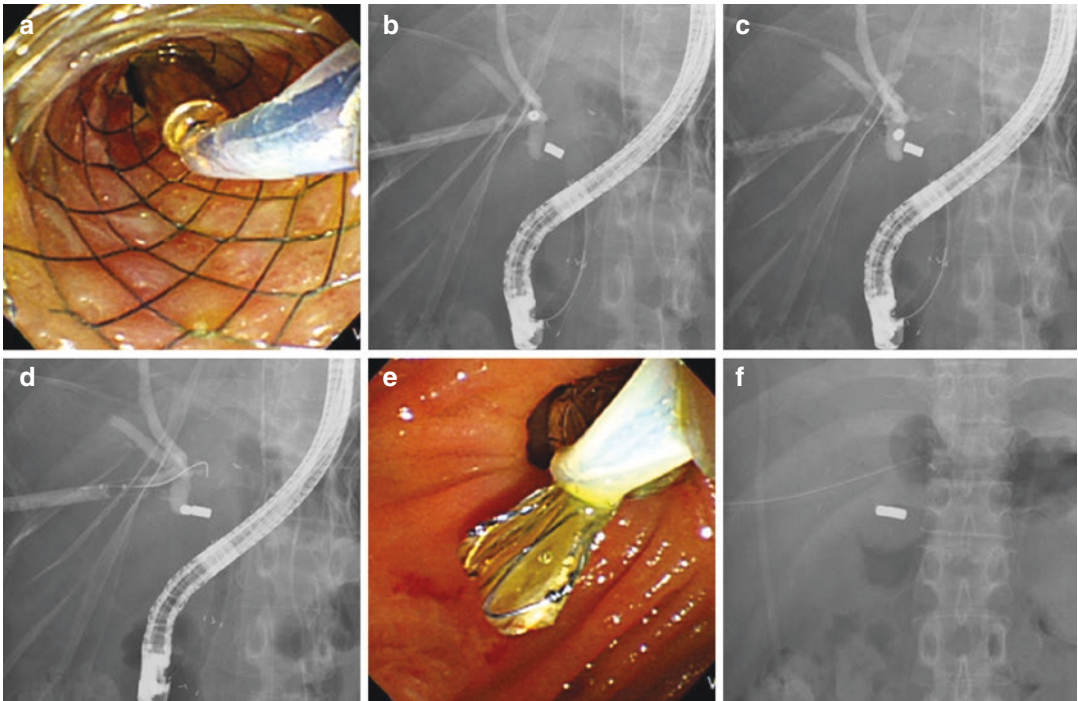
When a fistula is formed due to ischemic necrosis caused by an approximated magnet, the magnet

is moved naturally to the duodenum (Fig. 2.4). However, if spontaneous movement does not occur after 8–10 weeks, the magnet can be pushed out using a guidewire or catheter. Percutaneous transhepatic cholangioscopy (PTCS) can also be used to remove the magnet through the PTBD tube (Fig. 2.5).

### Magnet Preparation

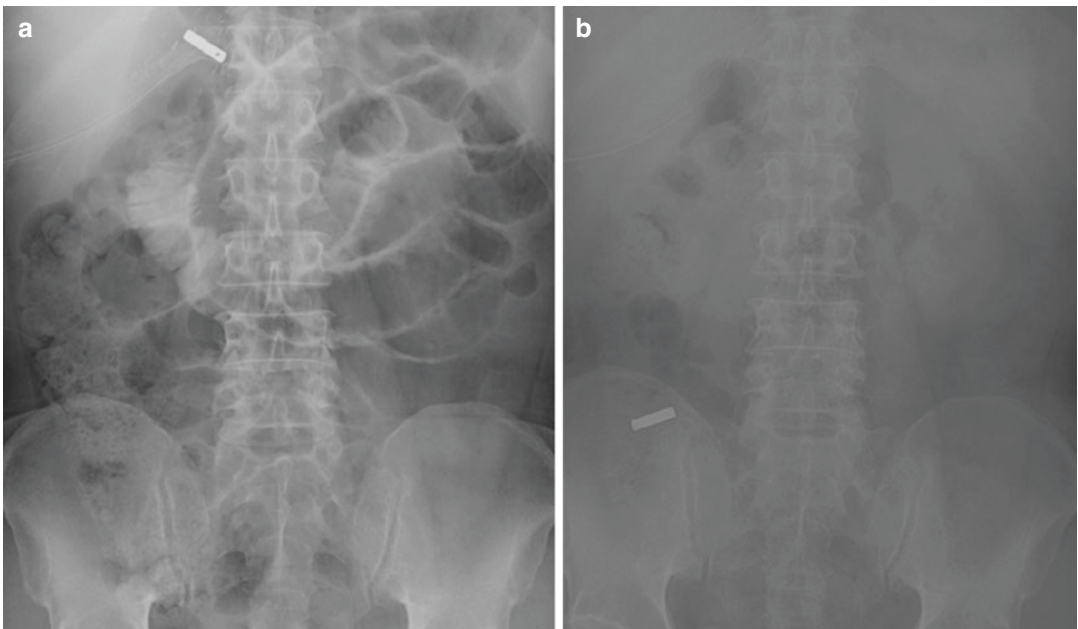
As the silk thread and magnet are separate and the magnet is difficult to manipulate during the procedure, we developed our own rare-earth magnets. We connected the silk thread by making a hole in the opposite side of the magnet. In addition, we made the magnets 4 mm in diameter, resulting in a 50% stronger magnetic force than the previously used magnets (Fig. 2.6) [17].





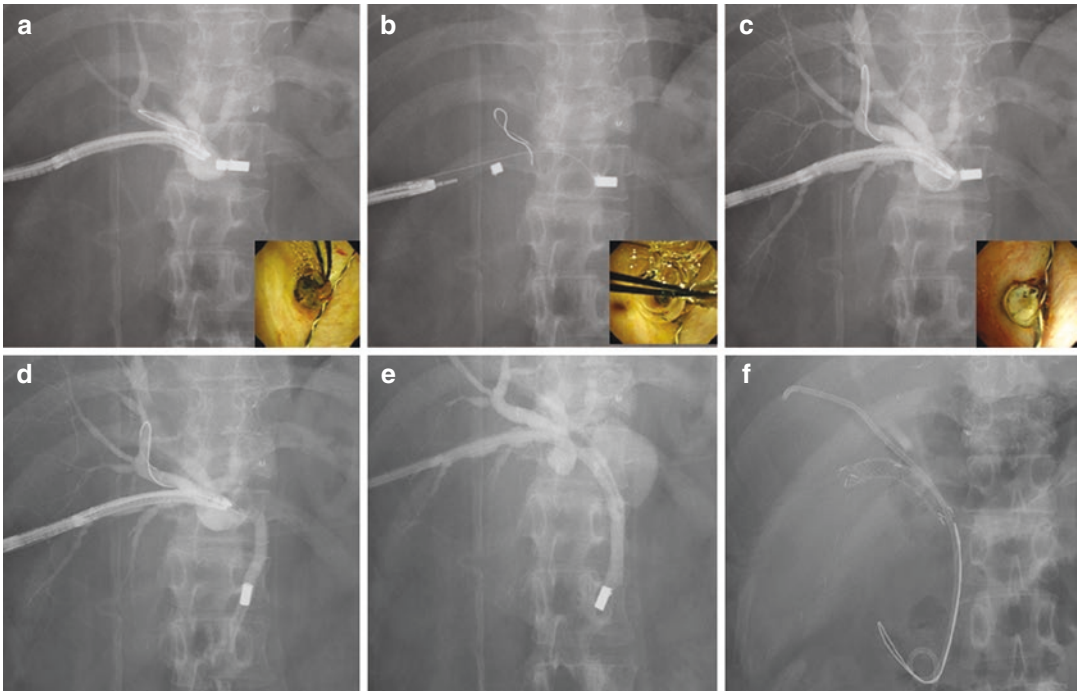
**Fig. 2.3** The process of magnet approximation. (a) A magnet attached to a polypectomy snare is delivered via fully converted self-expandable metal stent (FCSEMS) using an endoscopic retrograde cholangiopancreatography (ERCP) scope through the CBD. (b) Another magnet is delivered

(PTBD) sheath. (c) Two magnets draw close together due to the magnetic attraction between them. (d) The approximation of magnets is confirmed by fluoroscopy. (e) The FCSEMS in the common bile duct (CBD) was removed using a polypectomy snare. (f) The PTBD catheter (16 Fr) was inserted after magnet approximation was established



**Fig. 2.4** A simple abdominal image showing a spontaneously removed magnet. The approximated magnets may move to the bowel within 4–6 weeks after approximation.

(a) The approximated magnets were located at the stricture site. (b) Magnets that were removed spontaneously are present in the intestinal tract after 3 weeks



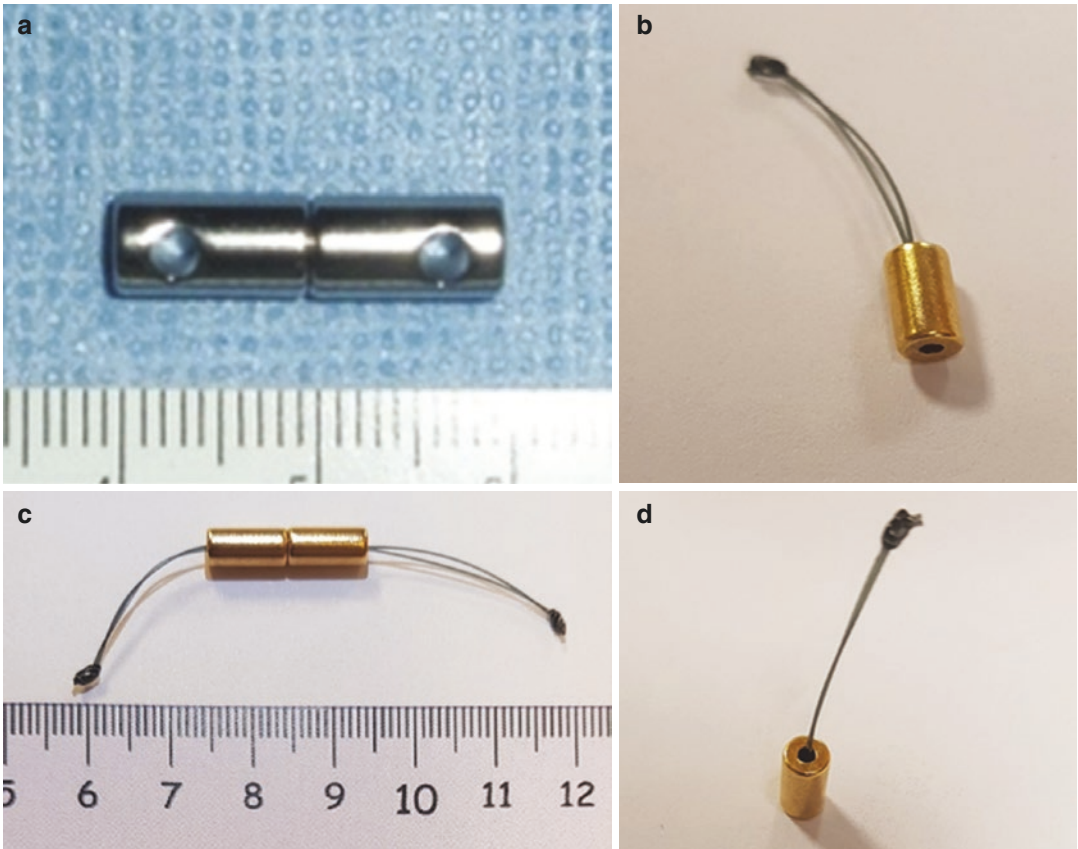
**Fig. 2.5** The process of magnet removal using percutaneous transhepatic cholangioscopy (PTCS). If the approximated magnets do not move spontaneously to the bowel within 8–10 weeks, they can be removed using a PTCS scope. (a) The approximated magnets are visualized using a PTCS scope. (b) The silk thread attached to the magnet was used to ease detachment from the approximated magnets. (c, d) The other magnet is removed by contrast injection

or pushing with a catheter. (e) A 16-Fr percutaneous transhepatic biliary drainage (PTBD) catheter is inserted through the newly formed fistula after the detached magnet is moved to the common bile duct (CBD). (f) A fully converted self-expandable metal stent (FCSEMS) is inserted at the newly formed fistula, and the previous PTBD catheter is removed

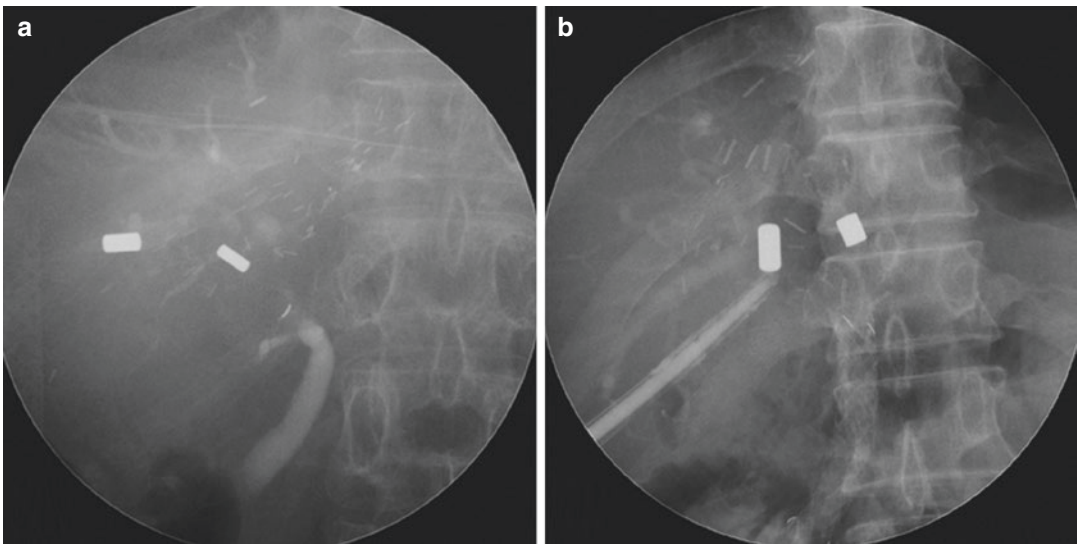
### Pre-evaluation for MCA

The pre-MCA evaluation is limited to planning outcomes and treatment methods. This problem should be improved. The success of MCA is determined by several factors, such as length of the stenosis, shape of the bile duct, orientation of the magnet, and the biliary axis. The main causes of MCA failure are a long stenosis, tapered or twisted bile duct, or misalignment [17, 18]. The longer the stenosis, the weaker the magnetic force. In this situation, necrosis due to compression does not occur, and no fistula forms. Therefore, an accurate assessment of the length of the stenosis is important before MCA. However, current noninvasive imaging studies, such as computed tomography (CT), ultrasound, and magnetic resonance cholangiopancreatography, cannot be used to accurately assess the length of

a stenosis. The evaluation of cholangiogram-based biliary ducts is fairly accurate, but it has the disadvantage of requiring invasive procedures, such as ERCP and PTBD. In addition to stenosis length, the axis and shape of the bile duct are important parts of the MCA pre-evaluation. If the bile duct is tapered and twisted, even if the stenosis is short, the magnet cannot reach the stenosis and the actual distance between the two magnets will be longer than the length measured before MCA, eventually leading to MCA failure (Fig. 2.7) [17]. The axis of the bile duct also determines the alignment direction of the magnet. Even if the distance between the magnets is short and MCA is successful, if the magnets align in parallel, the weak magnetic force eventually causes the procedure to fail [17, 18]. Noninvasive examinations are limited for finding suitable MCA candidates because factors such as



**Fig. 2.6** Magnet preparation. (a) The originally used magnet had a side hole. (b–d) A hole was drilled in the new magnet on the side opposite the alignment side. A silk thread was passed through the hole and attached with strong adhesive. This magnet was smaller but stronger than the first



**Fig. 2.7** Cholangiogram showing failed magnetic compression anastomosis (MCA). The main causes of unsuccessful MCA are long length of the stricture (a), tapered or tortuous duct, and/or parallel axis of alignment (b)



the length of the stenosis and the shape and axis of the bile duct needed for a successful MCA cannot be accurately determined. Therefore, the results can only be known when MCA is actually applied.

### Securing the Two-Magnet Route

The choice of magnet delivery method depends on the type of anesthesia required, history of the operation, and patient characteristics. Biliobiliary anastomosis delivers magnets through PTBD and ERCP. It is better to use 16- or 18-Fr sheaths through the PTBD tract to prevent damage to the duct during magnet transfer. Delivering a magnet to the CBD is more difficult than using the PTBD and often fails because it requires ERCP and must be through the ampulla of Vater. Delivering 5-mm magnets is difficult by EST alone, and balloon dilation is often used but makes manipulation of the magnet difficult [17]. To solve this problem, a metal stent can be temporarily inserted into the ampulla of Vater [17, 29]. To minimize stent migration and pancreatitis, it is advisable to minimize stent indwelling time, so that the stent is inserted 1 day before administration of MCA. In general, transferring magnets through ERCP in a Roux-en-Y bilioenteric anastomosis is difficult due to the long length of the E-loop and A-limbs and the risk of perforation. In this case, a colonoscopic scope with a transparent cap and a balloon endoscope may be helpful [18]. In all cases, however, there is no guarantee of success, and there is risk of intestinal perforation. A method to deliver a magnet through the skin/intestinal fistula operatively has been reported as an alternative [18, 46]. The magnet delivery method should be selected by considering patient characteristics, surgical history, and required anastomosis, but further development of safe and effective delivery methods is needed.

### Route 1: PTBD Tract and Endoscopic Approach

An endoscopic approach is the most commonly used MCA method for biliary stenosis after

living-donor liver transplantation (LDLT). It is a method of transferring magnets by securing a percutaneous pathway and carrying other magnets through an oral approach to achieve magnetic alignment (Fig. 2.8).

### Route 2: PTBD Tract and PTBD Tract

Both the left intrahepatic duct (IHD) and right IHD are anastomosed to the jejunum, and the right IHD is occluded. Two percutaneous transhepatic cholangioscopy scopes are used to deliver the magnet using percutaneous transhepatic biliary drainage through the right IHD tube (one scope) and another magnet through the left IHD tube (second scope) to approximate the magnets (Fig. 2.9).

### Route 3: PTBD Tract and a Surgically Formed Fistula

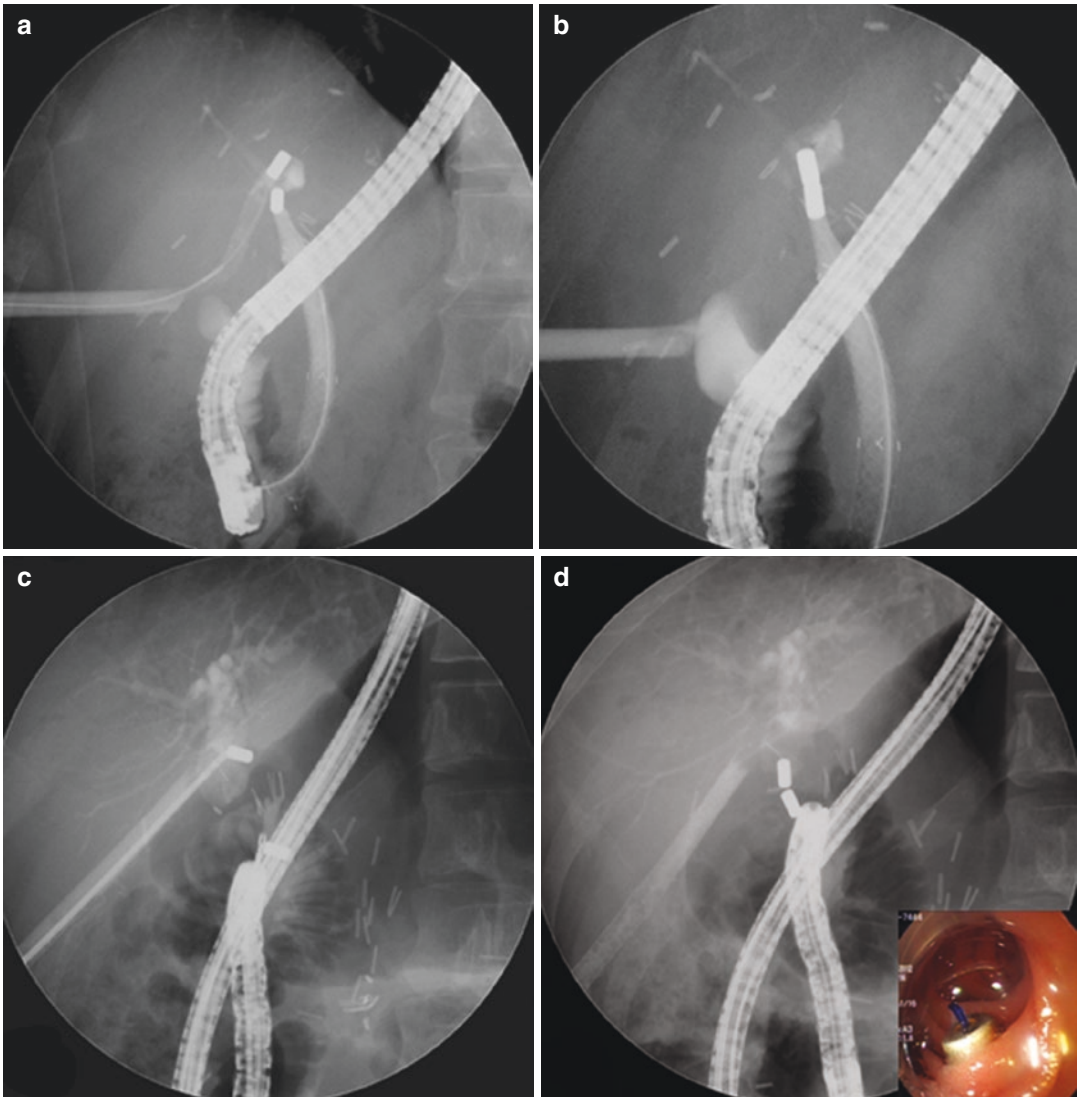
Patients who have undergone LDLT with hepaticojejunostomy often have difficulty accessing peroral endoscopy to the afferent loop. The procedures are described in more detail below. In this case, the magnet can be effectively delivered by passing the endoscope after incision in the afferent loop by performing a surgical intervention (Fig. 2.10).

### Removing the Magnets and Maintaining the Re-canalized Fistulous Tract

#### Removal of the Magnets

As a result of magnet approximation, the stricture tissue becomes sandwiched between the two magnets, and resulting compression causes ischemic necrosis to occur. As the magnets gradually approach each other, the attraction between them strengthens, and ischemic necrosis is accelerated, causing the formation of a new fistula. The approximated magnets may undergo spontaneous migration into the bile duct or bowel through this newly formed fistula (Fig. 2.4). To confirm whether the magnets pass through the anastomosis site, plain abdominal radiographs are taken at 2-week intervals for 6–8 weeks after successful





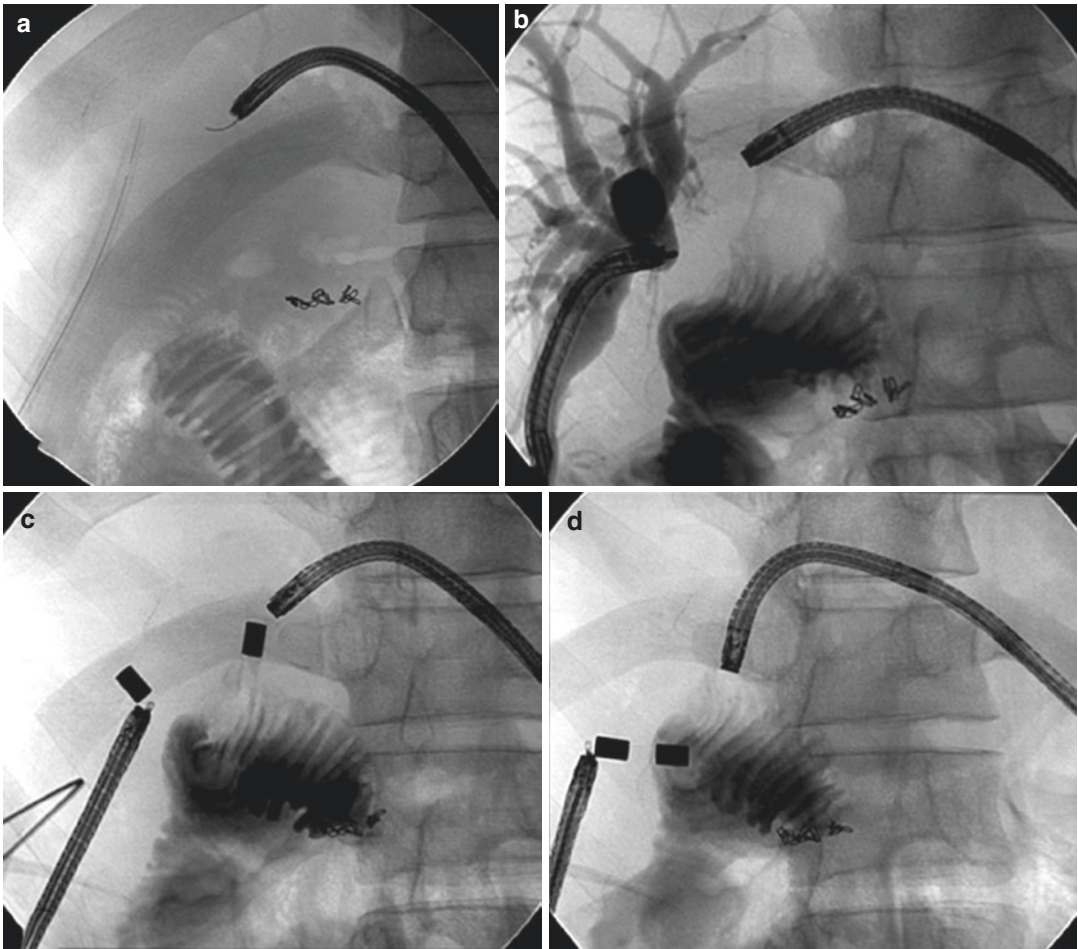
**Fig. 2.8** Magnet delivery method: percutaneous transhepatic biliary drainage (PTBD) tract and peroral tract. (a, b) One magnet is delivered via the PTBD tract and another magnet is delivered via the common bile duct (CBD) in a patient with biliobiliary stricture after living-donor liver

transplantation. (c, d) One magnet is delivered via the PTBD tract and another magnet is delivered via the jejunum using cap-assisted colonoscopy in a patient with bilioenteric stricture after Whipple's operation

magnet approximation. If the magnets maintain a close approximation without spontaneously moving after 10 weeks, they are removed through the PTBD tract using a PTCS scope (Fig. 2.5).

In a previous study, the mean time for successful magnet removal after magnet array was 53.3 days (range, 9–181 days) for a biliobiliary anastomosis and 7–40 days for a bilioenteric anastomosis [31]. The time to successful removal

of the magnet array is determined by the distance between the two magnets, the strength of the magnetic field, and the histological differences at the occlusion site. The distance between the two magnets (2–7 mm) is shorter for a bilioenteric anastomosis than for a biliobiliary anastomosis (2–15 mm). In general, partial reperfusion requires a minimum of 10 days for a short occlusion and up to 1 month for long lesions [31].



**Fig. 2.9** Magnetic compression anastomosis (MCA) using different delivery pathways to form bilioenteric anastomosis. (a) A catheter is inserted into the right intrahepatic duct (IHD) and percutaneous transhepatic cholangioscope (PTCS) enters the left IHD. (b) PTCS enters the

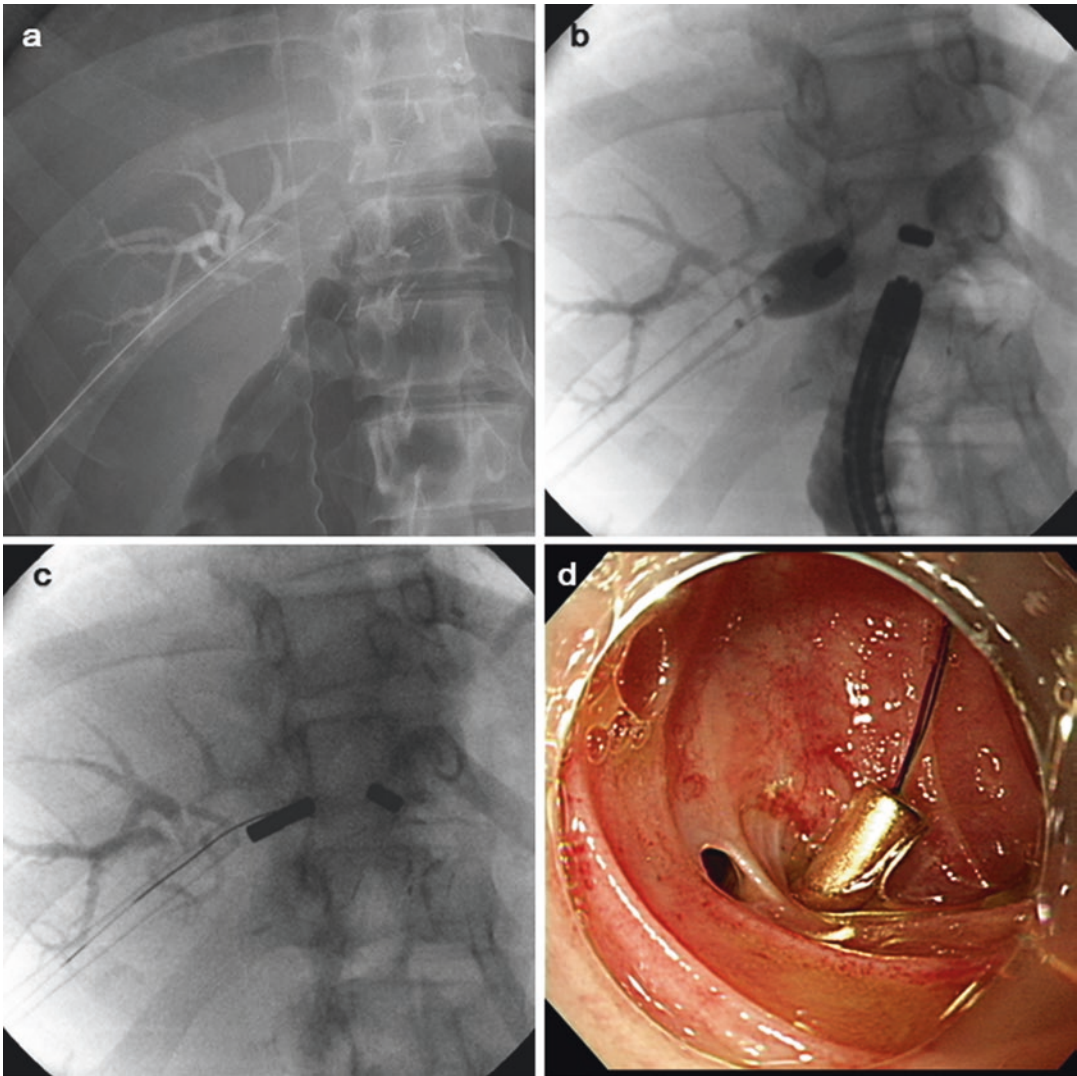
right IHD and total obstruction of the IHD and jejunum is confirmed. (c) Magnet delivery using both PTCS. (d) The magnet is delivered to the left IHD through the jejunum using the PTCS. Magnet approximation is achieved through magnetic force

### Recanalized Fistulous Tract

After the magnets have been removed, and the recanalized fistula has been confirmed endoscopically or fluoroscopically, a PTCS catheter or FCSEMS is temporarily inserted to maintain the tract after removing the magnets 4–6 months later (Fig. 2.11). Research on these two methods has been carried out. A total of 49 patients were enrolled in the study. The comparison between PTCS ( $n = 16$ ) and FCSEMS ( $n = 33$ ) showed that both methods were equivalent in terms of safety and efficacy. However, as PTCS has a long indwelling duration and has the disadvantage of being replaced, it is more convenient for patients to use FCSEMS [47].

### Recoiling

Current long-term clinical follow-up data after MCA treatment are insufficient. However, because MCA forms a fistula as a result of tissue necrosis without enlargement of fibrous tissue, the risk of restenosis due to reorganization of the fibrous tissue is low. Restenosis was not reported for 3 years in one patient who underwent a bilio-biliary anastomosis [30]. Twenty-one patients with biliary stenosis after LDLT were followed up for 331 days, and one patient underwent reperfusion using PTBD [17]. In one study, no restenosis was observed for 50 months [18]. No recurrence was observed 30 days after MCA in



**Fig. 2.10** Magnet delivery using the percutaneous transhepatic biliary drainage (PTBD) tract and a surgical fistula. (a) A stricture occurred after living-donor liver transplantation with hepaticojejunostomy, and the contrast agent did not move to the jejunum. (b) Magnet delivery via percutaneous transhepatic cholangioscopy and

intraoperative endoscopy to the incision in the afferent loop are performed. (c) Magnet approximation was successful by increasing magnetic power after increasing the number of magnets in the PTBD side. (d) The magnet in the jejunum was seen at the endoscopic view after approximation

patients with malignant tumors [22]. The low recurrence rate after MCA has been confirmed in a large, long-term follow-up study.

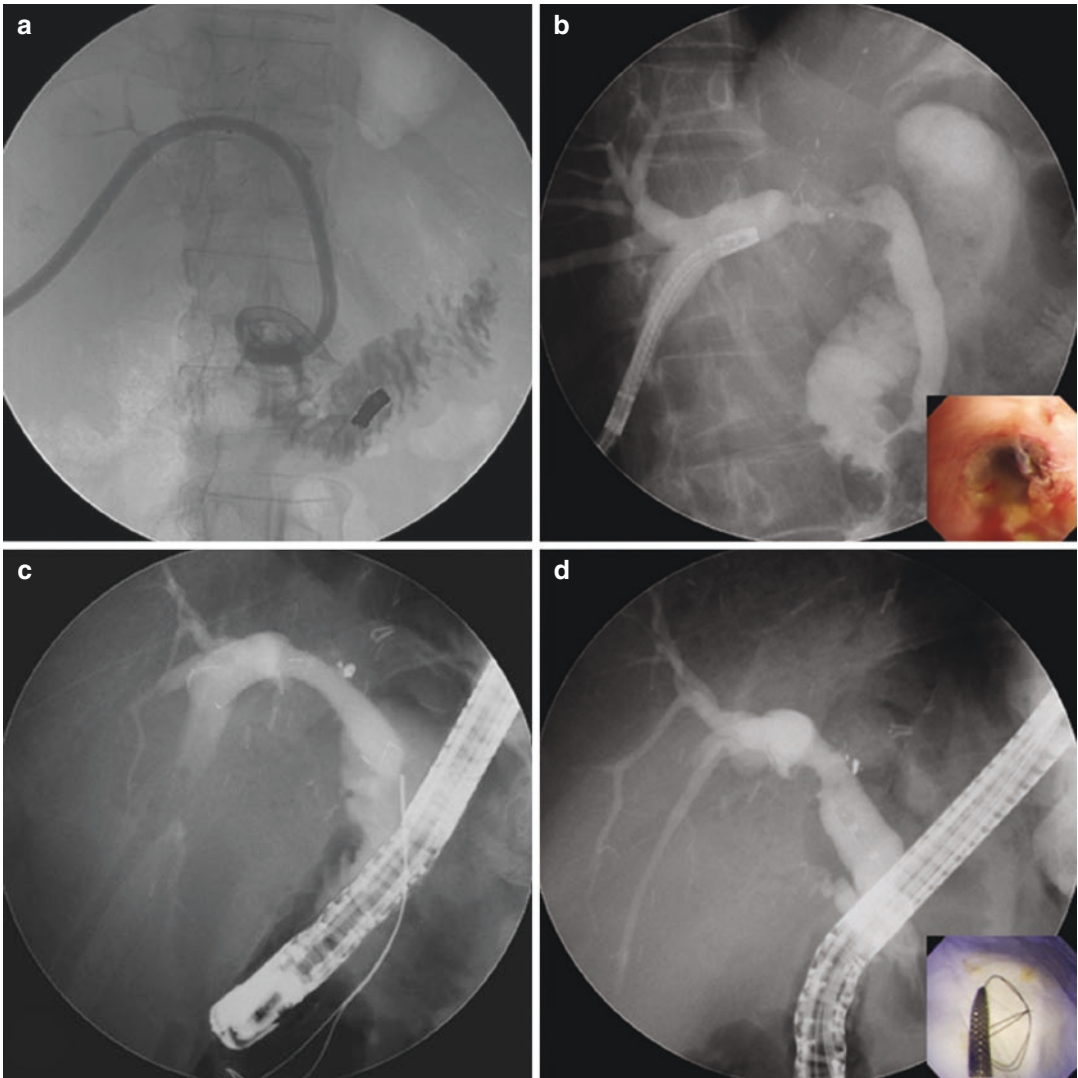
### Safety and Feasibility

The validity and safety of biliobiliary and bilioenteric anastomoses made using MCA has been demonstrated in both human and animal studies. In addition, Avaliani et al. [22] used MCA to form anastomoses between the bile

duct and the duodenum or jejunum in 34 patients with malignant strictures, but MCA was not used to recanalize a malignant obstruction. A re-procedure was required in six subjects. However, MCA is not routinely performed to treat malignant biliary obstructions that can often be treated using conventional peroral or percutaneous methods.

Doppler ultrasonography and follow-up may be performed because of the possibility of rupture





**Fig. 2.11** Two methods for maintaining a new fistula created by magnetic compression anastomosis (MCA). (a) Magnets were approximated via two delivery tracts in patients with post-living-donor liver transplantation (LDLT) stenosis. (b) A percutaneous transhepatic cholangioscopy (PTCS) catheter was inserted through the new fistula after removing the magnets. The PTCS catheter was maintained for 6 months by exchanging every

3 months and removed thereafter. A well-established fistula was seen on PTCS. (c) The magnets were approximated via two delivery tracts in patients with post-LDLT stenosis. (d) A fully covered self-expandable metal stent (FCSEMS) was inserted endoscopically through the new fistula after removing the magnets. The FCSEMS was removed after 3 months. The FCSEMS removed is shown at the bottom right of the photograph

during MCA treatment if there are blood vessels between the two magnets [26, 46]. However, no vascular tears or other complications have been reported in clinical trials. This is thought to be due to the relatively long time required to form the channel after MCA. Using two magnets makes them closer to each other. Therefore, compression or rupture is not anticipated even if there are blood vessels between them.

## Summary

MCA is a feasible and safe non-surgical treatment for occluded benign biliary strictures that are difficult to resolve using conventional endoscopic or percutaneous methods. MCA assessment methods, small and powerful magnets, and effective magnet delivery systems must be developed to predict outcomes for effective MCA and success-



ful re-opening. In addition, endoscopists should fully understand the mechanism and principles of MCA and expand the clinical indications of MCA to apply and develop technologies in various fields. Although the number of cases reported to date is small, MCA is effective and safe, with a lower recurrence rate and less invasiveness than other treatments for benign biliary stenosis.

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