


Anatomical biliary reconstruction as an ultimum refugium for selective cases—History and current state of knowledge

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Abstract

Reconstruction of extrahepatic bile ducts is a staple procedure of HPB surgery. The current standard for most cases is a nonanatomical bilioenteric reconstruction, a satisfactory option for the majority of patients. However, it cannot be used for a small number of selective cases (short bowel syndrome, severe abdominal adhesions), where an anatomical reconstruction with or without an interponate can be used. This review summarizes current knowledge about tissue and material usage for experimental and clinical anatomical bile duct reconstruction in the last 100 years. A Pubmed database was searched for published articles about anatomical extrahepatic bile duct reconstruction in experimental and clinical settings ranging from 1920 to 2022. To date, the truly optimal interponate material has not yet been found. However, evidence reveals important properties of such material, most importantly its biodegradability and neovascularization in the recipient's body. The role of internal bile duct stenting for anatomical reconstruction seems important for the outcome. Anatomical reconstruction of extrahepatic bile ducts is an uncommon but usable technique in unique cases when a nonanatomical reconstruction cannot be done. The optimal properties of interponate material for anatomical bile duct reconstruction have been more clarified, although further research is required.

KEYWORDS

bile duct injury, bile duct repair, bile duct stenosis, biliary reconstruction, cholecystectomy

1 | INTRODUCTION

From a current point of view, bile duct reconstruction is a routine procedure in the field of hepatopancreatobiliary surgery in various cases, such as oncosurgery when an extended hepatectomy, hemipancreatoduodenectomy or sole bile duct resection is needed for tumor presence, liver

transplantation, where a bile passage between the transplanted graft and recipient gastrointestinal tract needs to be restored to ensure its physiological function, bile duct injury caused both by trauma or iatrogenic surgery, or the presence of benign stenosis, with or without the influence of systemic disease such as primary sclerosing cholangitis.

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Bile duct reconstruction has been mostly unified in recent years, with bilioenteric anastomosis being the most common method, since other methods have been mostly abandoned due to the higher incidence of both short- and long-term complications,¹ an outflow reconstruction by choledocho/hepaticojejunostomy is often recommended by current guidelines.² This nonanatomical reconstruction faces specific challenges, since without a bile outflow regulation by the sphincter of Oddi, the possibility of reflux of intestinal contents and bacteria in the biliary tract opens,³ leading to severe complications like ascending cholangitis developing anytime from 1 month to 5 years after reconstruction.⁴ Modifications based on valve mechanism restoration have been proposed,⁵ but their effect is unclear.⁶

Furthermore, patients undergoing bilioenteric reconstruction have a higher chance of developing cholangiocarcinoma later in life.⁷

Being the least complicated option,^{8,9} nonanatomical reconstruction is the preferred method for many cases requiring biliary tract reconstruction, although a small pool of patients remains where bilioenteric reconstruction of bile outflow isn't possible (e.g., dense adhesions obliterating the abdominal cavity, short bowel syndrome).

In these cases, an anatomical reconstruction could be the only alternative to long-term percutaneous transhepatic biliary drainage with its specific complications¹⁰ in addition to primary disease.

Anatomical reconstruction can be done as duct-to-duct reconstruction, a routine approach for uncomplicated liver transplantation¹¹ or for selected perihilar tumor resections.¹² A requirement is sufficient length of both ends to achieve tension-free anastomosis;

otherwise, an early insufficiency or late stricture can develop.¹³ If tension-free primary reconstruction is not possible, anatomical reconstruction with an interponate between uninjured bile duct edges could be used, preserving Oddi's sphincter function. Origins of this idea were founded over 100 years ago¹⁴; unfortunately, no suitable material has yet been found to be widely utilized in clinical settings (Figure 1).

This review summarizes recent research on materials used for bile duct wall reconstruction in experimental and clinical settings, discussing applicability, limitations, promising alternatives, and future research direction for the ideal interponate for anatomical biliary tract reconstruction.

2 | METHODS

A Pubmed database was used for searching published articles about anatomical extrahepatic bile duct reconstruction in experimental and clinical settings ranging from 1920 up until 2022 with used keywords such as “bile duct reconstruction”, “bile duct substitute”, “bile duct replacement”, “bile duct graft”, “biliary interponate”, “biliary patch” or its combination. Articles were included based on critical decision by authors with long-term clinical experience and theoretical knowledge in biliary tract surgery, either HPB surgeons or tissue engineers. Articles without reference to duct-to-duct biliary reconstruction by an interponate were excluded, as well as articles where bile duct substitutes have been established only as an in-vitro model without testing in either experimental model or clinical situation. A review was then divided into two sections: Experimentally

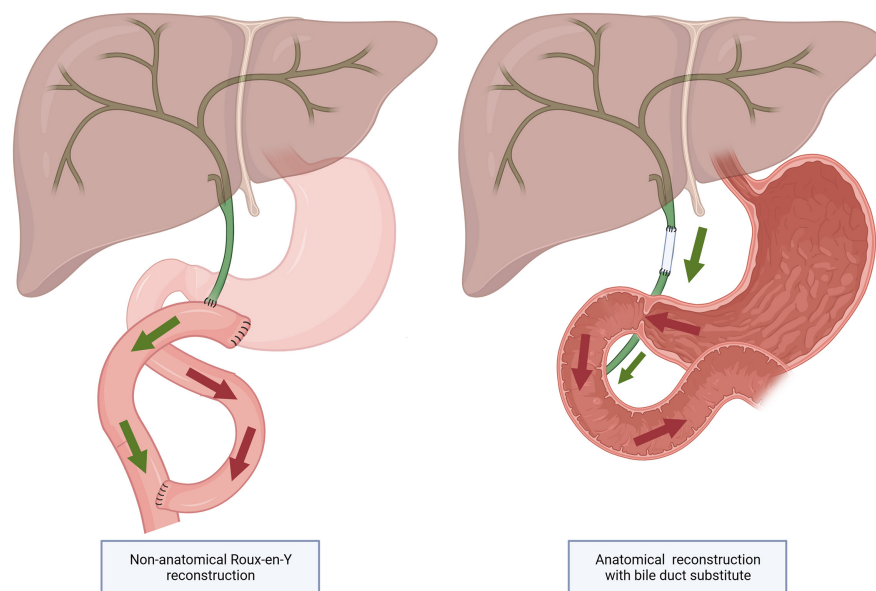


FIGURE 1 Main possible approaches to extrahepatic bile duct reconstruction.

verified materials and clinically applied materials to improve its informative clarity.

3 | EXPERIMENTALLY VERIFIED MATERIALS

Research on possible bile duct substitutes in experimental settings has lasted over 100 years,¹⁴ providing results that could predict its *in vivo* behavior and potential translation into clinical practice. The most commonly used animal models were domestic pigs, dogs, goats, rabbits, and mice.

3.1 | Autologous

Autologous tissues as a bile duct substitution were objects of interest for a long time. Its availability during an ongoing surgical procedure, absence of previous extensive preparation, and nonimmunogenicity would theoretically make it a perfect substitute. Autologous vessels, both arteries^{15,16} and veins^{17–23} have been tested extensively. Earlier dated experiments^{17,18,23} showed complications both in the short- and long-term range, either as a result of anastomotic dehiscence or extensive fibrosis and stricture formation.²³

Due to these findings, experimental research over the past 23 years focused on using vessel walls as a substitute for bile duct reconstruction supported it with bioabsorbable stents to ensure bile passage during substitute integration and fibrogenesis.^{20–22}

Heistermann et al.²¹ reported a common bile duct reconstruction with autologous external jugular vein graft supported by a biodegradable polylactic acid stent in domestic pigs. Animals survived up to 6 months without any signs of bile leakage or bile duct obstruction. Histological analysis after 6 months showed complete integration into the bile duct wall and covering by the biliary epithelium without signs of inflammation or significant fibrosis.

Similar results were found by Palmes et al.²² in groups of domestic pigs with a bile duct reconstructed with an external jugular vein graft, either supported with a biodegradable stent or without any stenting. Animals were observed up to 6 months, and all the animals with a stented reconstruction survived until the end of the experiment without any clinical or laboratory impairment. Four animals with an unstented reconstruction died prematurely due to bile leakage and biliary peritonitis, enabling comparison between stented and unstented reconstruction and its importance for possible clinical application.

Other reported autologous tissues used for reconstruction in experimental settings have been jejunum,²⁴ vascularized gallbladder flap,²⁵ greater omentum,²⁶ ureter²⁷

and skin grafts.^{28,29} The outcomes of these experiments were similar to usage of vessel grafts. Mortensen et al.,²⁵ reported reconstruction with a tubular structure formed from a vascularized gallbladder flap over an irremovable stent, resulting in stenotic formation at the reconstruction site as early as on postoperative day 10. Better results were achieved by usage of spherical shape substitute. The limitation of that study lies in the short observation period and the absence of histological examination.

The most promising results were published by Liang et al.,²⁶ who used a biodegradable stent for the reconstruction of a common bile duct defect in a Ba Ma mini pig in a sublay configuration (in relation to the native common bile duct wall) covered by the vascularized pedicle of the greater omentum. Pigs were observed for a period of up to 1 year, without any signs of bile leakage or bile duct stenosis. Histological evaluation showed increased fibrosis at the anastomotic site, insufficient for a stricture formation and bile flow obstruction.

Autologous tissue grafts have shown promise in anatomical biliary reconstruction, but their use in clinical settings is limited. Despite this, there are documented cases of similar methods used for bile duct injury repair in clinical practice.³⁰ The introduction of biodegradable stents has significantly changed result dynamics, decreasing early- and late-onset postoperative complications (Figure 2).

3.2 | Allogeneic

Allogeneic tissue is rarely used for bile duct injury repair in experimental settings, due to its biological behavior in a recipient's body, consisting of potentially complicated integration of autologous tissue in the biliary tract area and a recipient immune system reaction against donor antigens. This combination can promote inflammatory compound of graft biointegration, resulting in complications such as anastomotic dehiscence or bile duct stricture caused by excessive fibroproduction.

Myers et al.²³ published early findings on allogeneic tissue usage in experimental settings by reconstructing a common bile duct injury with allogeneic homologous segment of the donor common bile duct over a polyethylene tube in mongrel dogs. However, significant fibrosis around an implant site occurred in all experimental animals, resulting in stricture formation and bile flow obstruction. Similar results were found by Dunphy et al., who used allogeneic arterial grafts for common bile duct reconstruction in goats and dogs.³¹

Due to the combination of these findings and a need for a donor organism to obtain a suitable graft, the usage of allogeneic tissue in biliary tract surgery does not seem to be a promising pathway for future research.

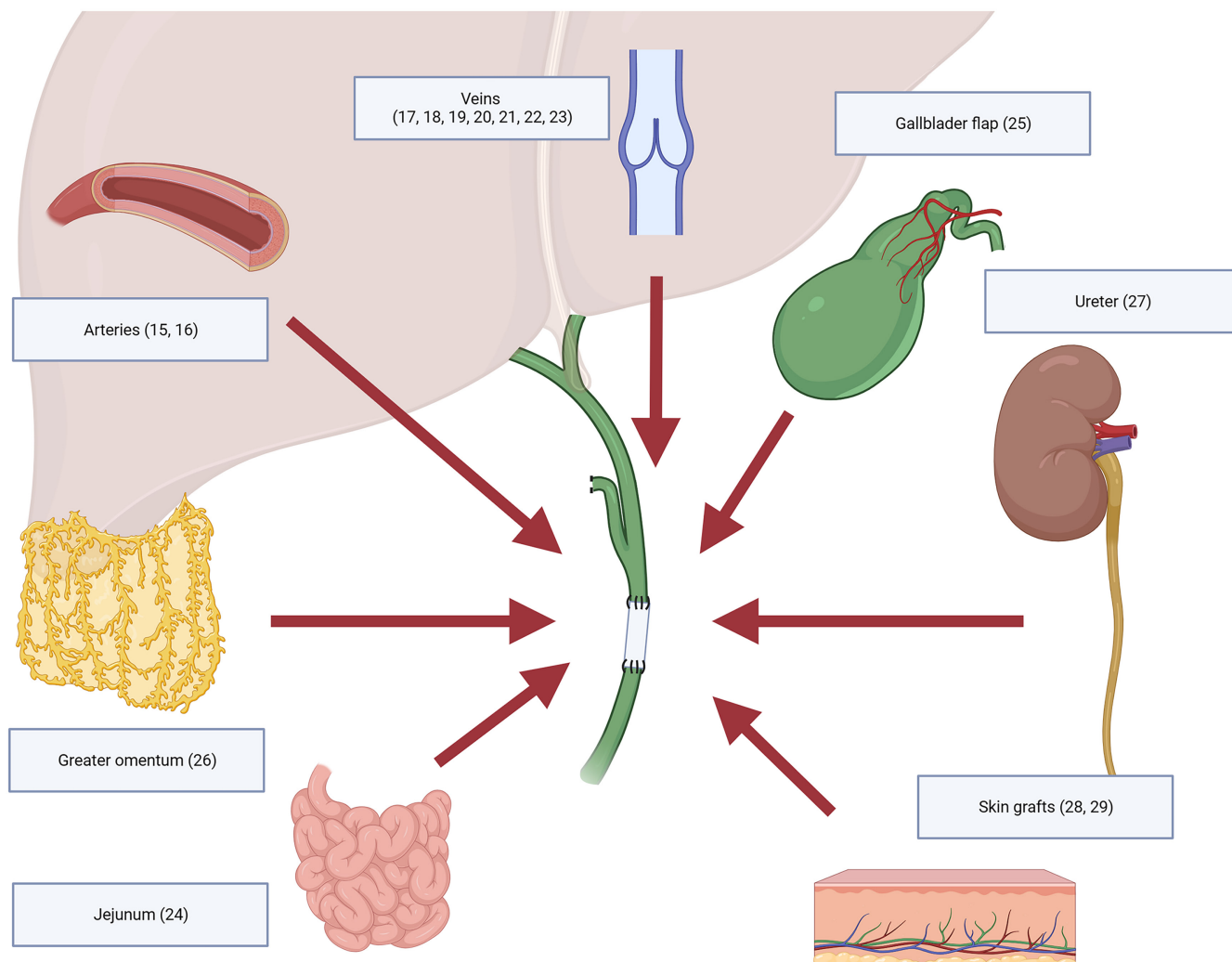


FIGURE 2 Autologous tissues used for extrahepatic bile duct anatomical reconstruction in in vivo experimental settings.

3.3 | Xenogenic

Xenogenic materials are also not the most frequent choice for biliary tract reconstruction in both experimental and clinical settings. The main suggested problem arises from its antigenic characteristics, which differ significantly from those of recipients, thus evoking an even stronger immune reaction than allogeneic tissue.³²

The most commonly reported xenogenic tissue used for biliary reconstruction is the human amnion.^{33,34} The first time it was reported by Scudamore et al. for the repair of common bile duct stricture in domestic pigs, either by stricture resection and reconstruction by a tube constructed of human amnion and polyglycolic mesh or by stricturoplasty by a double layered amniotic patch. The results of patch stricturoplasty were significantly more successful in comparison to group with segmental resection and reconstruction, where a 100% rate of reconstruction related complications was reported.³³

Similar results were obtained by Ismail et al. in an experimental study of common bile duct injury repair with human amniotic grafts with or without peritoneomuscular flaps in dogs. Their findings show satisfactory results for the group with noncircumferential common bile duct injury repaired with the amniotic patch. For a group with circumferential common bile duct injury repaired with a double layered tube formed from the human amnion, the incidence of bile leak was increased by 30% but was not registered in a group with circumferential repair using an amniotic tube graft supported by a peritoneomuscular graft of a recipient.³⁴

Another tissue of xenogenic origin that has been used for bile duct reconstruction is human pericardium graft in a porcine common bile duct stricture model published by Lexer et al., with no complications reported after 6 weeks.

Despite the high antigenicity difference and increased risk of graft rejection and its consequences, these studies produced valuable information about possible human

amnio usage in biliary tract surgery, which could be translated to clinical settings in the future, where the xenogeneity of grafts changes to a more compatible allogeneic relation between donor and recipient. The ability of amniotic tissue to promote healing of different tissues has been proven throughout the years,^{35–37} although the responsible acting mechanisms are still a subject of discussion.

3.4 | Synthetic

The use of synthetic material for biliary tract reconstruction originated and was thoroughly examined in the 1940s, at the same time both in clinical settings and experiments, with an increased examination in large animal models in the 1950s and 1960s. When promising substitute for bile duct reconstruction vitalium started to show its flaws^{38,39} in clinical settings, the need for new materials and their research shifted to experimental settings. Generally, examined synthetic materials can be divided into degradable and nondegradable groups, which predetermines their different biological behaviors in recipient organisms (Table 1).

3.4.1 | Nondegradable synthetic materials

In the past 70 years, a significant number of nondegradable materials have been examined, including Dacron (polyethylene terephthalate),^{40,41} collagen-coated Dacron,⁴² Teflon (polytetrafluorethylene),^{31,43–45} polyethylene^{46,47} and acrylate-amide.⁴⁸

In general, it has been shown that short-term bile passage and biliary tract continuity can be ensured by fully nonabsorbable grafts,⁴⁵ but with gradually decreasing function as the observation period prolongs, differing

slightly according to chosen graft material. There seem to be multiple mechanisms responsible for reconstruction failure. Regardless of the graft material used for bile duct reconstruction, a common sign observed during these experiments was a significant amount of fibrous tissue surrounding a site of graft implantation,^{31,43,48} which resulted in stenosis in anastomotic sites, obstructing bile flow even if the bile duct substitute was able to maintain its shape due to its mechanical properties. The reason behind this increased amount of fibroproduction after implantation could be explained by an immune system reaction to the foreign body resulting in chronic inflammation of tissues surrounding the implanted graft.⁴⁹ The other common phenomenon occurring after a nondegradable graft implantation is bile flow obstruction caused by a bile clog located on the implant itself,^{43,48} whose development is probably based on a combination of slow bile flow rate and the absence of an epithelial layer covering the inner surface of an implanted graft.

It has been reported that the neopithelial layer is not located at the inner side of a graft even after a prolonged period after implantation.⁴³ This absence of a nonadhering protective layer between bile, its contents and graft itself in combination with slower flow rates can result in higher precipitation of bile solid particles.^{50–52}

Due to these findings, late and current research on bile duct substitutes has not focused on nonabsorbable materials due to the combination of mechanisms potentially leading to dysfunction of bile duct reconstruction.

3.4.2 | Degradable synthetic materials

Due to imperfections and limitations seen after using non-resorbable materials, an idea of using resorbable materials that could support regeneration of missing portions

TABLE 1 Summation of nondegradable and degradable synthetic materials used for extrahepatic bile duct anatomical reconstruction in in vivo experimental settings.

Synthetic materials	
Nondegradable	Degradable
Polytetrafluorethylene (Teflon) ^{31,43–45}	Polycaprolactone with polylactic acid, reinforced with polyglycolic acid fibers ^{61,62}
Polyethylene terephthalate (Dacron) ^{40,41}	Polycaprolactone with gelatin methacryloyl hydrogel ⁵⁸
Polyethylene ^{46,47}	Polycaprolactone with polylactic-co-glycolic acid ⁶⁰
Collagen-coated Dacron ⁴²	Polylactic-co-glycolic acid ⁵⁹
Acetylate-amide ⁵⁰	Cross-linked collagen ⁶³
	Polypropylene mesh with collagen lining ⁶⁴

of the bile duct while not staying in recipient organisms for a longer period of time was formed. The main principle would be similar to the usage of decellularized tissue: Temporary bridge the defect with a biodegradable material while allowing recipients tissues to be incorporated into the bridging structure. With time progression, the bridging material would be partially or completely degraded and resorbed, while the defect would be closed by newly formed tissue, resembling the native bile duct as closely as possible.⁵³ That could theoretically eradicate a possible risk of foreign body reaction, even though cases of foreign body reaction to biodegradable implants have also been reported.^{54,55} Another significant advantage in comparison to nonresorbable materials would be a lesser chance of clot formation in substitute location, leading to obstruction and biofilm creation with subsequent recurrent episodes of cholangitis.⁵⁶ Another advantage is the possibility of designing and creating a material with a more defined rate of degradation and resorption, therefore reflecting its needed properties for optimized function.⁵⁷

To date, a significant amount of degradable synthetic materials have been used in experiments, predominantly in *in vitro* settings, with attempts to seed the materials with potential recipient cells.^{58,59} *In vivo*, common materials include polylactic acid, polycaprolactone, polyglycolic acid, polyvinylalcohol, their combination,^{60–62} or cross-linked collagen.⁶³ A combination of degradable and nondegradable materials, such as polypropylene and collagen⁶⁴ was also reported. General results of *in vivo* experimental testing of synthetic degradable materials as a bile duct substitute on large animal models are favorable, reporting a low incidence of bile duct stenosis or leaks, with the potential to regenerate missing portions of the bile duct to the point where even histological interpretation can hardly identify a difference between the native bile duct and regenerated portion after several months.^{60,61}

Degradable materials seeded with cells before implantation seem to have slightly better results in *in vivo* experimental testing than materials without any cell seeding before implantation, as proven by Zong et al.,⁶⁰ who used a bile duct substitute made from a combination of polyglycolic acid and polycaprolactone as a scaffold seeded by human mesenchymal stem cells in a porcine bile duct reconstruction. From his outcomes, it seems that preimplantation seeding with pluripotent cell lines could improve the biointegration process and long-term results, since animals with seeded substitute showed a higher level of re-epithelialization and structure resembling the native bile duct than a control group without seeding, without a reference to xenogeneic reaction and its impact.

Although these results certainly show a positive impact of preimplantation cell seeding on bile duct substitute biointegration, it is important to note that according

to published work results can differ based on the animal model, material and cell line used, as shown by Buisson et al.,⁶⁵ by a similar experiment on rabbit model using 3D printed substitute composed of polyvinylalcohol and polycaprolactone, seeded with human-derived hepatic progenitor cells. Results showed a positive impact of cell preimplantation cell seeding since none of the animals with acellular substitutes have not survived the observation period, while the experimental animals showed signs of re-epithelialization and biointegration of substitute into the native bile duct and surrounding tissues. An xenogeneic impact of the used cell line for this experiment cannot be evaluated, since an immunosuppression of experimental animals was used.

It seems that degradable synthetic materials could be a potential method for future development in the search for ideal bile duct substitutes, although there are several factors requiring attention, such as the length of biodegradation, when too long resorption could cause chronic foreign body reactions, thus not serving its original purpose. On the other hand, a short biodegradation interval could potentially lead to premature resorption without sufficient formation of recipient tissues around or within the substitute, potentially leading to the creation of new defects associated with bile leakage. Cell adhesion and integration into recipient tissues also differ according to cell lines and materials themselves.^{66,67} All these factors need to be considered in future research in this direction.

3.5 | Decellularized and recellularized tissues

Decellularized tissue has been a subject of interest in research on regenerative possibilities of the human organism for the past 15 years, already with a clinical application in selective situations.⁶⁸

The biggest possible advantage of decellularized tissue usage would be its ability to degrade and remodel in the recipient's organism, creating a temporary scaffold for cells to seed in followed by organizing into functional tissue instead of mere implanted graft, potentially limiting complications typical for nondegradable materials. In comparison to synthetic and other degradable materials, its behavior in the recipient body should be more natural and closer to native autologous tissue because of its decreased immunogenicity⁶⁹ and ability to provoke foreign body reaction (Figure 3).⁷⁰

While currently broad research has been done on the characterization and properties of decellularized/partially repopulated tissue with the suggestion of using it in biliary tract surgery,^{71–74} there have not been many trials in an experimental setting on animal models.

FIGURE 3 Decellularized porcine common carotid artery, hematoxylin-eosin, Verhoeff's green trichrome, 20× magnification.

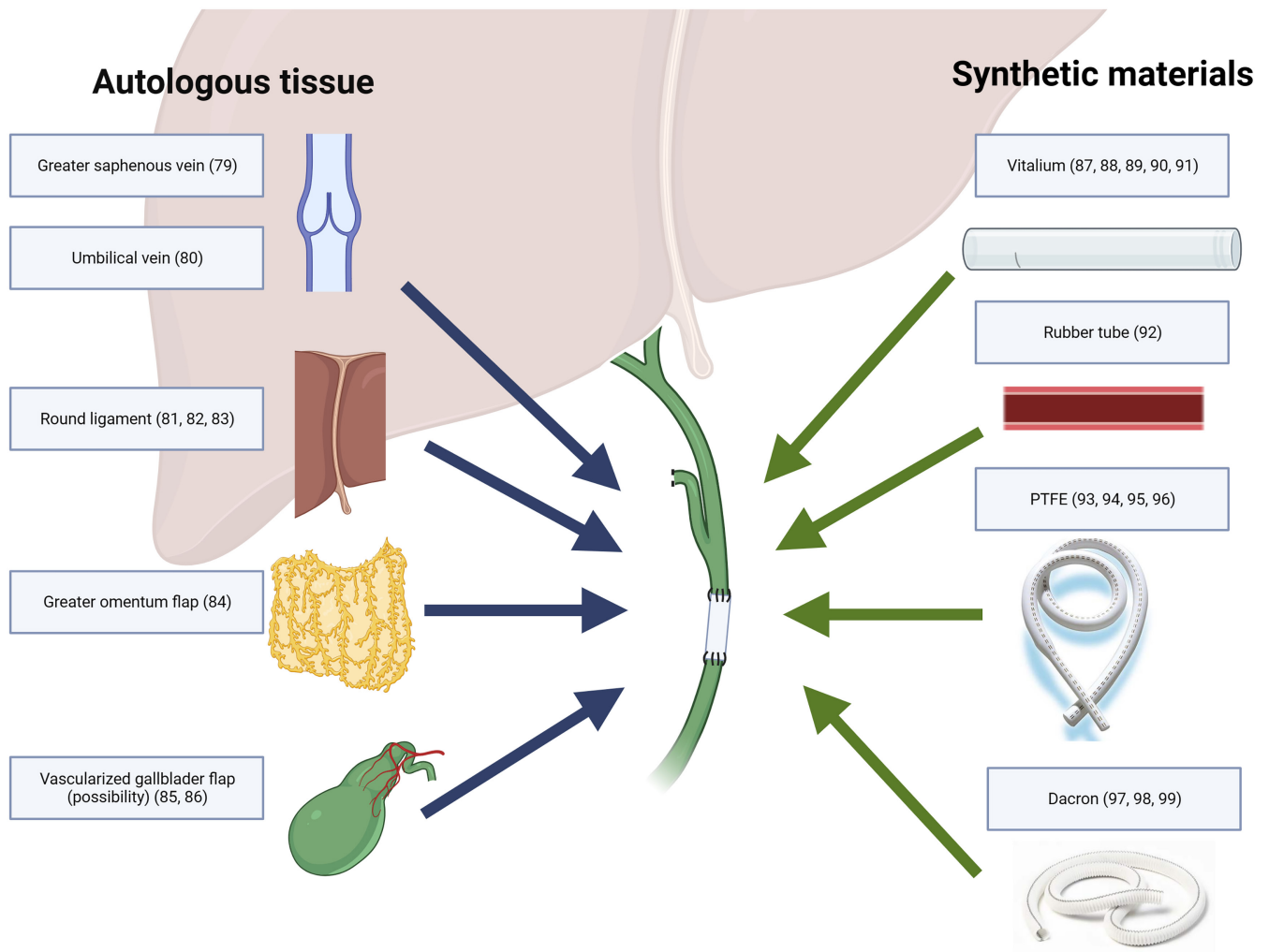
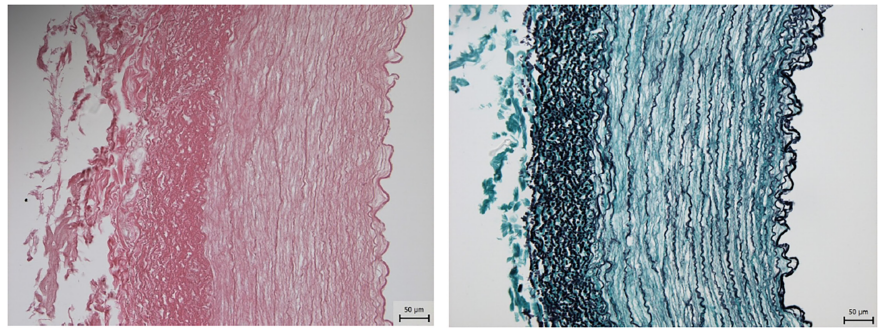


FIGURE 4 Reported materials and tissues used for extrahepatic bile duct anatomical reconstruction in clinical settings.

The first experiments of this kind were conducted by Struecker et al.,⁷⁵ who used decellularized and porcine allogeneic aortic grafts, partially repopulated by autologous cholangiocytes for the repair of common bile duct injury in domestic pigs. No complications were recorded and histological evaluation showed signs of neo-angiogenesis both in the graft and surrounding tissue after 14 days.

These findings must be interpreted in correlation with the short duration of the experiment and therefore the early stage of reparative changes in the reconstructed area.

A similar experiment was conducted by Chakhunashvili et al.⁷⁶ using a decellularized human umbilical artery partially repopulated by autogenous porcine cholangiocytes for common bile duct reconstruction in a model of severe

bile flow obstruction. Within the observation period of 84 days, no complications were recorded.

Final histological evidence showed a well-developed epithelial layer with mature cholangiocytes without any signs of transmural inflammation or fibrosis.

Slight differences were made in an experiment by Liu et al.⁷⁷ by using decellularized human splenic artery either with or without repopulation by porcine allogeneic cholangiocytes, labeled by lentivirus-mediated GFP gene. After a period of 8 weeks, decreased fibrotization of the common bile duct and its surroundings and smooth fusion with the native bile duct without any signs of stenosis/bile flow obstruction were found, with GFP-positive cholangiocytes detected by histology and immunofluorescence assay.

Cheng et al.⁷⁸ reported the reconstruction of common bile duct defects in domestic pigs by decellularized allogeneic ureter, with or without support by Kehr drainage or silicone stent. The survival period was 3 months, which produced more complex information about decellularized tissue behavior in biliary tract settings. Animals with Kehr drainage survived without any complications; one pig with silicone stent developed bile duct stenosis, while all animals without bile duct drainage or stenting died prematurely, most frequently from acute cholangitis following a bile duct stenosis creation.

Other attempts were made in the direction of utilizing the biocompatible properties of decellularized tissue while improving its lacking areas, particularly its mechanical properties by adding another compound, such as biodegradable polyurethane.⁷⁹ In vitro, testing of these grafts showed increased mechanical strength and excellent cytocompatibility to support fibroblast survival and proliferation. Subsequent in vivo implantation revealed a change in collagen content throughout new bile duct regeneration. Biliary epithelial cells were observed on day 70, and continuous biliary epithelial layer formation was observed after 100 days of implantation.

Experimental models show that in vitro repopulation by epithelial cells improves decellularized tissue's fate in the biliary system, decreasing fibrotization and promoting functional integration with surrounding tissues, even with creation of bile duct-specific structures such as biliary glands.⁷⁷ The possibility of improving the mechanical properties of decellularized tissue without compromising its advantages seems to be another direction for future research.

4 | CLINICALLY APPLIED MATERIALS

Anatomical reconstruction of the common bile duct by using a bile duct substitute regardless of origin was more

frequently used in the past, most commonly from the 1940s to the 1970s. Currently, it is rarely used due to the relatively safer option of nonanatomical reconstruction, yet there are still sporadic cases in clinical praxis, where anatomical reconstruction of the biliary tree can be performed, more often in situations when noncircumferential substitution of the bile duct wall is needed. In comparison to reported procedures in the 1940s and 1950s, when usually experimental testing of the material was later to actual clinical application, today's standard is to utilize some of the techniques verified by experiment on a large animal, most commonly a domestic pig (Figure 4).

4.1 | Autologous

Autologous tissue seems to be a more common choice of bile duct substitute for anatomical reconstruction of the biliary tree. Its advantage should lie in lesser chance of rejection and subsequent bile leakage in comparison with synthetic substitutes. From a long-term point of view, there should not be a foreign body reaction present in surrounding tissues; on the other hand, its disadvantage lies in its remodeling, leading to possible fibrosis of the substitute itself.

Most commonly utilized autologous substitutes have been made from recipient veins, usually saphenous³⁰ or umbilical veins.⁸⁰ For all these cases, intraluminal stenting was needed with the intention to prevent biliary congestion during the early postoperative period and stricture formation in the later phase of healing and substitute integration into surrounding tissues. In all cases, nonresorbable stents were used, with their removal ranging from 1 to 8 months postoperatively. The results could be considered successful, as Watanabe et al.⁸⁰ reported a small amount of bile leakage during the first three postoperative days as the only biliary complication in two out of four patients with follow-ups ranging from 5 months up to 96 months.

Usage of the round ligament over Kehr's drainage for bile duct reconstruction for noncircumferential necrosis has also been reported,^{81–83} with satisfactory results of having no signs of any significant complication during 2 months, 9 months,⁸¹ and 12 months^{82,83} of follow-up. Although these case reports represent only a small number of patients with bile duct reconstruction by round ligament substitute, it seems that this technique could be a promising later resort option for noncircumferential bile duct reconstruction. From the current point of view, there is a limitation in longer-range follow-up reports on these patients to make a final conclusion.

Similarly, an omental pedicle has been reported by Ng and Kow⁸⁴ in combination with bile duct stenting for Strasberg type D injury of the common bile duct.

According to this case report, this technique led to the temporary solution of bile duct leak with mild stenosis presented after 3 months postoperatively. This led to delayed final reconstruction by hepaticojejunostomy.

A gallbladder flap could also be a possible substitute for bridging defects of a bile duct, although in comparison to experimental reconstruction,²⁵ there are no reports on use for reconstruction of bile duct injury yet, and its possible usage in clinical praxis has already been described for hepatic duct confluence closure after right liver lobe harvesting during living donor transplantation⁸⁵ or for conduit creation to bypass a benign stricture of the common bile duct.⁸⁶

Due to the limited number of cases, it is difficult to evaluate the clinical significance and benefits of these techniques and their possible widespread application, but in some highly selective cases where the conventional approach and reconstruction fail or cannot be utilized, it could be a highly valuable salvage option for biliary reconstruction.

4.2 | Synthetic

Currently, the usage of synthetic materials as grafts for biliary reconstruction in clinical praxis is rare, but there has been an extensive history of clinical trials in the past century. The first material that received wider usage for circumferential bile duct defect reconstruction was vitallium in the 1940s and 1950s.^{87–89} Its application differed according to the case; in some cases, it was used as a stent to prevent stricture formation,⁹⁰ in other cases, it was used to bridge a defect itself,⁸⁷ and there are even reports about manufactured bifurcated vitallium tubes for hepatic duct confluence localization.⁹¹ Its usage gradually fell from favor due to mid-to-long-term complications in the form of plugging resulting in bile obstruction and acute cholangitis.

At the same time, rubber tubes were also reported to be utilized as a graft for bile duct reconstruction,^{91,92} although they were thought to be more prone to bile calculus formation and plugging by some authors⁹¹ than vitallium tubes.

Most likely, the most common synthetic material used in clinical praxis has been polytetrafluorethylene,^{93–95} with some cases sporadically reported up until recent years⁹⁶; unfortunately, the overall results are not too convincing for implementing it as a routine material used as a bile duct substitute.

In a similar position stands the Dacron prosthesis, reported to be used both for bypassing a common bile duct stricture⁹⁷ or a stricturoplasty of a common bile duct.^{40,98} Dacron generally does not achieve the same results as

polytetrafluorethylene in the biliary tract, as common complications such as biliary fistula formations, recurrent cholangitis and poor healing in anastomotic locations have previously been reported.

From a current standpoint, the usage of synthetic grafts as a bile duct substitute in clinical praxis seems to be a method of the past due to the number of possible complications linked to their interaction with recipient tissues, such as cholangitis, bile salt precipitation with subsequent plugging or poor integration in surrounding tissues, possibly leading to biliary fistula formation or anastomotic breakdown with subsequent biloma formation or biliary peritonitis. Due to these findings, in case of a need for an unconventional solution for bile duct reconstruction, a synthetic material as a bile duct wall substitute should be considered only as a last resort option.

5 | CONCLUSION

Problematics of biliary tract injury requiring surgical intervention and repair are vast, without a doubt complicated and challenging issues even for contemporary surgery, especially when long-term outcomes are considered with the intention of creating a definitive solution for a given patient.

Unfortunately, until today, a material enabling its usage as a bile duct wall substitute in clinical praxis regularly has not been found. Published data from the last 100 years provides a clearer picture of required properties, which seems to favor more resorbable materials, mostly supported by the intraluminal stent to ensure patency during initial biointegration in recipient tissues and its subsequent maturation.

There are interesting reports about human amnion usage and results of partially decellularized tissues, which opens up a new possibility for potential local cell therapy to improve healing characteristics of the bile duct itself as well as preimplantation reseeding of the materials with cholangiocytes, which improved outcomes in experimental models.

Due to the summation of these findings, an ideal material should be resorbable, preferably rather in the mid-term time range, to prevent early breakdown and possible bile leakage until recipients surrounding tissues have not fully integrated the implanted material, but also to be resorbed earlier than a possible fibrosis and stricture based on foreign body reaction of recipient's tissues can fully develop. An internal stent/stents should be placed intraluminally to support early stages of integration mechanically as an inner scaffolding ensuring that a sufficient inner diameter of reconstructed

portion remains. A temporary stenting should be considered, since as a foreign body it could lead to bile sludge precipitation and formation of lithiasis at the level of stent, or a bacterial colonization and biofilm creation, leading to recurrent cholangitis. A seeding/recellularization (for decellularized tissues) of the implanted material by either precursor or differentiated cells can be a possible future way to improve integration into tissues of recipients, although currently further research is needed in this area before a clinical application would be possible. Currently, there are still multiple questions requiring an answer before clinical usage of bile duct interponates can be routinely done in a clinical setting, although it seems that the current state is the closest to finally developing appropriate material with ideal properties for clinical application in its long history. Furthermore, there have been interesting findings about techniques for anatomical reconstruction of bile duct injury in clinical settings that could be used in selective cases as a last resort option, where a standard nonanatomical reconstruction cannot be performed.

AUTHOR CONTRIBUTIONS

Jan Sevcik: Conceptualization, data curation, writing – original draft. **Maria Stefania Massaro:** Data curation, visualization. **Richard Palek:** Data curation, visualization. **Vladimira Moulisova:** Writing – review and editing. **Vaclav Liska:** Supervision, writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing financial or nonfinancial interest that are directly or indirectly related to the work submitted for publication.

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