CLINICAL RESEARCH

Novel method of surgical preparation for transcatheter completion of Fontan circulation: Creation of an extracardiac pathway

Une méthode originale de préparation chirurgicale pour la réalisation d’une circulation de Fontan percutanée : création d’une voie extracardiaque

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Congenital heart defect; Fontan circulation; Transcatheter technique; Hybrid approaches

Summary

Background. — The alliance between surgeons and interventionists has inspired creative techniques to surgically precondition the heart for subsequent transcatheter repair. The interest stems from the need to avoid repeated surgeries. Transcatheter Fontan completion of intracardiac pathway has been reported.

Aim. — To report a new surgical preparation for transcatheter completion of extracardiac Fontan circulation.

Methods. — The inferior vena cava (IVC) was cut and anastomosed end-to-end with the inferior end of a Gore-Tex conduit in 20 lambs. A ring was placed around the IVC near the anastomosis. The superior vena cava was cut and connected with the right atrium (RA) auricle. In group 1

Abbreviations: IVC, inferior vena cava; PTFE, polytetrafluoroethylene; RA, right atrium; RAA, right atrial appendage; SVC, superior vena cava.

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Background

Children with functionally univentricular hearts face remarkable struggles throughout their lives. The development of the classic Fontan operation has significantly improved their long-term survival, but repeated surgeries impact on survival and quality of life. The incidence of atrial arrhythmias secondary to atrial scarring after classic Fontan ranges from 4% to 35% at 5-year follow-up, and up to 40% at 10-year follow-up [1]. Atrial arrhythmia may lead to reduced cardiac output and left ventricular dysfunction, both of which may detrimentally affect Fontan physiology. Extracardiac Fontan surgery deserves special attention as it reduces atrial scarring and thereby, the incidence of atrial arrhythmia. Furthermore, the incidences of obstruction of the cavopulmonary pathway, reoperation, thromboembolism and late death is reported low with extracardiac Fontan circulation [2].

The alliance between surgeons and interventional cardiologists during hybrid procedures has inspired some highly creative techniques to surgically precondition the heart for subsequent transcatheter repair. The interest for such procedures stems from the need to avoid repeated surgeries and accomplish Fontan completion with minimal invasion. The attributes of ideal surgical preparation for transcatheter completion of Fontan circulation include:

- achievement of a safe and viable preparation without the use of extracorporeal circulation and cardiac arrest;
- a minimal quantity of foreign material left in the systemic atrium;
- no interference with sinus rhythm;
- limited atrial scarring;
- the use of conduits of sufficient diameter to accommodate future cardiac growth and thus avoid surgical redo;
- most importantly, safe completion of Fontan circulation using transcatheter techniques.
Keeping these attributes in mind, we have developed new techniques of surgical preparation for further transcatheter completion. We have previously reported the creation of a model that mimics a Fontan circulation, thus allowing surgical conditioning and transcatheter completion to be tested [3]. Both intracardiac and extracardiac pathways were tested in ewes [3,4]. The extracardiac pathway initially consisted of a non-circulant pathway—an occluded Gore-Tex filled with saline was connected to create the Fontan-like circulation in a model of fully grown ewes. The aim was to test the non-circulant extracardiac pathway and a new circulating pathway in growing animals. In order to try to improve the pathway and see if the good results were sustained in a growing animal model of Fontan, we report here the evolution of a previously published extracardiac pathway in a population (growing animals) more closely related to clinical practice.

Methods

Animals

Twenty lambs weighing 20±2.5 kg were included and divided into two groups: nine in group 1 (non-circulant extracardiac pathway) and 11 in group 2 (circulant extracardiac pathway). Experiments on all animals in group 1 were completed prior to those on animals in group 2. All animals received humane care in compliance with the standards of European Convention on Animal Care. The study was approved by the local institutional ethics committee (INRA, Paris, France). Qualified personnel supervised the procedures and adequate anaesthesia using inhaled isoflurane (1–5%) was used to minimize unnecessary pain.

Surgical preparation

Animals underwent endotracheal intubation and mechanical ventilation under sedation. Surgical preparation was performed without extracorporeal circulation using temporary vascular clamping. The heart was exposed through a right thoracotomy. A Gore-Tex conduit was interposed between the superior vena cava (SVC) and the inferior vena cava (IVC). No anticoagulation was given to animals during the study.

Group 1 (non-circulant)

Animals in group 1 underwent the non-circulant extracardiac pathway surgical technique (Fig. 1) as has been previously reported [4]. Briefly, a 20-mm Gore-tex conduit—de-aired and filled with heparinized saline—was anastomosed to connect the SVC and the IVC. The IVC end was anastomosed in a termino-lateral fashion and the SVC end in a termino-terminal fashion; both ends were occluded with a polytetrafluoroethylene (PTFE) membrane. Due to the latero-terminal connection of the IVC, the blood from the IVC could flow freely to the right atrium (RA) as normal. Metallic rings were placed around the superior and inferior connections at the level of the occluding membranes (Fig. 1B).

Group 2 (circulant)

In animals in group 2, the connections were modified to create a circulant pathway (Figs. 2 and 3). At the IVC end, an end-to-end anastomosis was performed that directed all blood from the IVC into the conduit. A nitinol wire was used to create an open ring of diameter 16 mm. Using the property of memory alloy, after straightening and release of constraint, the wire regained its ring configuration. This ring was straightened, placed and fixed around the extracardiac conduit and the IVC just below the level of the anastomosis. In the middle section, a large connection (larger than "classical" fenestration) was created at the upper segment of the extracardiac Gore-Tex conduit. This was connected laterally to a similarly large opening in the RA to allow free flow and washout of the conduit by IVC blood. The SVC was cut and connected to the RA auricle in an end-to-end fashion. The upper end of the Gore-Tex conduit was occluded with a PTFE membrane. A venous segment harvested from a small Contegra conduit (Medtronic Inc., MN, USA) was connected between the Gore-Tex conduit and the SVC to reduce the diameter and allow a smooth connection with the SVC. An end-to-side anastomosis was performed between the venous segment and the SVC. A short stent (CP, Numed, NY, USA; 2 rows) was placed around or inside the venous segment as reported previously [4]. The stent was secured with single stitches before suturing to the SVC. The chest was then closed and lambs were sent to the farm to recover and heal for subsequent transcatheter Fontan completion.

Interventional catheter completion

At 1–3 months after surgical preparation, cardiac catheterization was performed using both right femoral and internal jugular veins (8Fr). Using fluoroscopic guidance, a 7Fr long Mullins sheath (Cook, IN, USA) was placed from the right common femoral vein in the conduit. A paediatric trans-septal needle was advanced into the Mullins sheath and positioned in contact with the membrane separating the conduit and the SVC by tilting the needle clockwise. The position was verified in two planes.

In group 1, we expected to advance a wire in the non-circulant conduit to get contact with the inferior IVC membrane after puncturing the superior SVC membrane. The second membrane would then be perforated and vascular stents would be placed as reported previously [4].

In group 2, the stent used in the interposed venous segment served as an important radiological landmark to position the needle. When in position, the needle was pushed through the membrane. A 0.014" wire was then passed through the lumen of the needle and snared from the neck. Following the perforation of the membrane, balloons of increasing diameters were inflated at the level of the stent until complete disappearance of the waist. A 14-Fr sheath was advanced over a stiff guide wire into the IVC. A covered stent graft (CP covered, Numed Inc.) mounted on 22-mm BIB catheter (Numed Inc.) was placed to cover and exclude the opening of the conduit with the RA (i.e. large fenestration). Additional bare metal stents (uncovered CP stent, Numed Inc.) were placed at the SVC and IVC connections when required.
Selective angiographies (Figs. 4 and 5) were performed at subsequent steps:
- initially, to confirm the competence of the occluding membrane;
- the patency of the SVC–RA connection;
- the patency of the fenestration;
- after re-establishment of the pathway between the SVC and the extracardiac conduit to confirm opening of the membrane;
- after placement of covered stents to confirm sealing of the covered stents.

Sacrifice

As per the study protocol, animals were planned to be converted 3 months after surgical preparation. However, following the results from group 1, the plan was modified. In group 2, the first animal was not converted, but was sacrificed after 2 months in order to macroscopically assess the integrity of the pathway. All animals except two were sacrificed just after the completion. The other two animals were planned to be electively sacrificed 3 months after completion.

Results

Group 1 (non-circulant)

Group 1 results are summarized in Table 1. All nine animals were successfully preconditioned; and no animals died in the interstage period separating surgical preparation and completion. Nine animals were brought to the cardiac catheterization laboratory for completion of their pathway 1 to 3 months following surgery (mean 2.5 months). Perforation of the SVC membrane was successfully achieved in
Figure 2. Circulant extracardiac pathway (group 2) surgical technique. (A) Internal and (B) external views showing the IVC with an RA rim connected to the Gore-Tex conduit in an end-to-end anastomosis fashion. (C) Internal and (D) external views after transcatheter completion; the superior membrane was perforated and a stent placed to cover the large fenestration. The IVC blood then flowed through the pathway. IVC: inferior vena cava; RA: right atrium.

Table 1  Schematic summary of the study.

<table>
<thead>
<tr>
<th>Step</th>
<th>Group 1: non-circulant extracardiac pathway (n = 9)</th>
<th>Group 2: circulant extracardiac pathway (n = 11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1: surgical preparation</td>
<td>Successful in 9/9</td>
<td>Successful in 11/11; 1 postoperative death</td>
</tr>
<tr>
<td>Step 2: transcatheter completion</td>
<td>Mean 2.5 months after step 1; successful in 0/9</td>
<td>Mean 2.2 months after step 1; attempted and successful in 9/9 surviving animals</td>
</tr>
<tr>
<td>Step 3: sacrifice</td>
<td>At the time of completion in 9/9; complete occlusion of the Gore-Tex conduit</td>
<td>At the time of completion (n = 7)</td>
</tr>
</tbody>
</table>

a Of the 11 animals, one died after the surgical preparation and one was sacrificed prior to transcatheter completion to check the integrity of the created pathway.
all animals, but we failed to create the expected pathway because the non-circulant Gore-Tex conduit was completely occluded from one end to the other. At autopsy, the conduit was filled with a compact fibrous tissue, which explained why the pathway could not be completed (Fig. 6).

**Group 2 (circulant)**

Group 2 results are summarized in Table 1.

**Preconditioning**

All 11 animals were successfully preconditioned. One animal died postoperatively secondary to an occlusion of the SVC–RA connection. At autopsy, the anastomosis was occluded by pectinate muscles with a large amount of blood exsanguinated in the thoracic cavity. The remaining animals showed uneventful recovery. As planned, the first surviving animal was sacrificed 2 months after surgery without undergoing completion to look for the integrity of the created pathway.
Transcatheter completion of Fontan circulation

SVC–RA anastomosis was patent but partially occluded by uncut pectinate muscles.

Assessment before completion

The remaining nine animals were brought to the cardiac catheterization laboratory for completion of their pathway at 1–3 months following surgery (mean 2.2 months; median 3 months). Angiographies showed free patent pathways in all animals except one. One animal had a stenosis at the level of the IVC anastomosis with a mean gradient of 2 mmHg. The fenestration was widely patent in all. The SVC–RA anastomosis was patent but partially stenosed in 3/9 animals with minimal gradient (0–2 mmHg; mean 1 mmHg). The PTFE membrane was still occlusive and pliable. In one animal, the gap between the SVC and the conduit was particularly long with an occluded segment of around 1 cm.

Completion

Perforation of the membrane was easily performed using a trans-septal needle placed from below in 8/9 animals. In the remaining animal (the one with the long occluded segment), it required multiple attempts before successful perforation. A mean of two balloon dilatations was required in all animals to completely open the conduit–SVC segment. In the animal with the long occlusion, a stent was required. Closure of fenestration was easily performed using covered stents. The animal with the stenosis of the IVC–conduit anastomosis required the placement of a stent in this region. This stent was easily placed and perfectly anchored partially within the conduit and maintained partially by the ring placed around the IVC during the previous surgery. There was no stent dislodgement or embolization noted in any animal. Haemodynamic assessment showed no gradient between the IVC, the conduit and the SVC. However, a significant SVC–right atrial appendage (RAA) gradient was noted in most animals (2–6 mmHg; mean 4 mmHg). This gradient increased after Fontan completion as the entire cardiac out-

Figure 5. Angiographic views showing the steps to perform the completion and the final pathway created after completion in animals in group 2. (A) Still frame showing a trans-septal needle perforating the occluding membrane. (B) Balloon dilatation of the stented venous segment. (C) Placement of a covered stent to exclude the fenestration. (D) Final result after completion.

Cardiac catheterization prior to sacrifice showed patent extracardiac pathway, patent conduit–RA opening, complete occlusion of the conduit–SVC connection and a patent SVC–RA connection. Haemodynamics showed no gradient between the conduit and the RA but a mean gradient of 2 mmHg between the SVC and the RA. At ex vivo examination, the IVC anastomosis was widely patent and the PTFE membrane was covered by fibrous tissue. The

Figure 6. Autopsic picture of non-circulant pathway (group 1) showing complete occlusion of the Gore-Tex conduit by dense, compact fibrous tissue.
put except for the coronary sinus blood was now passing through this relatively small SVC–RAA connection.

According to the protocol, two animals were sacrificed 3 months after Fontan completion. Haemodynamics were unchanged in these animals showing a mean gradient of 2 mmHg at the level of the SVC–RAA connection. At autopsy, the IVC was largely patent. The connection of the SVC with the RAA was partially occluded by uncut pectinate muscles. Covered stents were well-deployed with good apposition and complete occlusion of fenestration (Fig. 7).

Discussion

Despite its advent in the late 1990s, transcatheter techniques for Fontan completion are still considered largely experimental and are performed in selected few centres around the world. Moreover, the surgical technique to prepare the heart for transcatheter Fontan completion has seen multiple revisions since its introduction. New challenges surface at each change and the quest for an ideal surgical technique continues. Hausdorf et al. [5] were the first to attempt transcatheter completion of a hemi-Fontan with balloon dilatation of the banded cavo-atrial junction and fenestration closure using either a covered stent or occluders [6]. Subsequently, Klima et al. [7] developed a new approach by establishing bidirectional Glenn circulation and subtotal banding of the SVC at the cavo-atrial junction, along with PTFE cuff placement around the IVC; all performed in the absence of cardiopulmonary bypass. To facilitate placement of the graft stent in the SVC–RA junction, and to avoid residual obstruction around the SVC band site, Galantowicz et al. [8] and Cheatham et al. [9] closed the SVC–RA junction by a pericardial patch for a subsequent intracardiac stent. Konstantinov et al. modified this further by placing stents at the level of both atrio-caval junctions [10,11]. The atrial SVC was then connected to the inferior face of the unopened right pulmonary artery. We further modified this model by using a specially designed covered stent occluded in the centre by a PTFE membrane with excellent outcomes of transcatheter completion [12].

The use of extracorporeal circulation, cardiac arrest and the insertion of foreign material inside the heart with such techniques lead to significant atrial scarring and atrial arrhythmia in the long term. Atrial arrhythmia can reduce cardiac output and cause left ventricular dysfunction; both of which can prove highly detrimental for Fontan physiology. Extracardiac Fontan has minimal atrial scarring in contrast to the classic Fontan surgery. In lieu of such concerns and in the quest to create an ideal heart model, there is a compelling need to focus on new methods of surgical preparation with the creation of a unique pathway that would answer these questions.

We initially reported and tested a non-circulating pathway connecting an occluded Gore-Tex conduit to the SVC and IVC in adult animals, in which completion was possible. In this study, we wanted to test this pathway in a growing population but failed to complete the pathway as expected (group 1), showing the need for conduit washout. We therefore modified our approach (group 2) to create a circulating pathway (an evolution of the previous non-circulating pathway). The conditioning of animals from group 2 was designed to mimic the actual surgical gold standard technique of extracardiac total cavopulmonary connection. The technique we used is quite similar to what is done in most centres performing surgical extracardiac total cavopulmonary connections after partial cavopulmonary connection. Minor modifications to the existing technique were made to allow transcatheter completion. Firstly, we integrated a rim of RA tissue to allow the use of a 16–22-mm conduit that is sufficient in size even for an adult. The insertion of a 16-mm conduit would have been easier in our model. Large fenestration at the upper segment very close to the occlusive PTFE membrane allowed free flow from the IVC to the RA and complete washout of the conduit by IVC blood with no stasis or stagnation and thus less chance of thrombus formation. A short, stented segment harvested from a Contegra conduit was used in our study to interpose between the Gore-Tex conduit and the small native SVC (pulmonary artery in humans) diameter to allow smooth transition. This could probably be tailored from the neighbouring native tissue in humans. Using this new pathway, animals were easily converted in most cases.

One should understand what modifications were made for the creation of the Fontan model and what represents the surgical preparation of the transcatheter Fontan completion. The superior connection of the SVC to the RA auricle is only done to allow chronic survival in the animal model. This step is, of course, unnecessary in humans and should be replaced by connection to the right pulmonary artery as is usually performed in extracardiac total cavopulmonary connection (Fig. 8). The experimental results after transcatheter completion appear very promising. Complications theoretically possible with intracardiac transcatheter Fontan—such as sinus node lesion, conduction disturbances or thrombus formation in the systemic atrium—are unlikely to occur in the presented extracardiac pathway.

Clinical implications

We believe that our surgical preparation closely mimics the pre-Fontan preparatory stage of a univentricular heart from an interventional standpoint. The low rate of complications and no spontaneous deaths in the perioperative period and during follow-up favours the standardization of this technique for the creation of a chronic model for transcatheter completion of extracardiac Fontan completion. The uniform survival makes this a good, reproducible technique and also offers a stable platform for subsequent transcatheter completion. We believe that our method of surgical preparation marks a milestone for the further development of transcatheter and hybrid strategies to accomplish transcatheter completion of extracardiac Fontan in the same setting with a significant reduction in atrial scarring and intracardiac foreign material and, possibly, a reduced risk of stent failure [13,14].

Limitations

The lack of long-term outcome data is one limitation of this study. However, the platform created with the connection of the SVC to the RA does not modify the anatomy of the animal and allows long-term survival. Of course, this model does not mimic a Fontan circulation, but no
viable model of univentricular circulation is presently available to chronically test a Fontan circulation. However, it does allow testing of all the steps for a Fontan-like circulation from surgical preparation to transcatheter completion. Moreover, chronic complications (e.g., thrombus formation, stent fractures) of such procedures can be assessed as it is a viable model. The haemodynamics represent a Fontan circulation and can reveal and describe — along with angiographies — complications such as stenosis of the anastomosis/stent or small and restrictive fenestration.

The properties of the interposed materials (Gore-Tex, stent, Contegra segment) may pose challenges in the future with regard to cardiac growth. However, we tested the expansion properties of Contegra material, in vivo and in

Figure 7. The fenestration is shown after sacrifice in (A) acute and (B) 3-month evaluations (group 2).

Figure 8. The circulant pathway as it would be done in humans. (A) Internal and (B) external views of the surgical preparation. (C) Internal and (D) external views after Fontan completion. PTFE: polytetrafluoroethylene.
vitro, and it showed good expansion properties (data not shown) [15]. Moreover, we interposed large Gore-Tex conduits and stents to avoid the need for re-expansion.

Despite very good experimental results, questions remain for future clinical applications, e.g. what anticoagulation strategy would be required? Moreover, like any innovative technique, clinical studies will be necessary to compare the present surgical staged strategy and a hybrid approach.

Conclusions

An innovative way of surgical preparation using an off-pump surgical technique for subsequent transcatheter completion of extracardiac Fontan circulation is described. The surgical preparation opens new frontiers for transcatheter and hybrid techniques for completion of extracardiac Fontan circulation. Further long-term studies with a similar chronic heart model may be required before such techniques may be implemented clinically.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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