

# Total cavopulmonary connection in patients with apicocaval juxtaposition: optimal conduit route using preoperative angiogram and flow simulation<sup>†</sup>

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## Abstract

**OBJECTIVES:** Single ventricle with apicocaval juxtaposition (ACJ) is a rare, complex anomaly, in which the optimal position of the conduit for completion of total cavopulmonary connection (TCPC) is still controversial. The purpose of this study was to identify a pre-operative method for optimal conduit position using the IVC anatomy and computational fluid dynamics (CFD).

**METHODS:** Twenty-four patients with ACJ ( $5.3 \pm 5.7$  years) who underwent TCPC were enrolled. A conduit was placed ipsilateral to the cardiac apex in each of 11 patients, of which 9 were intra-atrial and 2 extracardiac (group A) and, in a further 13 patients, extracardiac on the contralateral side (group B). As control, 10 patients with tricuspid atresia were also enrolled (group C). The location of the IVC in relation to the spine was evaluated from the frontal view of preoperative angiogram, using the following index: IVC-index = IVC width overlapping the vertebra/width of the vertebra  $\times 100\%$ . Energy loss was calculated by CFD simulation.

**RESULTS:** IVC-index of group B was larger than groups A and C ( $45 \pm 26$  vs.  $20 \pm 21$  and  $28 \pm 19\%$ ,  $P = 0.03$ ). Postoperative catheterizations showed that, due to its curvature, conduit length in group B was significantly longer than the others ( $65 \pm 12$  vs.  $36 \pm 14$  and  $44 \pm 10$  mm,  $P < 0.001$ ), although there was no statistical difference in central venous pressure or cardiac output. CFD studies revealed less energy loss in group A conduits compared with group B ( $1.6 \pm 0.3$  vs.  $3.6 \pm 0.6$  mW,  $P = 0.05$ ), although this did not appear to be clinically significant. Moreover, CFD simulation showed significant energy loss within the Fontan circulation when the conduit was either compressed or kinked: 4.9 and 18.2 mW respectively.

**CONCLUSIONS:** In patients with ACJ, placement of a straighter and shorter conduit on the ventricular apical side provides better laminar blood flow with less energy loss. However, conduit compression and kinking are far more detrimental to the Fontan circulation. A preoperative IVC-index is pivotal for avoiding these factors and deciding the optimal conduit route.

**Keywords:** Total cavopulmonary connection • Apicocaval juxtaposition • Flow simulation • Computational fluid dynamics • Angiography

## INTRODUCTION

The presence of apicocaval juxtaposition (ACJ) in patients with single ventricle is a rare, complex anomaly that can complicate surgical approach at the time of completion of total cavopulmonary connection (TCPC) [1, 2]. Since Fontan *et al.* reported a surgical treatment for tricuspid atresia, Fontan operation including TCPC has been utilized as a surgical treatment for single ventricle variants [3, 4]. Currently, the two most commonly used procedures for TCPC include a lateral tunnel TCPC and extracardiac TCPC. Although the artificial conduit used for the extracardiac TCPC does not have growth potential, this extracardiac

method has become the preferred operation because it is relatively simple to perform; there is no need for aortic cross-clamping; there are fewer atrial wall sutures and perhaps more efficient, laminar flow with less energy loss [5].

However, in patients with ACJ, the heart is malpositioned and optimal positioning of the extracardiac conduit is therefore controversial. Conduit placement ipsilateral to the cardiac apex carries the risk of conduit compression posteriorly by the ventricle and conduit placement contralateral to the cardiac apex needs a long and curved conduit, which carries the risk of stagnant flow and conduit kinking [6, 7].

The purpose of this study was to determine the optimal conduit route in patients with single ventricle and ACJ. Clinical outcomes from two centres were reviewed and computational

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fluid dynamics (CFD) were performed using MRI and angiographic data to evaluate conduit route from an energy loss standpoint for future preoperative surgical planning.

## MATERIALS AND METHODS

### Patient population

Twenty-four patients with single ventricle and ACJ, who underwent TCPC, were enrolled from the Children's Hospital of Pittsburgh in the United States and Kobe Children's Hospital in Japan.

Three groups were identified; group A included patients whose intra-atrial or extracardiac conduit was placed ipsilateral to the cardiac apex; group B included patients with a conduit placed to the contralateral side of the cardiac apex and group C served as a control and included patients with tricuspid atresia (Fig. 1). Informed consent from all patients, plus institutional review board approval, was obtained to use patients' data for this clinical research.

### Surgical procedure in apicocaval juxtaposition

After median sternotomy, the pulmonary artery, superior vena cava (SVC) and inferior vena cava (IVC) were dissected and, depending on the IVC location, the conduit could be placed either ipsilateral or contralateral to the cardiac apex. If the IVC was located more towards the apex, the conduit was placed

ipsilateral and, if the IVC was located more medially, then the conduit was placed on the opposite side of the apex. (When the conduit is ipsilateral, the adhesions around the cardiac apex need to be dissected completely. When the conduit is contralateral, the adhesions from the IVC all the way to the pulmonary artery need to be dissected to make space for the conduit.) After establishing cardiopulmonary bypass—using arterial and bicaval cannulation and without cross-clamping—conduit placement from the IVC to pulmonary artery was completed using 16–24 mm Gore-Tex tube (W.L. Gore & Associates, Flagstaff, AZ, USA). If the conduit was placed intra-atrially or additional intra-cardiac surgery was needed e.g. valvuloplasty, then aortic cross-clamping was used. Intra-atrial TCPC was done by anastomosis between a conduit and the IVC inside the atrium and the conduit was led outside the atrium to be anastomosed with the pulmonary artery. In patients with bilateral Glenn anastomosis, it was placed in between the SVCs, regardless of conduit route. In patients with Glenn anastomosis in the opposite side of the conduit, the pulmonary side of the conduit was directed towards the Glenn side to distribute hepatic factor bilaterally.

### Inferior vena cava-index

The IVC-index refers to the distance of the IVC from the spine. This is evaluated from the preoperative frontal view angiogram and is defined as the percentage ratio between the part of the IVC overlapping the vertebra and the width of the vertebra.

$$\text{IVC-index} = \frac{\text{IVC width overlapping the vertebra}}{\text{Width of the vertebra}} \times 100$$

Additionally, the distance between the posterior wall of the IVC and the anterior margin of the vertebra was measured from the lateral view angiogram (Fig. 2).

### Computational fluid dynamics simulation

Energy loss was calculated with CFD simulation using either existing cardiac MRI or angiograms. CFD simulations were performed in three patients from each of groups A and B. Though CFD simulations in patients with single ventricle and ACJ were recently studied by Prahlad *et al.* [8], in this report we further

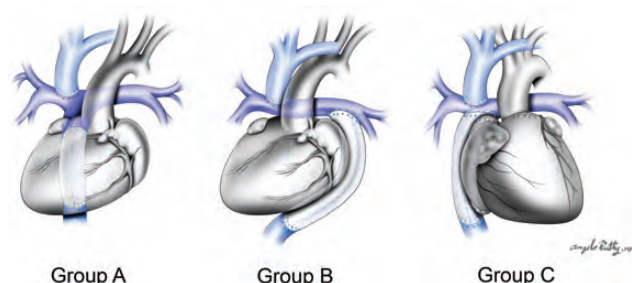


Figure 1: Grouping of patients according to the type of surgery.

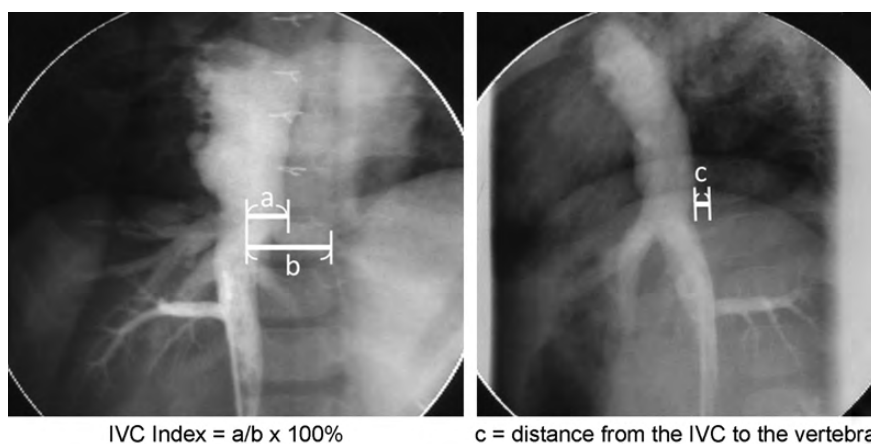


Figure 2: Measurement of the IVC location in relation to the vertebra.

analysed our previous *in-silico* studies by examining altered energy loss and pressure fields in two different simulated clinical scenarios: (a) compression of a straight conduit between the heart and the vertebra and (b) kinking of a curved conduit due to excessive curvature (Fig. 3).

An in-house cardiovascular flow solver incorporating a validated, second-order-accurate, multi-grid artificial compressibility numerical solver was used to simulate incompressible and Newtonian blood flow with constant haemodynamic properties ( $\rho = 1060 \text{ kg/m}^3$ ,  $\mu = 3.71 \times 10^{-3} \text{ Pa.s}$ ) in each *in-silico* model [8]. This was done under steady inflow conditions, assuming a constant inflow split (40% SVC; 60% IVC) and a cardiac output of 3.9 L/min. Pulmonary mass-flow split was set as a constant as per observations from PC-MRI (41% right pulmonary artery, 59% left pulmonary artery).

Internal energy loss was evaluated across each Fontan conduit, including kinked or compressed conduits, in comparison with their un-kinked and un-compressed versions.

Data analysis

Preoperative and postoperative data were retrospectively collected. Descriptive data for continuous variables are presented as mean  $\pm$  SD or as median with range; categorical variables are presented as relative frequency. Events were defined as conduit

stenosis, re-operation with conduit replacement, and death. Surgical mortality was defined as death within 30 days of operation. Analysis was performed with JMP 8.01 for Macintosh (JMP, Cary, North Carolina, USA).

RESULTS

There was no statistical difference in age, weight, conduit size or follow-up periods between groups. Situs solitus was seen in seven patients in group A, two patients in group B and all patients in group C; situs inversus was seen in three patients in group A and seven in group B; right isomerism was seen in one patient in group A and four in group B (Table 1).

Surgical mortality, caused by recalcitrant arrhythmia, was seen in one patient with right isomerism in group B. In one patient from group A who underwent extracardiac TCPC, the chest could not be closed due to conduit compression and required partial sternum bone resection. One patient from group B had excessive conduit curvature resulting in kinking and required revision from extracardiac to intra-atrial conduit. Both patients recovered completely after these additional procedures. Late mortality was seen in a 6 kg patient in group B who had a history of repaired total anomalous pulmonary venous obstruction and bilateral, bidirectional Glenn anastomosis for right isomerism. Due to space limitations and concern for pulmonary

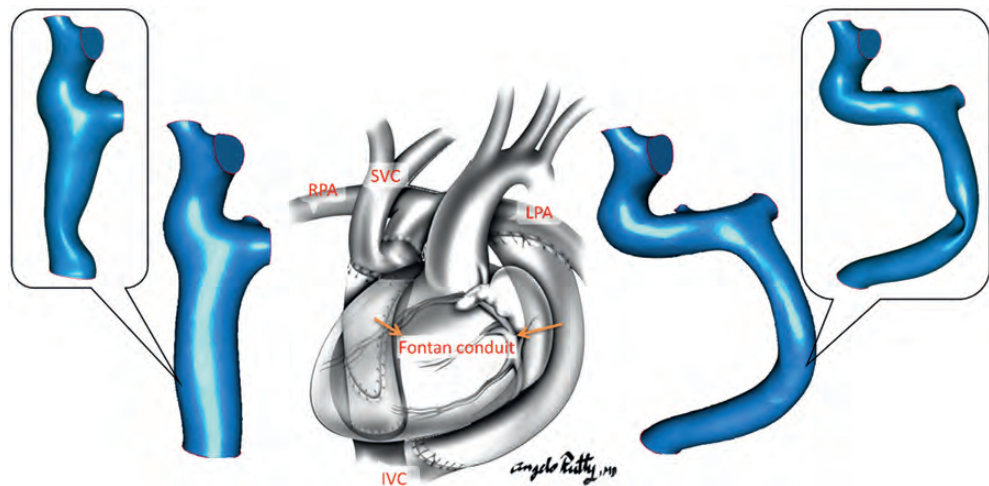


Figure 3: *In-silico* models for CFD simulation including compressed and kinked versions of the straight and curved conduits.

Table 1: Patient profiles and comparison

	Group A (n = 11)	Group B (n = 13)	Group C (n = 10)	P-value
Age, years	5.9 $\pm$ 7.1 (median 2.8)	4.8 $\pm$ 4.3 (median 3.3)	3.8 $\pm$ 1.9 (median 3.2)	n.s.
Weight, kg	19.5 $\pm$ 18.4 (median 12.2)	16.1 $\pm$ 11.7 (median 13.1)	12.5 $\pm$ 2.8 (median 11.8)	n.s.
Conduit size, mm	19.8 $\pm$ 1.7	19.4 $\pm$ 1.6	19.8 $\pm$ 0.7	n.s.
Follow-up, years	5.6 $\pm$ 3.3	5.0 $\pm$ 2.1	6.0 $\pm$ 1.8	n.s.
Situs	S: 7, I: 3, R: 1	S: 2, I: 7, R: 4	S: 10	

S: situs solitus; I: situs inversus; R: right isomerism.

venous obstruction, the extracardiac conduit was placed contralateral to the cardiac apex instead of ipsilateral. Unfortunately this patient developed significant liver dysfunction and died 2 months after surgery.

Group B IVC-index was larger than groups A and C ( $45 \pm 26$  vs.  $20 \pm 21$  and  $28 \pm 19\%$ ,  $P = 0.03$ , Fig. 4). The group A patient who required partial sternal removal had an IVC-index of 80% indicating that, in this case, placement of the extracardiac conduit contralateral instead of ipsilateral to the cardiac apex would have been a more appropriate position. The group B patient who required conversion to intra-atrial conduit had an IVC-index of 12%. In retrospect this conduit should have been placed ipsilateral to the cardiac apex since a 12% IVC-index can be associated with excessive conduit curvature when placed contralateral to the apex. In group B, a patient with late mortality had an IVC-index of 14.5. His liver dysfunction might have been caused by a long and excessively curved conduit.

The distance between IVC and the vertebral bone was  $7.6 \pm 3.5$ ,  $5.4 \pm 5.9$  and  $9.3 \pm 5.1$  mm, respectively. In the majority of the patients the IVC was located anterior to the vertebra and in one it was located 3 mm behind the vertebral bone.

In nine cases from each group, cardiac catheterization was performed 1 month after surgery. Data from the catheterization showed that the conduit length in group B was significantly

longer than groups A and C, respectively ( $65 \pm 12$  vs.  $36 \pm 14$  and  $44 \pm 10$  mm,  $P < 0.001$ , Fig. 5), due to its curvature. However there was no statistical difference in central venous pressure ( $13.6 \pm 2.7$ ,  $14.9 \pm 2.5$  and  $13.6 \pm 2.0$  mmHg) or cardiac index ( $2.7 \pm 0.6$ ,  $2.7 \pm 0.6$  and  $2.6 \pm 0.6$  L/min/m<sup>2</sup>), respectively.

CFD studies revealed less energy loss in group A conduit than in group B ( $1.6 \pm 0.3$  vs.  $3.6 \pm 0.6$  mW,  $P = 0.05$ ), however these numbers are both relatively low energy losses, associated with Fontan completion [9]. Further CFD simulation for significant conduit compression and kinked model showed energy loss of 4.9 and 18.2 mW, respectively, indicating that, in these clinical scenarios, significant energy loss could result within the Fontan circulation (Table 2). Pressure gradient measurements from the IVC to pulmonary artery revealed increased gradients resulting from kinking and compression, shown in Figure 6.

## DISCUSSION

In this study, once the early phase of Fontan circulation is completed, patients with ACJ were doing well without any difference in central venous pressure or cardiac index. Each of the two groups had one case where the conduit could have been placed to the opposite site to where it was actually done. It is necessary to find a reliable and helpful method of preoperative planning to decide the route of conduit, instead of making decisions only from operative findings.

Although CFD studies showed less energy loss in group A than group B, the degree does not appear to be clinically significant for Fontan circulation [9]. Blood flow collision, caused by a non-offset situation, could cause more energy loss than a curved

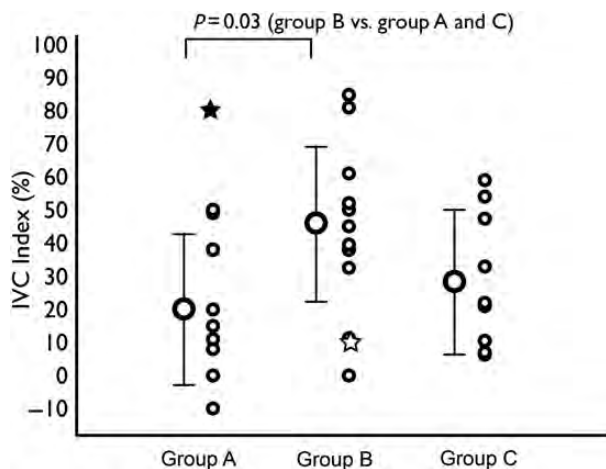


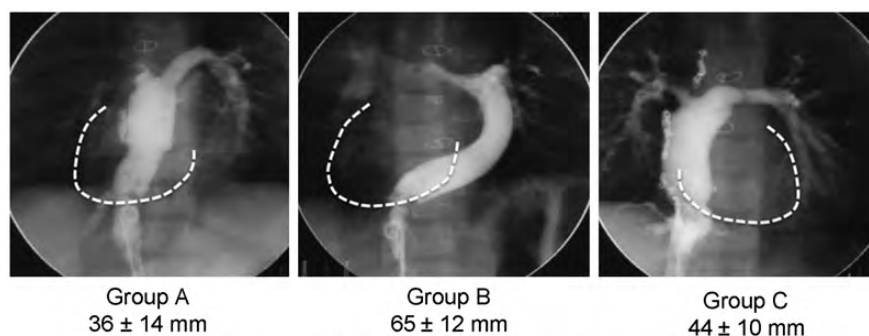
Figure 4: Results of IVC-index. The solid star represents the case who needed partial sternal bone resection. The empty star represents the case who needed conduit revision.

Table 2: Computational fluid dynamics energy loss comparisons between groups, including simulation of compressed and kinked conduit situations

	Group A (n = 3)	Group B (n = 3)	P-value
E <sub>Loss</sub> in the conduit, mW	$1.6 \pm 0.3$ 4.9 <sup>a</sup>	$3.6 \pm 0.6$ 18.2 <sup>b</sup>	0.05

<sup>a</sup>Compressed conduit model.

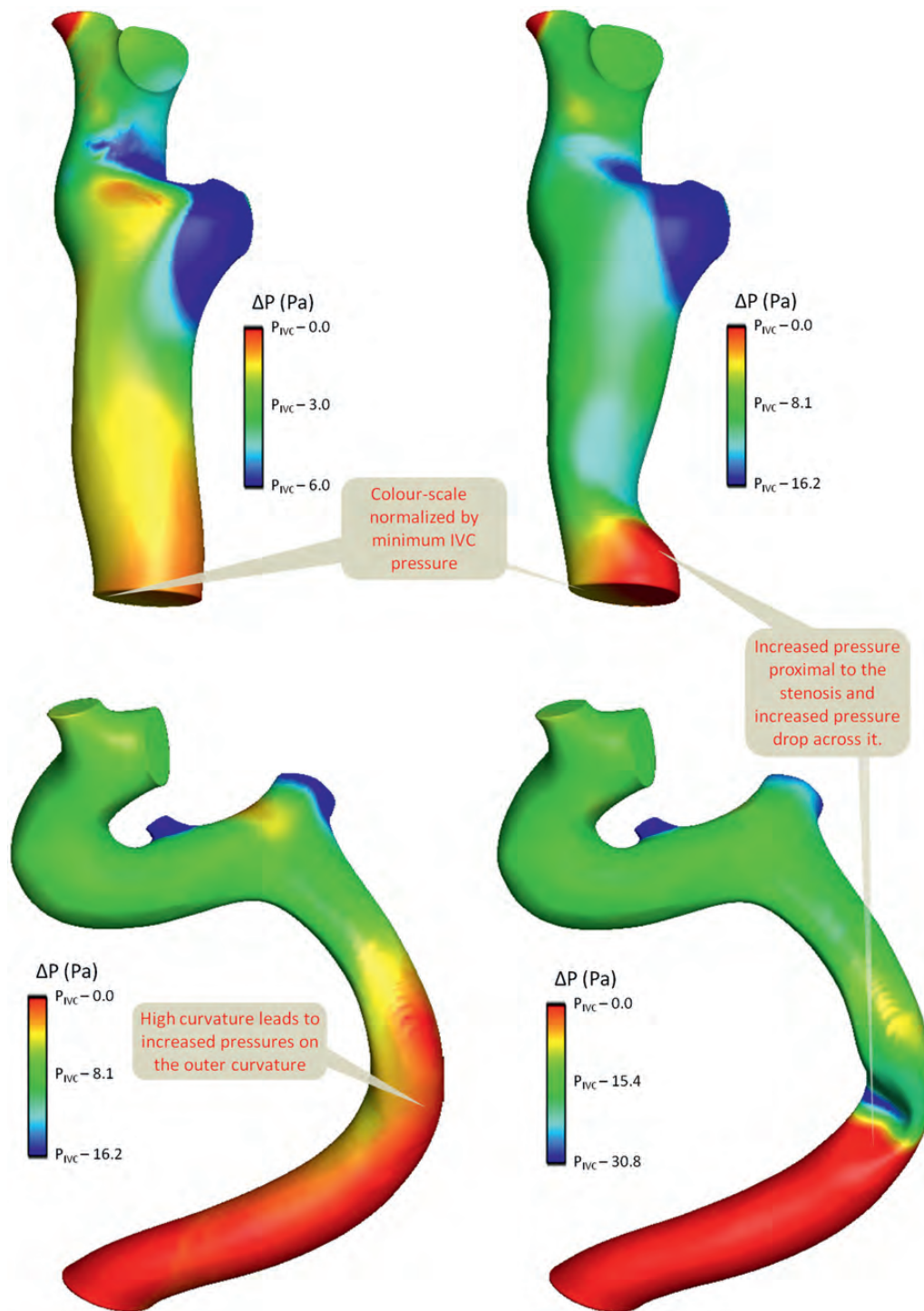
<sup>b</sup>Kinked conduit model.



$P < 0.001$  Group B vs. Groups A and B

Figure 5: Length of the conduits.





**Figure 6:** CFD pressure gradients compared between compressed or kinked conduits and un-compressed or un-kinked counterparts. Pressure gradient is plotted as a colour map relative to the IVC pressure.

conduit [8]. Furthermore, this study demonstrates that conduit compression and conduit kinking could result in significant energy loss that could jeopardize the Fontan circulation. In this special situation of TCPC with ACJ, it appears to be more important to avoid conduit compression and conduit kinking than curved and long conduits. Therefore a reliable method is required to avoid conduit compression or kinking.

Preoperative evaluation of the IVC location in relation to the spine is an important factor. Interestingly, the IVC is always

above the spine level, so the conduit never sits behind the spine. That means we do not have to hesitate to place the conduit contralateral to the cardiac apex because of concern over conduit compression from the vertebrae. Basically, compression can occur between the ventricle and the spine, when a conduit is placed ipsilateral to the apex. However, conduit kinking could also happen, as we experienced, when a conduit is placed contralateral to the apex for a patient whose IVC does not overlap the spine as much. Our data showed that a low

IVC-index is required to place a conduit ipsilateral to the cardiac apex and a high IVC-index around 40% or more is required to place the conduit contralateral to the apex.

Angiography was used to evaluate the IVC-index in this series because catheterization is always performed to evaluate Fontan candidate in our hospital. However IVC-index can be evaluated using CT scan or MRI. These latter modalities have additional benefits for surgical planning because they can provide further information about the shape of the spine and sternum, three-dimensional shape of the ventricle and pulmonary artery etc. Furthermore, CFD simulation using CT scan or MRI data might become standard for every case before Fontan operation in the future.

According to the patient situation, including adhesion, need for aortic cross-clamping, offset with Glenn anastomosis, hepatic factor to avoid pulmonary arteriovenous fistula (etc.), placement of the conduit should be decided based on multiple factors. However, in this study we found that, from the standpoint of energy loss and avoidance of conduit compression or kinking, the presence of a 40% IVC-index or greater is an indicator to consider placing the conduit contralateral to the cardiac apex.

Another important question is how to identify specific areas of the energy loss within the Fontan circulation in the long term. In our series, after a five-year follow-up, all patients who survived the initial operation are doing well. However a long and curved conduit might cause gradual but significant Fontan dysfunction, or a curved conduit might become straighter with somatic growth. Long-term evaluation of the conduit shape and CFD simulation is warranted to identify conduit dysfunction before significant clinical symptoms arise.

## CONCLUSION

In patients with ACJ, placement of a straighter and shorter conduit on the cardiac apical side provides better laminar blood flow. However, a conduit positioned either side can provide acceptable Fontan circulation, as long as it is neither compressed nor kinked. This study indicates that the location of the IVC in relation to the spine is a key component in avoiding these factors: thus preoperative evaluation is of paramount importance for deciding the optimal conduit route. Our study suggests that significant overlap of the IVC to the vertebra, with an IVC-index of more than 40%, is an indication for conduit placement to the contralateral side of the cardiac apex for optimal routing of the conduit.

**Conflict of interest:** none declared.

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## APPENDIX. CONFERENCE DISCUSSION

**Dr K. Matsuo (Chiba, Japan):** You report a detailed analysis of the Fontan circulation associated with apicocaval juxtaposition based on computational flow dynamics. In the longer term follow-up of Fontan patients, serious sequelae such as liver dysfunction or protein-losing enteropathy have been reported. They are probably due to chronic high CVP or low output. So your research to minimize energy loss would be truly important in deciding conduit route in this setting.

My question is: How do you make the compression model and the kinking model? Do you overlap the cardiac images obtained from the MRI or CT scan? My second comment is related to the first question. You are suggesting around 40% of the IVC index as a decision value for conduit route. But it seems to come from surgical results. Do you have some supporting data from CFD analysis?

**Dr Yoshida:** Yes, you are right. It is very important to minimize energy loss long-term. That's why we undertook this simulation study. But the interesting result is that either way—as long as the conduit doesn't have any compression or kinking—energy loss is sufficiently low to complete the Fontan circulation. So we don't know, even if the conduit doesn't have any kinking, whether that influences the longer term result or not, so we keep watching.

And your question on the kinking and compression model, the slide shows a simulation model using real patient MRI data but that patient doesn't have any kinking. So the kinking model we created by mimicking the conduit kink, just by imagination. Maybe if the actual kinking were more severe and the compression as well, we would get more energy loss than we showed if we were able to use an actual case.

Your other question concerns supporting data. Yes, more than 40% cases; we had one case that we put on the same side of the apex, but more than 40% means a very tight space between the heart and spine. So that's why, if you put the conduit on the same side, the conduit is easily compressed between them. That's why I recommend placing the conduit on the opposite side of the heart of the cardiac apex to avoid compression. In only one case, we did it the opposite way—which we needed to revise, as I showed in this presentation—otherwise from retrospective data, but in all these cases more than 40% supports this data and less than 40% the same side is usually okay.

**Dr M. Hazekamp (Leiden, Netherlands):** I have two questions. The first question is: Did you use, or did you consider using, reinforced conduit?

**Dr Yoshida:** No, usually, standard wall of Gore-Tex.

**Dr Hazekamp:** And would it be better to use a reinforced conduit?

**Dr Yoshida:** I think, even if you put the reinforced conduit on the same side of the apex in a case which has a higher IVC index, that heart does not compress the conduit. However, you cannot close the chest this time also, because the heart is going to be compressed instead of the conduit. So that's why even reinforced conduit doesn't solve this problem.

**Dr Hazekamp:** Okay, that's clear. And the second question is: Should you ever do this type B conduit, this long curved conduit. Should you ever do it? Because in my experience in the last years, we have seen at least three patients who had this conduit and who finally ended up with protein-losing enteropathy and problems.

**Dr Yoshida:** After you placed the longer conduit?

**Dr Hazekamp:** Yes. So my question is: Should you ever do it, or should you just leave it with Glenn shunts and additional blood flow?

**Dr Yoshida:** I don't know. I don't know the IVC index in that case; how much was it.

**Dr Hazekamp:** No, neither do I.

**Dr Yoshida:** But in my series, one month after the Fontan operation in all these cases, the two groups showed similar cardiac index. And also the follow-up period is around 5 years. All cases are doing well. So if you can make the appropriate decision, I think the patient is okay. But we need to keep watching over the long term for apico-caval juxtaposition cases. So in

your case, the conduit might be too long or over-curved than we simulated. Or there might be some kinking in some part, so if you can get a cardiac catheterization it might give you more information why that's possible.

**Dr R. Pretre** (Lausanne, Switzerland): Many of those patients also have a bilateral superior vena cava and you know that after bilateral cavopulmonary anastomosis, the segment of the pulmonary artery in between remains hypoplastic. Does that influence your decision to complete the Fontan circulation in this anatomy? Are you not better off with a straight connection—landing in the middle of the PA—than with this long, curved tube going far away on the left side, often on the lower lobar pulmonary artery?

**Dr Yoshida:** Usually we put a conduit between them. I didn't show simulation in this series about the influence of offset simulation. But, actually, if you can place the conduit on the same side of SVC, the energy loss is more there. But also that involves another issue. So if you can put a complete offset

situation, this might cause some AV malformation, but that's another story. But I wanted to show energy loss inside a Fontan conduit.

**Dr B. Maruszewski** (Warsaw, Poland): A little comment. I think we should differentiate between right-sided juxtaposition of the apex and the IVC and left-sided. In our experience it's crucial. When you get the apex on the right side and an IVC on the right side, it's usually no problem. We had three or four cases and in all of them we used the reinforced Gore-Tex tube, but actually the proximal anastomosis of the IVC with a conduit is higher than the apex.

I think the problem occurs when you have left-sided juxtaposition of the left-sided apex and the inferior vena cava. In these cases we always avoided this huge loop on the left side because of what René said, because of the risk of the compression on the pulmonary vein, and we managed to mobilize the IVC towards the right and do the right position conduit.

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## EDITORIAL COMMENT

# Re: Total cavopulmonary connection in patients with apicocaval juxtaposition: optimal conduit route using preoperative angiogram and flow simulation

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**Keywords:** Total cavopulmonary connection • Apicocaval juxtaposition • Flow simulation • Computational fluid dynamics • Angiography

Early and late results in cardiovascular surgery are intimately influenced by the flow dynamics of the reconstructed domains. The quality of those repairs has been greatly enhanced by major advances in cardiovascular imaging technology, such as echocardiography, computed tomography (CT) scans and magnetic resonance imaging (MRIs). More recently, mathematical modelling technologies such as computational fluid dynamics (CFD) have been used to optimize the flow dynamics of reconstructive surgery. In this issue of the journal, Yoshida *et al.* [1] apply those technologies to optimize the position of the conduit connecting the inferior vena cava (IVC) to the pulmonary artery while completing the total cavopulmonary connection (TCPC) in the unusual setup of apicocaval juxtaposition. The authors elegantly illustrate that the IVC index, which refers to the distance of the IVC from the spine, could be used as a guide to position the conduit ipsilateral or contralateral to the cardiac apex. If the IVC does not overlap the spine >40%, the conduit can be placed on the side of the cardiac apex. The authors have measured the IVC index on preoperative angiogram and they indicate that CT scan and/or MRI can provide additional information in this preoperative assessment.

The CFD simulations confirm that it is the loss of laminar flow produced by compression or the kinking of the conduit rather than its length that produces the greatest energy losses. The authors wisely indicate, however, that other factors such as the

flow competition between the superior vena cava and the IVC returns are even more important in terms of energy losses.

Patients with apicocaval juxtaposition often have complex cardiac anomalies, such as situs inversus or isomerism. Right isomerism, which was present in 5 of their patients, is often accompanied by anomalies of the pulmonary venous return and of the hepatic veins, which may drain separately into the atrial chamber. It is for these patients that some years ago, we had suggested using an intra/extracardiac conduit that is spatulated inferiorly in order to incorporate the IVC and all the hepatic venous return in a single anastomosis. In our experience, those intra/extracardiac conduits are ipsilateral.

A similar problem can arise in patients with left isomerism with azygos continuation of the inferior vena cava and separate drainage of the hepatic veins in the atrial chamber. This article is a neat example of bespoke surgery in which preoperative simulations could be used to optimize the flow dynamics of the individual patient.

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