Restoring the spiral flow of nature in transposed great arteries

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Abstract

Objectives: The great arteries are in a non-spiral relationship in their transposition, even after arterial switch operation (ASO) with the Lecompte manoeuvre. We aim to restore the natural spiral great arteries and compare such ASO with conventional ASO with the Lecompte manoeuvre to clarify the functional implications of the spiral great arteries. Methods: The early survivors of ASO (n = 130) were included in this retrospective study. In spiral ASO (n = 48), the main pulmonary artery ran alongside the aorta and gave rise to its branches posteriorly. Patients who underwent non-spiral ASO with the manoeuvre (n = 82) were compared. The survival, re-operation-free ratio and the anatomic details for re-intervention after ASO were reviewed. Results: Average follow-up was 5.6 ± 3.4 years (range: 2 months to 11 years). The estimated 10-year survival was similar (92.6% spiral vs 92.1% non-spiral, respectively). Significant pulmonary stenosis (PS) (>40 mmHg) was noted in five (10.4%) in the spiral group and seven patients (9.7%) in the non-spiral (p = NS). The re-operation-free survival at 10 years was not significantly different (87.4% vs 90.1%). The reasons for re-operation were subvalvular PS (n = 3) and residual defect (n = 2) in the spiral group, while supravalvular PS (n = 3), neo-aortic regurgitation (n = 1) and aortic neo-coarctation (n = 2) in the non-spiral group. Supravalvular PS and aortic neo-coarctation that occurred in the non-spiral group were not seen after spiral ASO. Conclusions: Intermediate-term results of spiral ASO were satisfactory. Transposition is not a mere reversal of the great arteries; therefore, recognition of non-spiral relationship should be appreciated. Spiral reconstruction would be beneficial to reduce supravalvular PS and neo-aortic kinking. Further recognition of spiral function and refined modification might justify the application of spiral ASO in the future.

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1. Introduction

The arterial switch operation (ASO) has become the procedure of choice for transposition of the great arteries (TGA) [1,2]. TGA is considered to be a mere reversal of the great arteries anteroposteriorly (Fig. 1A) [3,4]. Non-existence of the normal spiral relationship of the great arteries in TGA has not been widely appreciated. Posterior pulmonary bifurcation is mobilised anteriorly to the aorta (the so-called Lecompte manoeuvre) [5] in an effort simply to reverse transposed great arteries (Fig. 1B). Spiral ASO is seldom performed, because the functional implications of spiral relationship of the great arteries remain unknown (Fig. 1C). History of surgical treatment for TGA reveals that once the functional implications of two normal ventricles were well known, nobody selected the right ventricle as the systemic pumping chamber. In this era of ASO, we seek to clarify the functional implications of spiral relationship of the great arteries in nature and restore the spiral flow in TGA (Fig. 1D).

2. Methods

Between March 1998 and December 2008, 130 early survivors of ASO at our hospital were included in this retrospective study. The institutional research ethical committee approved this retrospective study. Spiral ASO

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was performed in 48 (36.9%), whereas conventional non-spiral ASO with Lecompte manoeuvre in 82 patients (63.1%). The technical details of spiral ASO are reported elsewhere [6,7]. In brief, the central pulmonary artery (PA) after main PA (MPA) bifurcation was retained behind the aorta, and MPA was routed alongside the neo-aorta anterolaterally to the central PA, using part of the aorta wall and a proper-sized pericardium (Videos 1 and 2 with narration). In the spiral group we placed new MPA on the left (27 cases, 56%), while the old aortic root is anterior or left anterior (Figs. 2 and 3) to the pulmonary annulus. On the contrary, 21 cases (44%) with a right anterior old aortic root had their neo-MPA located on the right of the neo-aorta. Posterior MPA could remain undivided to avoid difficult posterior haemostasis; bilateral hilar dissection was not necessary. We followed the principle of *in situ* transfer and common wall concept on both coronary and great arteries.

After surgical correction, 17 patients in the spiral group underwent computerised tomography 7.3 ± 3.3 years after total correction for follow-up. Continuous variables were reported as mean ± standard deviation or median (interquartile range). To test the statistical significance, Student’s *t*-test or Mann—Whitney *U* test was used to compare continuous variables. Chi-square test or Fisher’s exact test was employed to compare categorical data. Survival was estimated by the Kaplan—Meier method, and groups were compared with the log-rank test.

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**Fig. 1.** Spiral relationship of the great arteries in normal heart (C) was not restored by conventional ASO with Lecompte manoeuvre (B) on TGA (A). With spiral ASO (D), pulmonary bifurcation is free from posterior compression by high-pressure aorta. Note that acute angulation of arch that is present after Lecompte manoeuvre (B) is absent in other three illustrations. Acute angulation from the main pulmonary artery to its branches is also present in A and B, but not in C and D, in which main to branch pulmonary artery angle is wider and smoother. (A—C) Modified from Prétre et al. Results of the ASO in neonates with transposed great arteries. Reprinted with permission from Elsevier (The Lancet, 2001;357:1826—30).

**Fig. 2.** Techniques of spiral ASO with neo-MPA in left anterior portion. Semilunar valves are all omitted for clear illustration. (A) Aorta is amputated along with the aortic lip (refer to Fig. 3B for its purpose) taken from the anterior aortic sinus wall, that excision also facilitates exposure on coronary transfer. Left-posterior wall of MPA is not divided. Two J-shaped incisions are made on facing parts of the great arteries. Anterior wall of MPA is cut back along dashed line to accommodate ascending aorta. (B) Annulus of facing commissure in old aorta is fixed to left anterior wall of MPA (depicted by Y stitches). Lateral edges of two J-shaped incisions facing each other are sutured together (depicted by X stitches) to form aortopulmonary window. Then semi-flap of MPA is placed into opposite aortic sinus and sutured so that it acts as posterior wall of neo-MPA and as anterior wall of neo-aorta. (C) Suture for MPA semi-flap in sinus 2 (depicted by Y stitches) is finished. Anterior lip of cut back MPA is everted to left. Distal aorta is sutured to posterior wall of MPA along dotted line. Aortic lip will cover the left-sided portion of neo-aortic stump. (D) Neo-aortic Anastomosis is finished. Cut edge of MPA near right PA is attached to posterior aorta from right. (E) The rest of MPA cut edge is attached to posterior outer wall of aorta from left. Caudal edge of anterior MPA flap is attached to amputated edge of aortic sinus 1 and non-facing sinus to form floor of pulmonary pathway. (F) Finally, attaching anterior MPA flap to ascending aorta completes roofing of pulmonary pathway.
3. Results

Median age and weight at operation were 9 days (range: 1—4376 days) and 3.3 kg (range: 2—46 kg), respectively. TGA with ventricular septal defect was found in 60 patients (46.2%); Taussig—Bing anomaly in 16 (12.3%) and usual coronary pattern in 73 (56.2%). The demographic data of two groups were similar (Table 1). Cross-clamp time was significantly lower ($p < 0.005$) in the spiral group (127 ± 31 min) than in the non-spiral group (144 ± 38 min), and cardiopulmonary bypass time was similar in both groups (265.9 ± 74.6 spiral, 254.1 ± 68.7 min non-spiral, $p = 0.372$). The average follow-up was 5.6 ± 3.4 years (range: 2 months to 11 years). Kaplan—Meier survival was 92.6 ± 4.1% at 10 years for spiral repair, similar to that for the non-spiral group (92.1 ± 3.1%, Fig. 4). The re-operation-free ratio was similar at 11 years after spiral (87.4 ± 5.3%) and non-spiral ASO (90.1 ± 4.0%, Fig. 4). Reasons for re-operation included subvalvular pulmonary stenosis (PS) ($n = 3$) and residual defect ($n = 2$) in the spiral group, while those in the non-spiral
group were supravalvular PS (n = 3), neo-aortic regurgitation (n = 1) and neo-aortic coarctation (n = 1). In the follow-up echocardiography, significant PS (pressure gradient > 40 mmHg) was noted in five (10.4%) in the spiral group, and in seven patients (9.7%) in the non-spiral group (p = 0.448). The incidences of significant aortic stenosis (3 (6.3%) vs 8 (11.1%)) and those who required re-catheterisation (10 (20.8%) vs 22 (30.6%)) were also similar in the spiral and non-spiral groups. Although PS still occurred, it was mainly related to the subvalvular level (Fig. 5C), and not to the supravalvular level as in the non-spiral group (Fig. 5A). Aortic neo-coarctation that occurred in the non-spiral group (Fig. 5B) did not occur in the spiral group (Fig. 5D).

Follow-up computerised tomograms showed harmonic natural spiral relationship of the great arteries, and their

![Fig. 4. Kaplan–Meier actuarial survivals of both groups were similar up to 11 year after ASO, the same was true for free from re-operation. The bars indicate standard errors.](image)

![Fig. 5. Typical angiographic findings in two groups (A to D). Wide, open arch window in the spiral group, but a narrower arch window in the non-spiral group. The aortic neo-coarctation occurred after non-spiral ASO, a slit-like arch window (B’) after Lecompte manoeuvre, that was wide open before ASO (A’). The window remained open after spiral ASO (D). In the non-spiral group, PS occurred mostly at the supravalvular level near MPA bifurcation (A). In the spiral group, bifurcation is fine (C), right ventricular outflow obstruction is usually seen at the subvalvular level (C’ arrow), probably related to an unusual coronary artery traversing the infundibulum (D’ arrowhead), 2 of them were associated with a dystrophic neo-pulmonary valve, possibly related to our technique of coronary transfer.](image)
branches could grow in the spiral group (Fig. 6). The concern that gradual ‘untwisting’ as the child grows that might cause pressure gradient at the ‘common wall’ site did not occur; and growth of the common wall was shown.

4. Discussion

Both survival and re-intervention rates in spiral ASO were satisfactory, and similar to those in conventional ASO. The aortic neo-coarctation and supravalvular PS that occurred in the non-spiral group was not seen in the spiral group. We believe that these two complications are related to the Lecompte manoeuvre and the unnatural relationship of the great arteries.

As illustrated in Fig. 1, the rationale of spiral ASO included (1) widening of main to branch PA angle, (2) avoiding compression by the aorta posteriorly, (3) widening of arch window and (4) examining computational fluid dynamics as described in the following.

4.1. Widening of main to branch PA angle

First-branch PA hypoplasia is not an infrequent finding in TGA before ASO. Its pathogenesis was related to a posterior inclination of the proximal MPA in this setting (Fig. 1A) [8]. To facilitate PA growth, it is best to mobilise the posterior inclination of the proximal MPA and restore its ‘normal’ position (Fig. 1C) with a natural and smooth direction of blood flow into the PAs in the neonatal period, as a principle of surgical treatment. As a consequence, widening this acute angle to both PAs in spiral fashion (Figs. 1D and 5C) is more helpful than the Lecompte manoeuvre with a huge patch (Figs. 1B and 5A) for promoting PA growth [9—11].

4.2. Avoiding compression by the aorta posteriorly

4.2.1. Flattened MPA after non-spiral ASO

The systemic high-pressure ascending aorta may compress the neo-MPA from its posterior end towards its anterior end. Insufficient dissection of the distal PAs was suggested to describe this flattened (oval-shaped) MPA in 1988 [12], but a later study showed that the cross section of the MPA is still flattened 6–22 months after conventional ASO with hilar dissection and the Lecompte manoeuvre [13]. The flattened MPA after the Lecompte manoeuvre is the result of non-spiral arrangement. In spiral arrangement as in the normal heart, there is space for the pulmonary pathway free from compression by the ascending aorta at its left-lateral and also left-posterior portions. On the contrary, in non-spiral arrangement, compression on the posterior portion of the MPA from the aorta results in its oval shape. Thus, spiral ASO is preferred.

4.2.2. Bronchial compression by the stretched PA

After the Lecompte manoeuvre, however, not only is the anterior MPA (low-pressure) flattened [13], resulting in branch PA stenosis with increased peak velocity during systole [14], but the posterior left bronchus may also be compressed (airway-pressure with cartilage) [15,16]. This occurs when the high-pressure ascending aorta is not restored to its natural location.

4.3. Widening of arch window in spiral relationship of the great arteries

Ironically, the high-pressure aorta may suppress itself. This implies that acute angulation of the aortic arch after the Lecompte manoeuvre (Figs. 5B and B’, 1B) may cause hypoplastic arch and even aortic neo-coarctation. In the literature, there were 10 cases of aortic neo-coarctation after ASO documented [17,18], including four cases from the Marie-Lannelongue Hospital in Paris among their 746 cases in 1995. Coarctation was not present before ASO in all 10 cases described in the literature and our two cases (Figs. 5A’ and 1A). The reported incidence with significant pressure gradient is not common because of the systemic pressure inside the aorta, but angulation is still present (Fig. 5B); the space in front of ascending aorta is occupied by presence of MPA.

4.4. Computational fluid dynamics study

We used computational fluid dynamics on mathematical modelling to compare the flow phenomena of the spiral and non-spiral models under various body surface areas (BSAs) [19]. The velocity profile and wall-shear stress distribution are more uniform for the spiral than the non-spiral model. The pressure drop and power loss ratio are smaller for the spiral than the non-spiral model for all BSAs investigated. The functional superiority of the spiral over...
the non-spiral model is demonstrated because the blood flow within is more streamlined than that within the non-spiral model. Thus the functional implications of spiral relationship of the great arteries have been demonstrated. After the Lecompte manoeuvre, not only supravalvular PS at pulmonary bifurcation can occur as a consequence of posterior compression of MPA by the ascending aorta [12,20], but aortic neo-coarctation was also reported [17,18], as in this series. We therefore switched the great arteries in a spiral fashion (Figs. 1D, 2 and 3). In this era of ASO, we now clarify the functional implications of spiral relationship of the great arteries. This is to say, the great arteries are normally in a spiral fashion, thus pulmonary bifurcation is prevented from being compressed by the aorta, and the arch window is kept wide open by the adjacent pulmonary bifurcation (Figs. 1C, D and 5D).

Potential limitations of our study merit consideration. First, the number of cases studied is small. Second, this is a retrospective study, and longer-term follow-up is mandatory to ascertain the benefit or possible drawbacks of spiral ASO over non-spiral ASO. Subvalvular PS still occurred, but mainly related to infundibular hypertrophy, and not supravalvar as in the non-spiral group. Subvalvular PS was probably related to an unusual coronary artery traversing the infundibulum (Fig. 5D), which may be associated with a thick subaortic muscle bundle that can produce subpulmonary narrowing after ASO [21].

In conclusion, intermediate-term results of spiral ASO were satisfactory, and spiral relationship of the great arteries can grow on follow-up. The technique offers an alternative of ASO. TGA is not a mere reversal of the great arteries; non-existence of spiral function in TGA should be appreciated. Spiral reconstruction would be beneficial to reduce supravalvular PS and aortic neo-coarctation. Recognition of spiral function and further modification might justify the application of spiral ASO in the future.

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References


Appendix A. Conference discussion

Dr R. Prêtre (Zurich, Switzerland): I had the opportunity to discuss a little bit with Dr Chiu yesterday and asked him to emphasise the technical aspects and not so much the statistical analysis of his study. It’s a very intriguing concept, and I’m not sure I understood all the technical details. But anyway, I think it’s worth to comment and discuss it. Dr Chiu restores the spiraling of the great arteries, at least at the great artery level, because the septum will remain parallel, a characteristic feature of transposition of the great arteries. From the aortic annulus down to the aortic isthmus, your technique, Dr Chiu, might create a more harmonious and streamlining pattern of blood, and probably also at the pulmonary level. This assumption seems to be confirmed by your studies, because you had no stenosis down the line distal to the semilunar valves. Now, I think we have to remember the past. The arterial switch operation was more or less conceived like that, at the very beginning, and it led to a lot of distortion problems and stenosis of the pulmonary arteries until Yves
LeCompte came out with the now so-called ‘LeCompte manoeuvre’, which really was a breakthrough and allowed us to do the switch operation in a much safer way.

So I guess this initial experience will restrain many of us from embarking on your technique, at least the oldest of us, those who have lived in the era of the first arterial switch operations.

I have a few questions to you, Dr Chiu. One, your team has been pioneering this approach for more than 10 years now, and in your series it has been done in only one-third of the patients. Why is it so?

Dr Chiu: Regarding one-third of patients in the hospital?

Dr Prétre: Yes.

Dr Chiu: Because we have four independent cardiac surgeons doing paediatric cases in our centre, and only I was doing the spiral switch exclusively.

There are two younger staffs. They started this practice recently. People tend not to change once they get familiar with their conventional method.

Dr Prétre: Well, Dr Chiu, if you are unable to convince your own colleagues with your technique, you will have difficulties in convincing us to perform it.

My second question. The anatomy of a normal heart sees the pulmonary artery lateral to the ascending aorta, with the right pulmonary artery curving around and underneath the aorta. Nature has also put the left coronary artery in a very posterior and proximal position in the coronary sinus, probably to prevent it from being compressed by the pulmonary artery. In the transposition of the great arteries, the coronary arteries have an abnormal anterior location. And after they have been transferred surgically, they are still in an anterior position but also in a more distal position, usually around or above the sinotubular junction. In your repair, are you not afraid to provoke a compression of the coronary arteries, especially the left main coronary artery, with you pulmonary artery ‘spiraling’ around an anteriorly and distally positioned coronary artery?

Dr Chiu: I think most important is the thinking process behind the conception of our technique. I’m sorry that I don’t have enough time to answer all these things.

But the basic principle is that once you use the in situ technique or common wall technique to reconstruct coronary arteries, you cannot sacrifice pulmonary arteries. The concept of common wall and in situ technique has to be applied also to the pulmonary artery.

How can we avoid the compression of coronary arteries by the adjacent low-pressure vessel? Although the pulmonary artery is a low-pressure vessel, it can become high because of the vicious circle. In our opinion, secure coronary redirection is more important than the absence of a nearby vessel.

I will use a slide how we avoid this compression. In the case of a huge main pulmonary artery and left-sided aorta, you can make a good flap from that anterior wall of main pulmonary artery. And another pedical flap, I call it aortic lip, is taken from the anterior nonfacing sinus of the aorta. No coronary artery here, you can take the whole button along with the distal aorta.

This pedicle flap redirect the left coronary artery in situ and let the right pulmonary artery sling underneath aorta, thus avoid the compression on the left coronary ...

Dr Comas (Madrid, Spain): Mr Chiu you have ten minutes for presentation. No more time for slides. You have to finish here. Any other comment, Rene?

Dr Prétre: Yes. Just I enjoyed your paper very much and the discussion it creates and also your rationale to try to restore a natural spiraling of the great arteries.

Appendix B. Supplementary data