Work in progress report - Congenital
Comparative computational fluid dynamic study of two distal Contegra conduit anastomoses

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Abstract

A computational fluid dynamic (CFD) study compared two configurations of distal anastomosis of 12 mm Contegra® conduit: conventional ‘circular’ vs. oblique ‘elliptical’ anastomosis extended on the left PA, evaluating pressure and velocity profiles, and shear stress, from PA origin to the bifurcation. ‘Elliptical’ anastomosis provides larger (~54% difference) cross-sectional area than ‘circular’ anastomosis. Velocity contours showed important stagnation at PA bifurcation in ‘circular’ anastomosis and minimal in ‘elliptical’ configuration, where fluid flow occurred preferentially in left PA. Pressure contours showed peak pressure zone at bifurcation in ‘circular’ anastomosis, while ‘elliptical’ exhibited more uniform pressure distribution. Shear stress distribution was more homogeneous in ‘elliptical’ than in ‘circular’ anastomosis. At bifurcation and in right PA artery velocity and pressure were higher for ‘circular’ than ‘elliptical’ anastomosis, while in left PA velocity was much higher for ‘elliptical’ anastomosis. CFD study demonstrates more homogeneous pressure, velocity, and shear stress distributions for ‘elliptical’ compared to ‘circular’ anastomosis at PA bifurcation, and preferential flow in left PA. CFD results suggest that clinical application of ‘elliptical’ anastomosis, with cross-sectional area larger than conventional ‘circular’ anastomosis, may reduce incidence and degree of distal stenosis, particularly for small size conduits.

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1. Introduction

Contegra® (Medtronic Inc., Minneapolis, MN) conduit provided encouraging results as right ventricular outflow tract reconstruction in complex congenital heart defects [1–8] and as pulmonary valve replacement during Ross operation [1, 2, 4, 6–8].

A disturbing sequence of publications recently reported a variable incidence of stenosis at level of conduit distal anastomosis [6–12].

To investigate the potential role of the surgical technique in the occurrence of distal stenosis, a CFD study has been designed to compare two different configurations of distal anastomosis of the conduit.

The working hypothesis was that ‘elliptical’ configuration provides a larger connection than conventional ‘circular’ anastomosis, with a lower resistance to flow, and thereby provides beneficial effects towards reduction of incidence and degree of distal stenosis.

2. Materials and methods

A 12 mm Contegra® conduit has been used as the model for a CFD study, because the literature indicates late stenosis particularly for smaller Contegra® diameters [5–11].

Two types of distal anastomosis of conduit to PA have been evaluated (Fig. 1):

a) conventional end-to-end ‘circular’ anastomosis
b) oblique ‘elliptical’ anastomosis, with incision extended on anterior aspect of left PA, and an oblique tailoring of the distal end of conduit

A cross-sectional area obtained with two surgical techniques was measured at location of anastomosis of conduit to PA using a grid overlaid on cross sections taken at precisely the same planar cut for both configurations.

2.1. Computational fluid dynamics (CFD) model

A geometrical model for PA was designed with proximal section at level of pulmonary valve, and distal section taken upstream with respect to PA bifurcation.

Our overall geometrical representation of normal PA bifurcation is based on a previously reported study [13].

Blood was modeled as Newtonian fluid having viscosity = \(4 \times 10^{-3}\) Pa·s and density = 1060 kg/m³. Assumed flow rate was 1.5 l/min, corresponding to laminar Reynolds number
of 700. A steady-state, with fully open pulmonary valve, was considered as first-step to solving a complex problem. Calculations were performed using a respected code NSMB. Both geometrical domains were discretized into 548288 finite-volume cells, with 24 blocks for ’circular’ type and 38 blocks for ’elliptic’ type. Implicit time scheme was implemented with 4th-order central scheme in space. No-slip boundary condition was used on artery walls, inlet velocity at PA trunk was set at 0.22 m/s corresponding to required flow rate, and atmospheric pressure condition was set at artery outlet regions allowing pressure to develop naturally in flow field. All calculations were made on PC cluster composed of four Pentium 4, 3.6 GHz, and processors having 3 Gigabytes of memory each. Convergence was ascertained when the L2-residues of pressure and velocity solutions were stabilized, corresponding to about 20,000 n-step iterations.

CFD model evaluated pressure and velocity profiles, and shear stress. Pressure and velocity values obtained have been compared along three arbitrary lines, respectively, from origin of main PA to its bifurcation (line A), and downstream at outlet of right (line B) and left (line C) PA (Fig. 2). Values of pressures (with respect to outlet value) and velocity taken at fixed points of 5 mm intervals for line A (PA bifurcation), and 2 mm intervals for lines B (right PA) and C (left PA), have been compared to evaluate percentage difference between the two configurations.

3. Results

A cross-sectional area at location of anastomosis measured 110 mm² for ’circular’ type of anastomosis and 169 mm² for ’elliptical’, with a difference ≈ 54% in favour of ’elliptical’ configuration.

3.1. Computational fluid dynamics (CFD) model

Comparison of velocity contours showed stagnation at PA bifurcation in both configurations: navy blue recirculation zones, well evident in ’circular’ type of anastomosis, were minimized in ’elliptical’ type, where fluid flow occurred preferentially in left PA. A comparison of pressure contours showed a peak pressure zone at bifurcation in ’circular’ type of anastomosis, while ’elliptical’ geometry exhibited more uniform pressure distribution. Shear stress evaluation demonstrated zones of high stress at anastomosis and around PA bifurcation in both techniques. Nevertheless, shear stress distribution, as well as all other parameters, was more homogeneous in ’elliptical’ type of anastomosis than in ’circular’ geometry (Fig. 3).

On line A (PA bifurcation) values of velocity were higher for ’circular’ than for ’elliptical’ configuration, as well as values of pressure, with exception of last corresponding to site of conduit anastomosis. On line B (right PA) values of velocity and pressure drop were higher for ’circular’ than for ’elliptical’ anastomosis. On line C (left PA) values of pressure drop were higher for ’circular’ than for ’elliptical’
anastomosis almost everywhere, while values of velocity were much higher for ‘elliptical’ anastomosis because of preferential flow condition created by this geometry (Fig. 4).

Calculated distribution of total pulmonary flow (≈1.488 l/min) between right and left PA was the following:

- in ‘circular’ configuration 0.636 l/min (≈42.7%) for right PA and 0.852 l/min (≈57.3%) for left PA
- in ‘elliptical’ configuration 0.606 l/min (≈40.7%) for right PA and 0.882 l/min (≈59.3%) for left PA

Calculated difference failed to reach statistical significance.

4. Discussion

The introduction of Contegra® as an alternative to homografts has been supported by several proven advantages [1–8].

The most frequently reported complications have been thrombus, particularly in correspondence of the valve [4, 12] and premature valve incompetence, generally correlated with elevated PA pressures and resistance [4–6, 11, 12].

The most disturbing complication, with a reported incidence variable between 6% and 50%, has been stenosis at distal anastomosis, with proximal conduit dilatation, and occasionally formation of aneurysm or pseudo-aneurysm, particularly in infants requiring small size conduits and after repair of truncus arteriosus [6–12].

The increasing rate of stenosis at distal anastomosis has also been observed as a progressive problem in time [5, 6, 9, 11, 12]. This observation contrasts with other studies reporting mild pressure gradients remaining stable during follow-up [2, 3], or increasing only in younger patients with small size conduits [5, 6, 8].

4.1. Potential mechanisms of distal stenosis

a) Presence of hypoplasia and/or distal stenosis of PA branches

Establishment of normal pulmonary blood flow can unmask the presence of peripheral stenosis [5, discussion of 6, 7, 8, 11]

b) Discrepancy in size between conduit and PA

Patient–conduit mismatch definitely has a role in occurrence of distal stenosis, particularly in infants with relatively small PAs [5–7, 11].

c) Type of surgical technique

Potential surgical reasons responsible for inducing distal stenosis are tailoring of distal end of conduit, incision on PA, suture technique with purse-stringing running sutures, and excessive length of conduit creating a kinking at distal anastomosis [3, discussion of 6, 7, discussion of 8, 1].

d) Local immunologic/inflammatory reaction

This mechanism has been denied by observers who at re-operations have found absent active inflammatory reaction, valve leaflets remaining pliable, and integrity of Contegra® conduit [6, 8]. Other investigators have instead described local immunologic reaction [discussion of 6, 14], with peri-adventitial inflammation [14].

e) Local peel formation

Peel formation has been reported in correspondence of distal anastomosis, very similar to neo-intima found in vascular grafts, with excessive intimal peel formation and severe peri-graft scarring reaction [6, 9, 11, 12].

f) Thrombosis

Thrombus formation has been considered as one of the factors potentially responsible for distal stenosis, particularly in the absence of anti-platelet and/or anticoagulant treatments [6–8] or after inadequate rinsing of glutaraldehyde used for conduit preservation [discussion of 8].

g) Combination of two or more of the above

Multi-factorial cause of stenosis in correspondence of distal anastomosis is of course the most appealing hypothesis.

4.2. Surgical technique

The surgical technique has been taken into consideration since our first report of Contegra® as pulmonary valve replacement during Ross operation [1]. Our later study with multi-gated CT-scan showed that values of diameters of implanted Contegra® conduit at level of proximal and distal anastomosis, as well as valve, remained unchanged during follow-up [8]. Disturbingly, pressure gradients recorded in these patients were all at the location of distal anastomosis, but without increase during follow-up [8].

After these observations a different surgical technique has been introduced, following the same principle applied.
in the repair of tetralogy of Fallot where a trans-annular patch is required, tailoring the distal end of Contegra® conduit in oblique fashion, and opening the PA with an incision extended into left PA. The resulting end-to-end connection, instead of being ‘circular’ like in the conventional technique, becomes ‘elliptical’ (Fig. 1).

Not only the advantages of ‘elliptical’ vs. ‘circular’ configuration should be intuitive, but should repeat the clinical experiences obtained with vascular anastomosis in general. In fact the measurement of the cross-sectional areas confirmed that ‘elliptical’ configuration provides a substantially larger (=54% difference) cross-sectional area than conventional ‘circular’ anastomosis.

In our CFD model, designed following previous studies on distribution of pulmonary blood flow [13, 15], the evaluation of pressure, velocity, and shear stress contours show more homogeneous flow distributions in ‘elliptical’ than in ‘circular’ type of anastomosis (Fig. 3). The comparison of curves of pressure and velocity also shows more favourable flow distribution for ‘elliptical’ than for ‘circular’ type of
anastomosis, with preferential flow in left PA (Fig. 4). Despite preferential flow towards left PA observed with ‘elliptical’ anastomosis, flow distribution remained quite homogeneous, without any statistically significant difference compared to ‘circular’ anastomosis.

4.3. Limits of the study

a) Single size conduit (12 mm) with similar size (12 mm) of main PA has been used. Occurrence of distal stenosis has been reported more frequently in small conduits, and discrepancy in size between conduit and PA has already been proved to be one of the factors predisposing distal stenosis.

b) Fixed pulmonary blood flow (1.5 l/min) has been considered. We have calculated the highest flow possible in an infant suitable for 12 mm conduit implantation.

c) Only end-to-side types of surgical techniques have been studied. The end-to-side type of anastomosis has been excluded not to complicate the calculations because of simultaneous presence of antegrade pulmonary blood flow.

d) Steady-state calculations were performed assuming fully open pulmonary valve. Our study did not account for pulsatile nature of flow or for difference in compliance between graft and native tissue, because it constitutes first-step CFD approach to a complex problem. The potential effect of these variables would equally affect both configurations.

e) The current study makes no attempt to account for tissue variation due to grafting, as this would require Fluid Structure Interaction study, substantially more complex and computation intensive.

f) The problem of Contegra® distal stenosis generally occurs as late complication, while this is an acute study. We might speculate that creating a larger and hemodynamically more favourable anastomosis could reduce the incidence and severity of this late complication, independently from the problem of late occurrence of fibro-intimal hyperplasia or peel formation.

g) To date clinical validation has not been yet reported. After having seen the CFD and clinical advantages of the ‘elliptical’ technique, we are not considering a return to ‘circular’ anastomosis for a prospective clinical comparison.

5. Conclusions

Our CFD study demonstrates more homogeneous velocity, pressure and shear stress distributions for ‘elliptical’ than for ‘circular’ type of anastomosis at PA bifurcation, with flow preferentially occurring in left PA. This induced homogeneity of flow precludes substantial flow recirculation which is conducive to stagnation and thus, by extrapolation, to distal stenotic formation.

These CFD results provide preliminary proof that clinical application of the ‘elliptical’ anastomosis with larger cross-sectional area may reduce the incidence and degree of distal stenosis, particularly for small size conduits.

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