European Journal of Cardio-thoracic Surgery 21 (2002) 268–275

EUROPEAN JOURNAL OF CARDIO-THORACIC SURGERY

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Aortic and pulmonary root: are their dynamics similar?☆

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Received 14 October 2001; received in revised form 20 November 2001; accepted 24 November 2001

Abstract

Objectives: The long-term behavior of the pulmonary autograft in the aortic position (Ross procedure) remains uncertain. Using three-dimensional (3D) sonomicrometry (200 Hz) we compared the dynamics of the aortic and pulmonary roots. **Methods**: Twenty-four crystals were implanted in each aortic (eight sheep) and pulmonary roots (six sheep) at: base (3 × 2), commissures (3 × 2), sinotubular junction (3 × 2), ascending aorta (3) and pulmonary trunk (3). Under stable hemodynamic conditions, geometric changes were time-related to left ventricular pressure (LV) and aortic pressure. **Results**: The expansion of the aortic root is twice that of the pulmonary root. During the cardiac cycle, the aortic root volume increased by 37.7 ± 2.7% (mean ± SEM) versus 20.9 ± 1.0% for the pulmonary root. Both were cone-shaped at end diastole. Because expansion at commissures was twice that of the base, both roots became more cylindrical during ejection. Although both roots started to expand prior to ejection and reached maximal expansion during the first third of ejection, the commissural and sinotubular junction dynamics were different in each root. While in the aortic root, expansion at commissural and sinotubular junction levels was significantly different (63.7 ± 3.6% versus 37.0 ± 2.1%), in the pulmonary root, they were similar (29.0 ± 1.3% versus 27.7 ± 1.4%). Expansion of the three sinuses was also different ($P < 0.001$). In the aortic root: the right expanded more than the left and more than the non-coronary sinus. In the pulmonary root: the right sinus expanded more than the anterior more than the left. **Conclusions**: Dynamic differences might explain the global pulmonary root dilatation when subjected to systemic pressure, particularly at the level of the sinotubular junction which might result in the autograft failure. Differences in the asymmetrical expansion of the aortic and pulmonary roots should be considered for the implantation of the pulmonary autograft in the most physiological position.

Keywords: Pulmonary valve; Aortic valve; Ross procedure

1. Introduction

Because valve replacement with prosthesis has been the standard treatment for aortic valve disease, a detailed knowledge of the aortic and pulmonary valve complex was not required. Recently, the increased use of pulmonary autografts demands a better understanding of the aortic and pulmonary valve functional anatomy [1,2]. Although the aortic root dynamics have been studied in detail, the dynamics of the pulmonary root remain unknown [3–7]. The anatomy of the pulmonary root and right ventricular outflow tract has been described in detail [8,9], and biomechanical comparisons between the aortic and pulmonary roots have been performed to assess the feasibility of the Ross procedure [10–15]. However, so far, no description has been made of the comparative dynamics of the aortic and pulmonary roots in their orthotopic position during the cardiac cycle. The purpose of this study is to analyze the time-related anatomical changes of the aortic and pulmonary roots during each phase of the cardiac cycle using three-dimensional (3D) sonomicrometry [6,7].

2. Materials and methods

Eight adult sheep (45 ± 2 kg (mean ± SEM)) underwent implantation of 12 ultrasonic crystals in the aortic root using cardiopulmonary bypass (pump time = 158 ± 8 min, cross clamping time = 75 ± 3 min). Six of them also underwent simultaneous implantation of 12 ultrasonic crystals in the pulmonary root.

☆ Presented at the joint 15th Annual Meeting of the European Association for Cardio-thoracic Surgery and the 9th Annual Meeting of the European Society of Thoracic Surgeons, Lisbon, Portugal, September, 16–19, 2001.

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1010-7940/02/$ - see front matter
PII: S1010-7940(01)01132-0

2.1. Surgical protocol

Anesthesia was induced with intravenous (i.v.) ketamine (1.0 mg/kg) and (propofol 4.0 mg/kg) body weight and was maintained with endotracheal isoflurane (1.5–2.5%). Artificial ventilation was achieved with a volume regulated respirator (North American Drager, Telford, PA 18969, USA) supplemented with oxygen at 2 l/min. The heart was exposed through a standard left thoracotomy through the fourth intercostal space. The left femoral artery (16 Fr) and left internal thoracic (10 Fr) arteries were cannulated. A venous cannula was inserted into the right atrium (32 Fr). The aorta and arch vessel were cross-clamped and cold crystalloid cardioplegia was infused into the root. Through a transverse aortotomy approximately 1-cm distal to the sinotubular junction, 12 ultrasonic crystals (Sonometrics, London, Ontario, Canada) were implanted to study the aortic valve complex. To avoid inter-operator variability, the same surgeon placed all crystals. Ultrasonic crystals (1 mm) were placed and secured with 5/0 polypropylene sutures at: the lowest point of each sinus of Valsalva, corresponding to the so-called aortic base (B:3); the aortic commissures (C:3); the highest point of each supra-aortic crest or sinotubular junction (STJ:3); and at the wall of the ascending aorta (AA:3) (Fig. 1). On the ascending aorta, a left, right, and non-coronary (NC) crystal were lined up with the crystals placed at the left, right, and NC of the base and at the sinotubular junction. The crystals were oriented so that they all pointed toward the lumen. The crystal's electrodes were exteriorized through the aortic wall at each point of insertion to reduce their possible interference with the aortic valve movements. After closing the aortotomy, the aorta was unclamped and a transverse pulmonary arteriotomy was performed approximately 1-cm distal to the sinotubular junction under full cardiopulmonary bypass with the heart beating. A total of 12 ultrasonic crystals were used to study the pulmonary trunk in the same positions as in the aortic root. Ultrasonic crystals (1 mm) were placed and secured with a 5/0 polypropylene suture at: the lowest point of each sinus of Valsalva, corresponding to the so-called pulmonary base (B:3); the pulmonary commissures (C:3); the highest point of each supraaortic crest or sinotubular junction (STJ:3); and in the wall of the pulmonary trunk (PT:3) (Fig. 1). On the pulmonary trunk, the left, right, and anterior crystals were lined up with the crystals at the left, right, and anterior bases and at the sinotubular junction. High fidelity catheter-tipped pressure transducers (model 510, Millar Instruments, Houston, TX, USA) were placed in the proximal ascending aorta and pulmonary trunk and in the right and left ventricular cavities. Flowmeter rings were placed around the ascending aorta and the pulmonary trunk (Transonic flowmeter T206, Transonic Systems Inc., Ithaca, NY, USA).

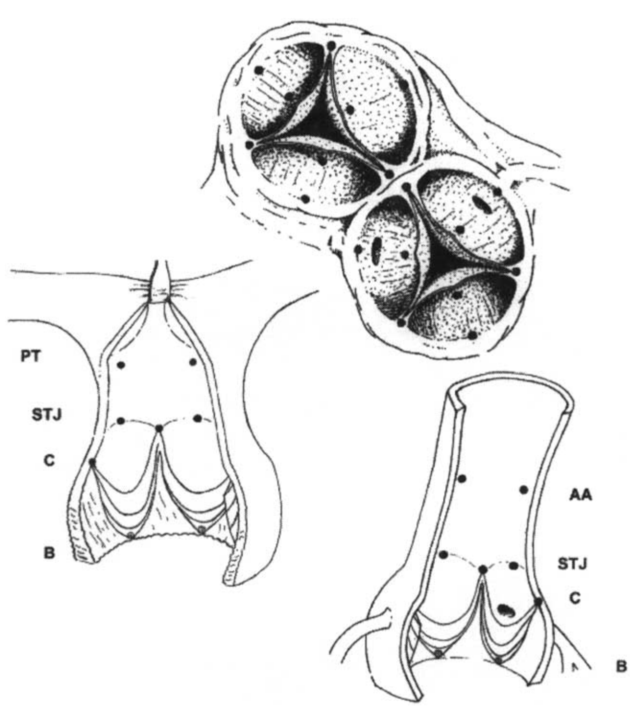

Fig. 1. Location of the sonomicrometry crystals in the aortic and pulmonary root. B, base; C, commissures; STJ, Sinotubular junction; AA, ascending aorta; PT, pulmonary trunk.

2.2. Experimental design

After discontinuing cardiopulmonary bypass, and once the animal was hemodynamically stable (at least 15 min), recordings were taken at 200 Hz (200 data-points/s). Aortic and pulmonary root dynamics were recorded separately. Epicardial echocardiography with color Doppler was used to assess the competence of the aortic and pulmonary valves. At the end of the experiment, the heart was arrested by lethal injection of potassium chloride, explanted, and the correct position of the crystals was checked. All animals received humane care in compliance with the principles of the Animal Welfare Act, the guide for care and use of laboratory animals from the United States Department of Agriculture, and the Institutional Animal Care and Use Committee of the University of Montana.

2.3. Definition of the phases of the cardiac cycle

The aortic (and pulmonary) root geometric changes were time-related to each phase of the cardiac cycle defined from the aortic or pulmonary pressure tracings and from the left or right ventricular pressure (RV) tracings (Fig. 2) [16]. End diastole or beginning of systole (beginning of isovolumic contraction) was defined as the beginning of LV (or RV) pressure increase ($dp/dt > 0$). The end of isovolumic contraction was defined as the beginning of ejection at the crossing point of LV (or RV) and aortic (or pulmonary) pressure tracings (gradient aortic/LV pressure = 0). The dichrotic notch in the aortic (or pulmonary) pressure curves defined end ejection. The end of isovolumic relaxation was defined as the lowest point of LV (or RV) pressures after ejection ($dp/dt = 0$) [5].

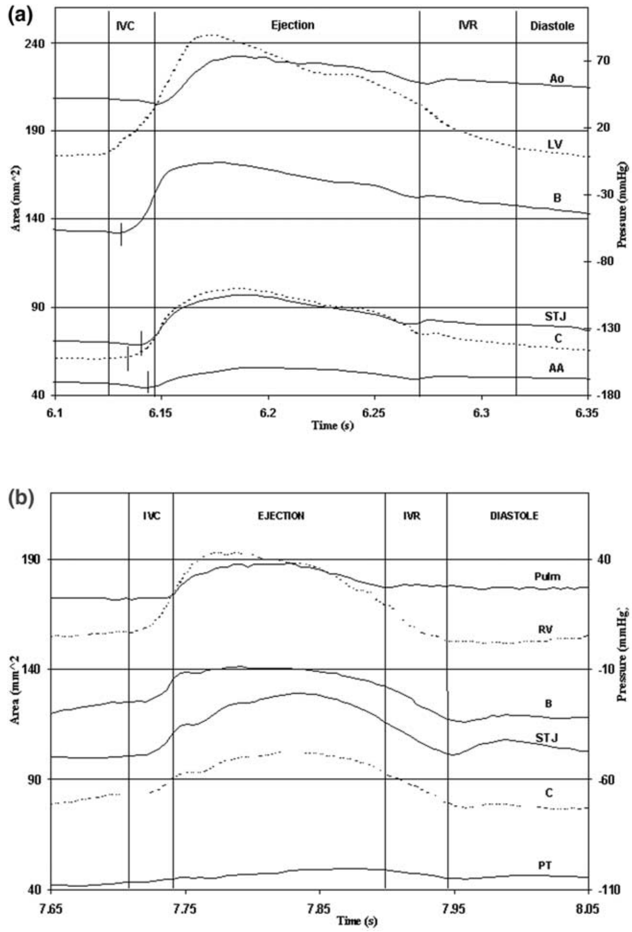

Fig. 2. Dynamic changes at the different levels of the aortic root (a) time-related to left ventricular and ascending aorta pressures and of the pulmonary root (b) time-related to right ventricle and pulmonary trunk pressure. B, base; C, commissures; STJ, Sinotubular junction; AA, ascending aorta; PT, pulmonary trunk; Ao, aortic pressure; LV, left ventricular pressure; RV, right ventricular pressure; Pulm, pulmonary pressure.

2.4. Definition of the anatomic regions

The aortic and pulmonary roots were divided into four cross-sectional areas defined by three crystals each: basal, commissural, sinotubular junction, and ascending aorta or pulmonary trunk areas (Fig. 1). Each sinus of Valsalva was defined as the area delineating the perimeter of each sinus calculated from two adjacent commissural and the corresponding basal and sinotubular crystals.

2.5. Data acquisition and calculation of root deformations

Crystal displacements were measured with the Sonometrics Digital Ultrasonic Measurement System TRX Series 16 and 1-mm Transmitter/Receiver crystals. A post-processing program (SonoSOFT Ver 3.1.4, Sonometrics Corporation, London, Ontario, Canada) was used to examine each individual length tracing between crystals and for 3D reconstruction of the crystal coordinates. All crystal distances, pressures, and flows were synchronized and recorded at the same time line on the same screen by the Sonometrics system. Length data were obtained directly from the measured distances between pair of crystals, and Lagrangian strain was used to define the deformation from the original length at end diastole [17]. Each level of the pulmonary root was represented by a triangular area defined from the three corresponding crystals and calculated using Heron's Formula [18]. The angle between basal and commissural planes was calculated using Vector and Analytic Geometry in Space, and was defined as the tilt angle of the aortic and pulmonary roots [19]. A post-processing program Sonovol (Sonometrics Corporation, London, Ontario, Canada) was used to calculate aortic root volumes using the convex hull approach. Crystals at the base, sinotubular junction, and commissures were used for these calculations. Each length, area, and volume was defined by two percentages: (1) total percentage change with reference to minimum and maximum value; and (2) percentage change for each phase of the cardiac cycle relative to the total changes over the entire cardiac cycle.

2.6. Measurement and statistical analysis methods

After close examination of the data, three consecutive heartbeats that contained the least amount of noise were chosen for analysis. The summary statistics are reported as mean ± one standard error for the mean (1SEM). The significance level used was 0.001. Area changes of the aortic and pulmonary root levels were tested for significance using Student's *t*-test for paired observation (significance level $P < 0.05$). Univariate generalized linear model (GLM) statistical methods were used to test for significant differences between sinuses area expansion. All statistical analysis were done using SPSS 0.9 program.

3. Results

3.1. Model characteristics

At the time of recording, the hemodynamic conditions were: heart rate, mean ± SEM 145 ± 8 min^{-1}; aortic pressure, 70/45 ± 5/4 mmHg, pulmonary pressure, 32/18 ± 4/2 mmHg; stroke volume, 20 ± 2 ml; cardiac output, 2.8 ± 0.3 l/min. Except one with a trivial leak, all valves were competent on epicardial echocardiography control. In all necropsy check ups, all crystals were in the correct position.

3.2. Aortic and pulmonary root dynamic similarities

At end diastole, the aortic and pulmonary root had a truncated cone shape with a basal area twice larger than the commissural area. During the cardiac cycle, both root volumes increased (Tables 1 and 2). In both roots, expansion started prior to ejection during isovolumic contraction at the base and commissures, followed by the sinotubular junction, and then by the ascending aorta or pulmonary trunk (Fig. 2).

Table 1
Phase related changes at each level of the aortic root for each phase of the cardiac cycle[a]

	IVC	Ejection		Diastole			Total expansion
		First third	Last two thirds	IVR	Mid	End	
Base (%)	+50.7 ± 4.5*	+49.2 ± 4.5*	−54.4 ± 2.0*	−44.1 ± 3.8*	−18.9 ± 1.5*	+17.5 ± 3.0*	29.8 ± 3.3*
Area (cm^2)	+1.45 ± 0.12	+1.63 ± 0.09	+1.45 ± 0.11	+1.30 ± 0.12	+1.24 ± 0.12	+1.29 ± 0.12	1.63 ± 1.29
Sinus of Valsalva (%)	+35.8 ± 4.8*	+64.2 ± 4.8*	−74.9 ± 3.8*	−31.0 ± 2.2*	−6.3 ± 1.5*	+12.2 ± 2.4*	38.4 ± 1.1*
Area (cm^2)	+1.44 ± 0.08	+1.76 ± 0.07	+1.40 ± 0.08	+1.24 ± 0.07	+1.21 ± 0.06	+1.27 ± 0.04	1.76 ± 1.27
Commissures (%)	+32.8 ± 3.2*	+67.1 ± 3.2*	−66.6 ± 1.4*	−29.4 ± 1.2*	−8.6 ± 1.1*	+4.7 ± 0.9*	63.7 ± 3.6*
Area (cm^2)	+0.72 ± 0.05	+0.98 ± 0.05	+0.73 ± 0.04	+0.62 ± 0.04	+0.59 ± 0.04	+0.60 ± 0.03	0.98 ± 0.60
Sinotubular junction (%)	+13.8 ± 1.9*	+86 ± 1.9*	−68 ± 2.6*	−14.2 ± 2.3*	−17.5 ± 2.7*	−0.2 ± 0.6*	37.1 ± 2.1*
Area (cm^2)	+0.65 ± 0.07	+0.85 ± 0.09	+0.70 ± 0.08	+0.67 ± 0.08	+0.62 ± 0.07	+0.62 ± 0.07	0.85 ± 0.62
Ascending aorta (%)	+6.6 ± 1.0*	+93.3 ± 1.0*	−64.3 ± 3.0*	−10.9 ± 3.2*	−18.2 ± 3.6*	−6.4 ± 2.4*	26.3 ± 0.9*
Area (cm^2)	+0.60 ± 0.09	+0.74 ± 0.10	+0.64 ± 0.09	+0.63 ± 0.09	+0.60 ± 0.09	+0.59 ± 0.09	0.74 ± 0.59
Aortic root volume (%)	+36.7 ± 3.3*	+63.3 ± 3.3*	−53.1 ± 1.3*	−39.1 ± 3.6*	−19.0 ± 2.4*	+11.3 ± 2.4*	33.7 ± 2.7*

[a] Data are displayed: (1) as percentage of area changes for each phase of the cardiac cycle relative to the total changes over the entire cycle; (2) as raw area value measured at the end of each phase of the cardiac cycle. Results are expressed as mean ± one standard error of the mean ($* : P < 0.05$).

Ejection was divided into two phases: (1) a first third of ejection where both root expansions reached maximal expansion, and (2) the last two thirds of ejection when both root volumes decreased. The maximum area changes occurred at commissural level compared to the base and the sinotubular junction. Thus, during ejection, the aortic and pulmonary roots became less cone-shaped and more cylindrical in order to maximize ejection (Figs. 3 and 4). A dichrotic notch was identified on each pressure curve at end ejection. Diastole was divided in two phases: (1) a root volume decrease until mid diastole, and (2) a root re-expansion during end diastole (Tables 1 and 2).

3.3. Aortic and pulmonary root dynamic differences

Although the general dynamics of the aortic and pulmonary roots looked very similar during each phase of the cardiac cycle, several differences were detected. The expansion of the aortic root was twice that of the pulmonary root. During the cardiac cycle, the aortic root volume increased by 37.7 ± 2.7% versus 20.9 ± 1.0% for the pulmonary root (Tables 1 and 2). Although both roots started to expand prior to ejection and reached maximal expansion during the first third of ejection, the commissural, and sinotubular junction dynamics were different (Figs. 3 and 4; Table 3). In the aortic root, the commissural and sinotubular area expansions were significantly different (63.7 ± 3.6% versus 37.0 ± 2.1%), while in the pulmonary root they were similar (29.0 ± 1.3% versus 27.7 ± 1.4%). Expansion of the three sinuses was also different ($P < 0.001$). In the aortic root, the right sinus (+32.4 ± 2.4%) expanded more than the left (+29.3 ± 3.2%), and more than the NC sinus (+25.8 ± 1.7%). In the pulmonary root, the right sinus (+26.3 ± 2.0%) expanded more than the anterior (+22.0 ± 2.0%), and more than the left (+16.6 ± 0.9%). However, the degree of expansion was not correlated with the size differences between each sinus area. In the aortic root, the left was larger than the right, and the right was larger than the NC sinus (in six of eight sheep). In the pulmonary root, the anterior was larger than the left, and the left was

Table 2
Phase related changes at each level of the pulmonary root for each phase of the cardiac cycle[a]

	Isovolumic contraction	Ejection		Isovolumic relaxation	Diastole		Total expansion
		First third	Last two thirds		Mid	End	
Base (%)	+25.1 ± 7.1*	+74.8 ± 7.1*	−93.9 ± 10.0*	−19.0 ± 6.1*	−8.0 ± 0.5*	+21.7 ± 7.1*	13.6 ± 3.0*
Area (cm^2)	+1.21 ± 0.07	+1.30 ± 0.06	+1.13 ± 0.07	+1.14 ± 0.08	+1.14 ± 0.08	+1.16 ± 0.09	1.30 ± 1.16
Commissures (%)	+16.5 ± 4.1*	+83.4 ± 4.1*	−86.9 ± 5.3*	−9.1 ± 4.5*	−8.6 ± 1.7*	+4.7 ± 2.0*	29.0 ± 1.3*
Area (cm^2)	+0.99 ± 0.08	+1.21 ± 0.10	+0.98 ± 0.10	+0.96 ± 0.09	+0.93 ± 0.09	+0.94 ± 0.09	1.21 ± 0.94
Sinotubular junction (%)	+8.5 ± 2.6*	+94.9 ± 2.6*	−66.3 ± 4.4*	−4.3 ± 5.5*	−38.5 ± 4.7*	+5.7 ± 2.3*	27.7 ± 1.4*
Area (cm^2)	+0.90 ± 0.09	+1.12 ± 0.10	+0.96 ± 0.10	+0.97 ± 0.10	+0.88 ± 0.09	+0.88 ± 0.09	1.12 ± 0.88
Pulmonary trunk (%)	+3.3 ± 1.2*	+99.6 ± 1.3*	−53.4 ± 3.8*	+20.1 ± 8.8*	−63.7 ± 8.9*	−5.8 ± 4.6*	15.3 ± 0.8*
Area (cm^2)	+0.53 ± 0.12	+0.62 ± 0.14	+0.58 ± 0.13	+0.59 ± 0.13	+0.54 ± 0.12	+0.53 ± 0.12	0.62 ± 0.53
Pulmonary root vol. (%)	+9.0 ± 3.5*	+91.0 ± 3.5*	−69.8 ± 7.2*	+7.0 ± 5.5*	−38.9 ± 7.8*	+1.8 ± 3.5*	29.0 ± 1.0*

[a] Data are displayed: (1) as percentage of area changes for each phase of the cardiac cycle relative to the total changes over the entire cycle; (2) as raw area value measured at the end of each phase of the cardiac cycle. Results are expressed as mean ± one standard error of the mean ($* : P < 0.05$).

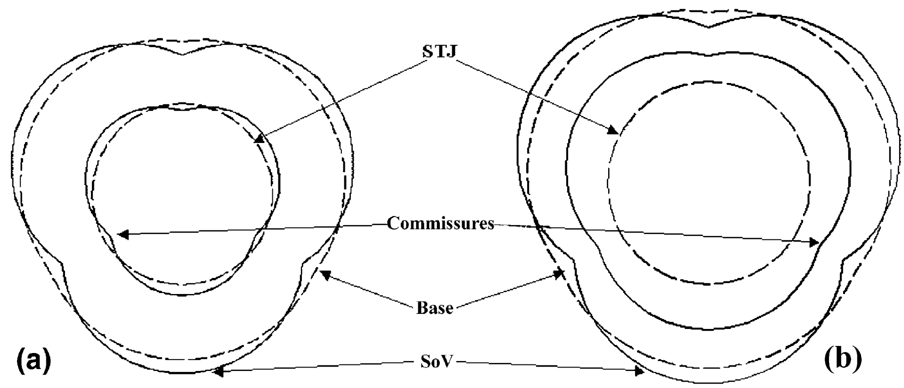

Fig. 3. Relative cross-sectional area diagram of the aortic root at end diastole (a) and at maximum expansion (b) during ejection. SoV, sinus of Valsalva; STJ, sinotubular junction.

larger than the right sinus (in five of six sheep). As a consequence, both roots had an asymmetrical systolic expansion, which resulted in a difference in the tilt angle between the planes of the base and the planes of the commissures. In the aortic root at end diastole, the root was tilted by $16.3 \pm 1.5°$ (angle oriented posteriorly and to the left), and during systole this tilt angle was reduced by $-6.6 \pm 0.5°$. In the pulmonary root at end diastole, the root angle was tilted by $9.16 \pm 1.44°$ (angle oriented anteriorly and to the left) and during systole, this tilt angle was reduced by $-5.38 \pm 0.71°$. According to these findings, Fig. 5 suggests the more physiological orientation (in a sheep model) of the pulmonary root when transferred into the aortic position in order to match the orientation and asymmetrical expansion of the normal aortic root as closely as possible.

4. Discussion

In 1967, Ross was the first to replace a diseased aortic valve with a pulmonary autograft [1]. Since then, many others have followed and a considerable number of studies have been published on the anatomical basis of the so-called *Ross Procedure* [2–4,20]. Although several authors enhanced the distensibility of the pulmonary autograft when submitted to the systemic pressure in the aortic position [21–23], so far no studies have been performed on the normal dynamic changes of the pulmonary root during the cardiac cycle and their comparison with the aortic root dynamics. The importance of the sinuses of Valsalva as an integral part of the aortic valve was already intuitively shown by Leonardo da Vinci, but it was only in the 1970s that the systolic aortic root expansion at the commissural level was described as an essential part of the aortic valve opening mechanism to reduce shear stress on the leaflets [3,4]. Since then, further descriptions were provided on the time-related changes of the aortic root dynamics as well as the mechanism of the aortic valve opening [5–7]. In the present study, as expected, the general dynamics of the aortic and pulmonary roots in their orthotopic position looked very similar during each phase of the cardiac cycle. However, significant differences were also found. The aortic and pulmonary root started to expand prior to ejection and reached maximal expansion during the first third of ejection; however, the aortic root volume expansion was twice that of the pulmonary root ($37.7 \pm 2.7\%$ versus $20.9 \pm 1.0\%$).

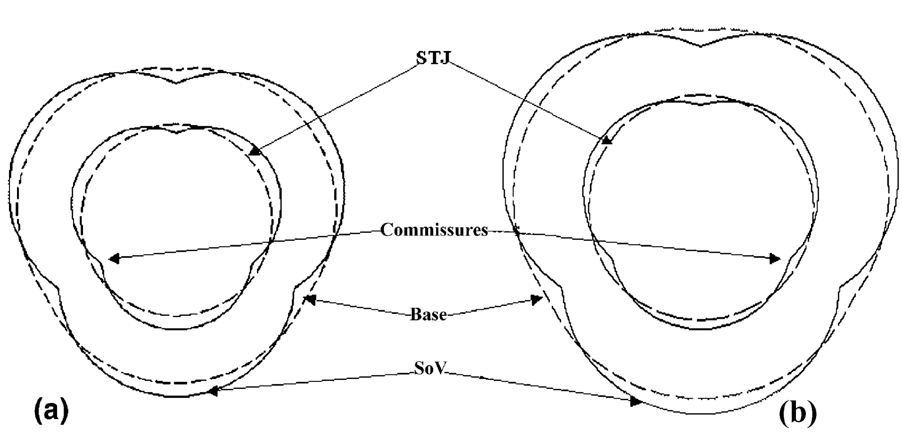

Fig. 4. Relative cross-sectional area diagram of the pulmonary root at end diastole (a) and at maximum expansion (b) during ejection. SoV, sinus of Valsalva; STJ, sinotubular junction.

Table 3
Comparative area expansion at each level of the aortic and pulmonary roots during the cardiac cycle[a]

Area expansion	Base	Commissures	Sinotubular junction	Ascending aorta/pulmonary trunk
Aortic root (%)	29.8 ± 3.3*	63.7 ± 3.6*	37.0 ± 2.1*	26.3 ± 0.9*
Area (cm^2)	1.63 ± 1.29	0.98 ± 0.60	0.85 ± 0.62	0.74 ± 0.59
Pulmonary root (%)	13.6 ± 3.0*	29.0 ± 1.3*	27.7 ± 1.4*	15.3 ± 0.8*
Area (cm^2)	1.30 ± 1.16	1.21 ± 0.94	1.12 ± 0.88	0.62 ± 0.53

[a] Data are displayed: (1) as total percentage of area changes; (2) as the range of raw area value (maximum to minimum) at each level of the aortic and pulmonary roots (* : $P < 0.05$).

Previous in vitro studies have reported different aortic and pulmonary root expansion at physiologic pressure ranges [12,14]. Nagy et al. showed that while the aortic root expanded by 35% in a linear pressure-related fashion when the pressure rose from 0 to 120 mmHg, the pulmonary root had a non-linear response to increasing pressure to a total dilatation of 46%; at pressures rising from 0 to 30 mmHg it expanded by 33%, but from 30 to 120 mmHg of pressure, it dilated only 13% [15]. Biomechanical studies described either similar tensile viscoelastic properties of porcine pulmonary and aortic valves at physiological strain rates [10] or a higher extensibility of the pulmonary leaflets in the radial direction related to significantly lower collagen content than in the aortic leaflets [11]. Although we must be aware of the possible deleterious effect of overdilatation of the pulmonary autograft, the excellent long-term results of the Ross procedure suggest the adaptability of a living tissue to systemic pressure conditions [2,24]. Also of interest are the dynamic differences observed between the pulmonary and the aortic roots at the level of the commissures and sinotubular junction. While the pulmonary root commissural and sinotubular area expansions were similar (29.0 ± 1.3% versus 27.7 ± 1.4%), in the aortic root they were significantly different (63.7 ± 3.6% versus 37.0 ± 2.1%). These dynamic differences might explain the global pulmonary root dilatation when subjected to systemic pressure, particularly at the commissural and sinotubular junction levels, which can result in the autograft failure. These findings reinforce the important role played by the supraaortic ridge for proper valve competency [25] and the need for surgical maneuvers designed to support this area of the autograft. Also, our finding of the different asymmetrical expansion of the sinuses of Valsalva should have surgical relevance. During ejection, this asymmetrical expansion determines a reduction in the root tilt angle, with the planes of the base and of the commissures becoming more parallel. The connection between the outflow tracts and great vessels becomes straighter facilitating ejection. During diastole the tilt angle enlarges, increasing the great vessel curvature (probably a stress reduction mechanism). Santiago et al. [20] suggested the advantage of finding the best fitting position of the autograft in the aortic root by pairing each of the smallest cusps.

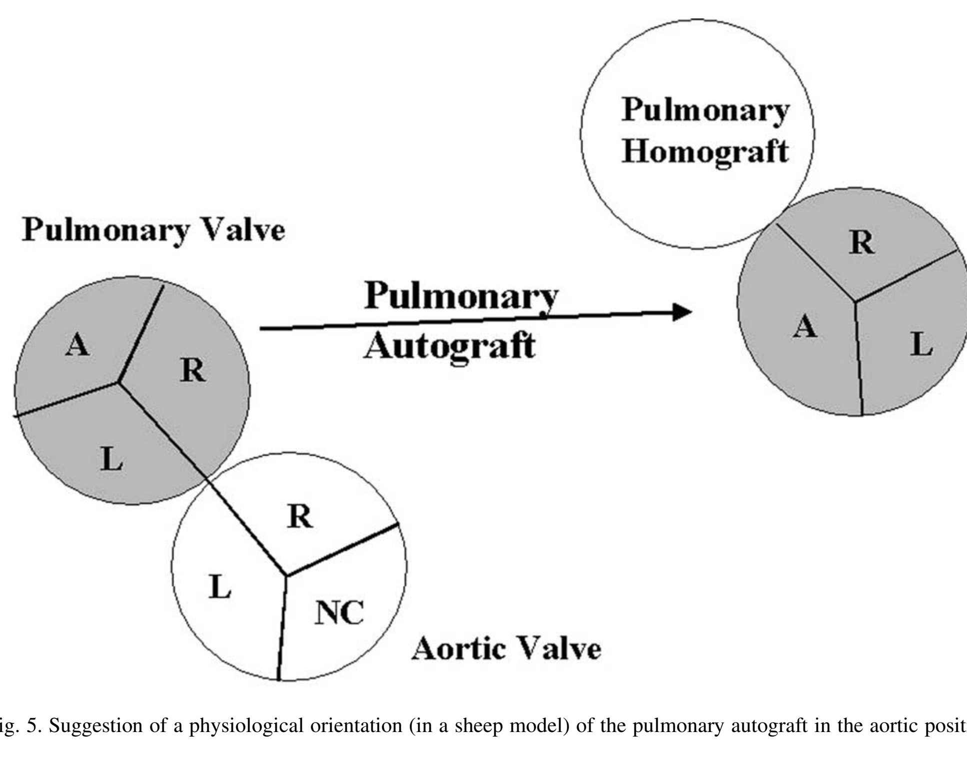

Fig. 5. Suggestion of a physiological orientation (in a sheep model) of the pulmonary autograft in the aortic position.

Although our findings in the sheep cannot be translated into the human, the principle of rotating the autograft in the most physiological orientation seems valid.

In conclusion, the dynamic differences between the aortic and pulmonary roots might explain the global pulmonary root dilatation when subjected to systemic pressures. This is particularly significant at the level of the supraaortic ridge, with subsequent spraying out of the commissures and autograft insufficiency. Differences in the asymmetrical expansion of the aortic and pulmonary roots should be considered if the pulmonary autograft is to function under the most favorable physiological conditions.

4.1. Limitations of the study

Several methodological limitations of the present study must be pointed out. First, all the data were obtained under the abnormal conditions of an acute, anesthetized, and open-chest model. Also, the recordings were made soon after weaning from cardiopulmonary bypass and cardioplegia, which explains the high heart rate, and relative low systemic and high pulmonary pressures. The administration of a fast acting β blocker to reduce the heart rate was considered, but discarded because of the further decrease in contractility that would ensue. However, the main point of the study was to study the comparative differences in dynamic behavior of the aortic and pulmonary roots that, although not proven, probably are maintained under all hemodynamic levels. In the clinical setting, the autograph is also subjected to a variety of hemodynamic conditions, including those under anesthesia with an open chest. Variability in the location of the crystals, and possible interference by the electrodes can be another possible source of error. Conscious of this possibility, all electrodes except those placed on the valve free edges were exteriorized through the vessel wall at the site of each crystal implantation, and therefore outside the blood stream. Also, the same surgeon did all surgeries in order to minimize inter-investigator variability. The relevance of our findings to the clinical Ross procedure can also be questioned. Ideally, this study should have included a number of animals with the pulmonary root in the aortic position. This was attempted, but abandoned due to the prohibitive mortality in the sheep. The species differences between sheep and human cannot be ignored. However, in our opinion, the main objective of the study has been achieved. The surgeon should be made aware that the pulmonary and aortic roots cannot be interchanged with total impunity, and cannot be rotated indiscriminately. Surgical maneuvers to compensate differences in diameter between the pulmonary and aortic diameters should be extended to protect the autograph from the changes in pressure environment.

Acknowledgements

We wish to thank Kathleen Billington and Leslie Trail for their effort and support that were essential to the completion of these experiments. We would also like to thank Reed Mandelko for providing illustrations for the paper.

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Appendix A. Conference discussion

Dr M. Turina (*Zurich, Switzerland*): These very important findings are of course explained by the lower pressure in the pulmonary artery when you test the pulmonary valve previously. That is correct?

Dr Lansac: That is correct. All these data are normal anatomical data in orthotopic position: on the pulmonary side, the values are according to right ventricular and pulmonary pressure.

Dr Turina: Did you perform any measures to stiffen the sinotubular junction to see if the behavior of the pulmonary root can be changed in terms of making it less pliable with the external support?

Dr Lansac: We haven't tried yet the external support because the purpose of this study was initially to describe the normal dynamic anatomy of both roots and see if they were exactly similar or if there were several differences. But it has been tried on the aortic side, and showed that when you reduced the diameter of the sinotubular junction, timing and stress of the aortic valve closure were increased.

Dr D. Metras (*Marseille, France*): You have demonstrated the fact that the dilatation of the pseudo sinuses of Valsalva of the pulmonary artery are asymmetrical. Do you think it supports the concept that during the Ross operation the autograft should be rotated and not put orthotopically?

Dr Lansac: All those data come from a sheep model, therefore it is very difficult to extrapolate on humans. However, this study corroborate Santiago et al.'s findings who suggested to match the position of the pulmonary autograft in the aortic position according to the smallest cusp. I haven't detailed everything but the expansion of the aortic and pulmonary root were also asymmetric. This asymmetrical expansion resulted in the variation of the angle between the plane of the base and the commissures of either root and was defined as the tilt angle of the aortic and pulmonary valve. During ejection, the plane of the base and the commissures became more parallel in order lined up the left ventricular outflow tract and the ascending aorta, and therefore maximize ejection. Trying to match the asymmetry of either root might be the position of choice if the pulmonary autograft is to function under physiological condition.

Dr R. Deac (*Tirgu-Mures, Romania*): From what you presented, I understood that the aortic valve complex is more compliant, although, as Professor Turina pointed out, is it tested under higher pressure?

Dr Lansac: No, we haven't tested the pulmonary valve under systemic pressure because it was tested in the orthotopic position on the right side just to document normal anatomical description of the pulmonary dynamics. So when we say the expansion of the aortic root is twice that of the pulmonary root, it is also related to pressure. In physiological conditions the pulmonary root expand by 20% and the aortic root by 40%. Other authors have documented the overdilatation of the autograft when subjected to systemic pressure, however, the excellent long-term results of the Ross procedure advocated for the adaptability of this alive valve to high pressure conditions.

Dr Deac: And the second question, do you plan to correlate this data with the mechanical behavior of tested samples of every sinus?

Dr Lansac: You mean to modelize those data?

Dr Deac: No, I mean to compare the behavior under the condition you studied with physical testing of samples of tissue from each sinus.

Dr Lansac: No, we haven't planned to do it. However, other authors have compared the elasticity of the aortic versus pulmonary root. Contrary to the aortic, the expansion of the pulmonary root was nonlinear over 30 mmHg which could explain the adaptability of the pulmonary autograft after a Ross procedure.