J. Anat. (1987), **151**, pp. 107–115
With 4 figures
Printed in Great Britain

Growth of the internal diameters in the pulmonary arterial tree in infants and children

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(*Accepted* 25 *April* 1986)

INTRODUCTION

Nowadays children with tetralogy of Fallot or with pulmonary atresia are operated on at an earlier age than was the case several years ago. Successful surgical treatment of these patients depends on new methods for correction but may also be dependent upon the anatomical condition, especially the size of the pulmonary arteries (Kirklin *et al.* 1979, 1984; Oelert *et al.* 1984). After a total corrective operation the pulmonary arteries must be able to accept the total right ventricular output. When the pulmonary arteries are too small the children will die postoperatively because of the persistent low cardiac output syndrome (Oku *et al.* 1978; Tucker, Turley, Ullyot & Ebert, 1979). Therefore reference data on the normal internal diameter of the pulmonary trunk and left and right pulmonary arteries may be essential in deciding whether or not the pulmonary arteries, in cases with tetralogy of Fallot or with pulmonary atresia, are large enough for a successul operation. With non-invasive *in vivo* methods such as two dimensional and M-mode echocardiography the pulmonary trunk and arteries are not easily visualised or accurately measured (Gussenhoven *et al.* 1983; Cloez *et al.* 1984; Benson *et al.* 1985). Therefore, we present in this paper postmortem data on the normal growth of the pulmonary trunk and pulmonary arteries of children with ages ranging from 21 weeks of gestation up to 10 years, who died from non-vascular diseases.

MATERIALS AND METHODS

The material consisted of 126 hearts and great arteries of infants and children who had died from non-vascular diseases. The ages ranged from 21 weeks of gestation up to 10 years after birth. The internal diameters of the pulmonary ostium, of the pulmonary trunk (1–2 cm beyond the valve) and of the left and right pulmonary arteries were measured, in the unfixed specimens within 24 hours of death, with probes calibrated on whole mm differences in diameter. This method and its reliability have been described previously (van Meurs & Klein, 1974; van Meurs, Klein & Krediet, 1977). The internal diameters of the pulmonary arterial tree were compared with the internal diameter of the ascending aorta, measured 1 cm beyond the valve. Furthermore the internal diameters of the descending aorta, measured 1 cm distal to the insertion of the ductus arteriosus (or ligamentum arteriosum), were compared with the sum of the internal diameters of the corresponding left and right pulmonary arteries, as described in the clinical studies of Kirklin *et al.* (1984) and Oelert *et al.* (1984). Linear regression analysis was used to investigate the

Table 1. *Relation between body length (cm) and internal diameters of the pulmonary ostium (mm): mean value with 5 % and 95 % limits of the data as plotted in Figure 1. N.B. ratio of pulmonary ostium: aortic ostium = 1·14:1 (van Meurs et al. 1977)*

Body length (cm)	Internal diameter mean value (mm)	5% and 95% limits (mm)
40	6	3–9
45	7	4–10
50	8	5–11
55	9	6–12
60	10	7–13
65	11	7·5–14
70	11·5	8·5–15
75	12·5	9·5–16
80	13·5	10·5–16·5
85	14·5	11·5–18
90	15	12–18·5
95	16	13–19·5
100	17	14–20·5
105	18	15–21·5
110	19	16–22·5
115	20	17–23·5
120	21	18–24
125	21·5	18·5–25
130	22	19·5–26
135	23·5	20·5–27
140	24·5	21·5–28

relations of the internal diameters of the various vessels and body length. Statistical analysis of the results was carried out using Student's *t*-test. A difference was considered to be significant if the two-tailed probability was $< 0{\cdot}05$ (Sachs, 1973).

OBSERVATIONS

The measurements of the internal diameters of the various parts of the pulmonary arterial tree (Tables 1–4) were plotted against body length in centimetres. Figure 1 shows such data for the pulmonary ostium, Figure 2 for the pulmonary trunk, Figure 3 for the left pulmonary artery and Figure 4 for the right pulmonary artery. The 95 % limits of the data are included. The data show a linear correlation between, on the one hand, an approximately sixfold increase of the internal diameter of the pulmonary ostium and pulmonary trunk and, on the other, an increase of body length from 30 to 140 cm. Although the internal diameter of the pulmonary trunk tends to be larger than its pulmonary ostium, there is no significant difference in growth (pulmonary trunk $b = 0{\cdot}16$, in $y = a+bx$, versus pulmonary ostium $b = 0{\cdot}15$). Similarly, the data for the left and right pulmonary arteries show a linear correlation between, on the one hand, an approximately ninefold increase of their internal diameters and, on the other, an increase of body length from 30 to 140 cm. The internal diameter of the right pulmonary artery tends to be larger than that of the left but there is no significant difference in growth (left pulmonary artery $b = 0{\cdot}11$ versus right pulmonary artery $b = 0{\cdot}11$).

In a previous paper the internal diameters of the ascending and descending aorta were measured in the same postmortem material (van Meurs & Krediet, 1982). Plotting these earlier data on the internal diameters of the ascending aorta against

Table 2. *Relation between body length (cm) and internal diameters of the pulmonary trunk (mm): mean value with 5% and 95% limits of the data as plotted in Figure 2*

Body length (cm)	Internal diameter (mm)	5% and 95% limits (mm)
40	6·5	3·5–9·5
45	7·5	4·5–10·5
50	8·5	5·5–11·5
55	9·5	6·5–12·5
60	10	7–13
65	11	8–14
70	12	9–15·5
75	13	10–16·5
80	14	11–17·5
85	15	12–18·5
90	16	13–19·5
95	17	14–20·5
100	18	15–21
105	18·5	15·5–22
110	19	16–22·5
115	20	17–23·5
120	21	18–24·5
125	22	19–25·5
130	23	20–26·5
135	24	21–27·5
140	25	22–28·5

Table 3. *Relation between body length (cm) and internal diameters of the left pulmonary artery (mm): mean value with 5% and 95% limits of the data as plotted on Figure 3.*

Body length (cm)	Internal diameter mean value (mm)	5% and 95% limits (mm)
40	3·5	1·5–5·5
45	4	2–6·5
50	4·5	2·5–7
55	5·5	3·5–8
60	6	4–8·5
65	7	5–9·5
70	7·5	5·5–10
75	8	6–10·5
80	9	7–11
85	9·5	7·5–12
90	10·5	8·5–13
95	11	9–13·5
100	11·5	9·5–14
105	12·5	10·5–15
110	13	11–15·5
115	14	12–16·5
120	14·5	12·5–17
125	15·5	13–18
130	16	13·5–18·5
135	16·5	14–19
140	17·5	15–19·5

Table 4. *Relation between body length (cm) and internal diameters of the right pulmonary artery (mm): mean value with 5% and 95% limits of the data as plotted in Figure 4*

Body length (cm)	Internal diameter (mm)	5% and 95% limits (mm)
40	3·5	0·5–6·5
45	4·5	1·5–7·5
50	5	2–7·5
55	6	3–9
60	6·5	3·5–9·5
65	7	4·5–10
70	8	5–10·5
75	8·5	5·5–11·5
80	9·5	6·5–12
85	10	7·5–13
90	10·5	8–13·5
95	11·5	8·5–14·5
100	12	9·5–15
105	12·5	10–15·5
110	13·5	10·5–16·5
115	14·5	11·5–17·5
120	15	12·5–18
125	16	13–19
130	16·5	13·5–19·5
135	17	14·5–20·5
140	18	15–21

the present data on the internal diameters of the pulmonary ostium yielded, as might be expected, a linear correlation. The ratio pulmonary ostium:ascending aorta was 1·09 ± (S.D.) 0·12 (n = 126). This ratio ranged from 0·83 to 1·50. With a similar treatment of the data for the pulmonary trunk we found a ratio of 1·12 ± 0·12 (n = 126) with values ranging from 0·83 to 1·50. For the left pulmonary artery we found a ratio of 0·67 ± 0·12 with a range of 0·38 to 1·00 and for the right pulmonary artery these values were 0·69 ± 0·13 and 0·44–1·00. A similar mathematical approach was used for the relation between, on the one hand, the internal diameter of the descending aorta, measured 1 cm beyond the insertion of the ductus arteriosus and, on the other, the sum of the internal diameters of the left and right pulmonary arteries; a ratio was found of 0·60 ± 0·12 (n = 126) with a range from 0·41 to 1·00.

DISCUSSION

Successful surgical correction in patients with tetralogy of Fallot or with pulmonary atresia may be impossible because of the small size of the pulmonary arteries. Operation in children with small or even hypoplastic pulmonary arteries can cause right ventricular failure, low cardiac output syndrome and even operative death (Oku *et al.* 1978; Tucker *et al.* 1979). However, small pulmonary arteries, as present pre-operatively, can increase in size after total correction or palliative operations (Kirklin *et al.* 1984; Laas *et al.* 1984). To estimate the size of the pulmonary arteries and pulmonary trunk the internal diameters of these vessels are in most clinical studies related on the angiogram to the size of the ascending aorta (Dailey, Stinson, Griepp & Shumway, 1978; Blackstone *et al.* 1979; Oelert *et al.* 1984; Laas *et al.* 1984; Sebening *et al.* 1984). It is on the basis of such estimations that the selection

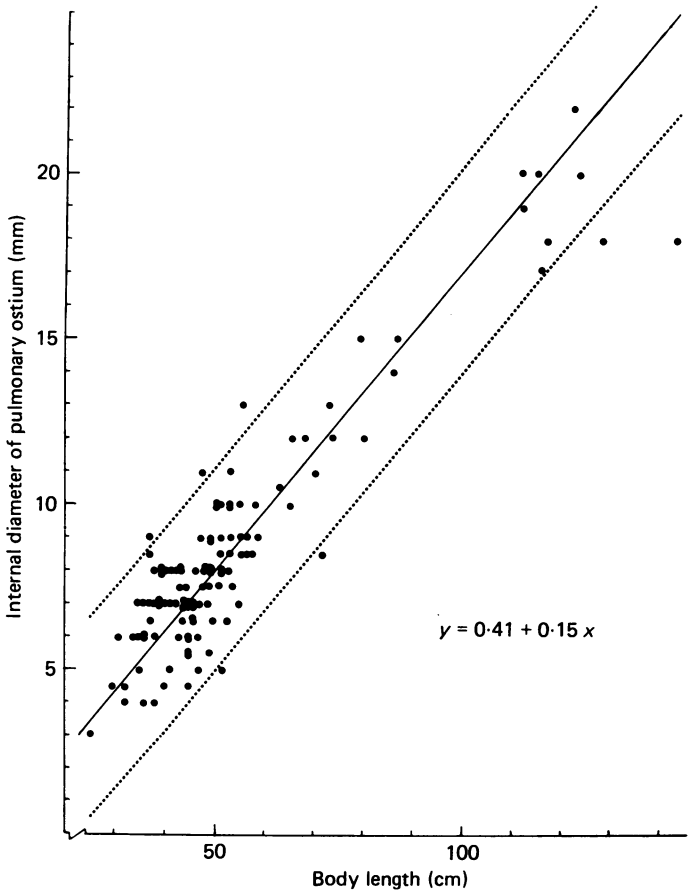

Fig. 1. Relation between internal diameters of the pulmonary ostium (mm) and body length (cm); interrupted lines indicate 95% limits.

of a surgical method is usually made. According to Sebening *et al.* (1984) a total corrective operation is only feasible with a relative diameter of the right pulmonary artery on the angiogram of at least 30% of the internal diameter of the ascending aorta. However, other investigators stated that more exact information on the condition of the pulmonary arteries can be obtained by comparison of the sum of the diameters of the pulmonary arteries with the diameter of the descending aorta, which is thought to vary much less in size than that of the ascending aorta, especially in children with tetralogy of Fallot (Kirklin *et al.* 1984; Oelert *et al.* 1984). To be able to evaluate the condition of the pulmonary trunk and pulmonary arteries in children with these cardiac malformations it may be helpful to know the increase of the size of the pulmonary arterial tree during bodily development in normal infants and children.

Accordingly, we set up the present investigations. We chose body length as a parameter rather than body surface since, shortly before death, body weight, on which surface estimates are based, can change in a few days or hours.

We also compared the size of the measured parts of the pulmonary arterial tree with that of the corresponding ascending aorta and as proposed by Oelert and coworkers (1984) the sum of the internal diameters of the left and right pulmonary

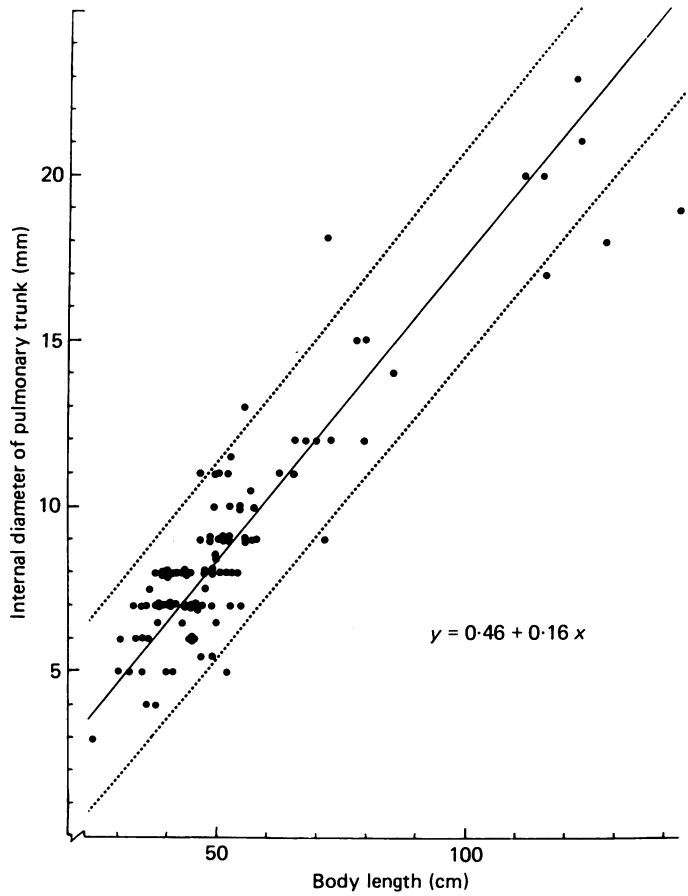

Fig. 2. Relation between internal diameters of pulmonary trunk (mm) and body length (cm); interrupted lines indicate 95% limits.

arteries with the internal diameter of the descending aorta. Measurements of the ascending and descending aorta in the same postmortem material have been described in a previous paper (van Meurs & Krediet, 1982) and have been used as reference data in the present paper.

Data on the normal internal diameter of the pulmonary vessels are few. In the past the external diameters have been compared with the age of the infants and children (Beneke, 1879), but since in recent years children are growing faster in height than previously, we are not able to compare these measurements with our own. With the new non-invasive methods such as M-mode and two dimensional echocardiography the pulmonary trunk and arteries are not easily visualised and accurately measured (Gussenhoven *et al.* 1983; Cloez *et al.* 1984; Benson *et al.* 1985). We therefore used unfixed postmortem material to study the normal growth of the pulmonary arterial tree of infants and children.

Comparing the internal diameters of the pulmonary ostium, pulmonary trunk and left and right pulmonary arteries with those of the ascending aorta, ratios of respectively 1·09, 1·12, 0·67 and 0·69 were found. In children with tetralogy of Fallot these four ratios are much lower. Laas and his coworkers (1984) described in a group of 31 children with tetralogy of Fallot pre-operative ratios, derived from

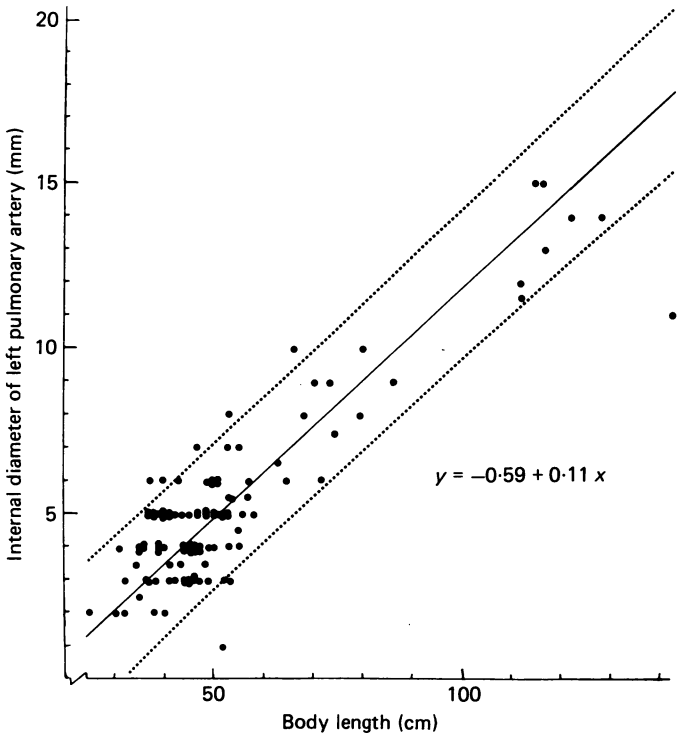

Fig. 3. Relation between internal diameters of left pulmonary artery (mm) and body length (cm); interrupted lines indicate 95% limits.

measurements on the angiogram, of respectively 0·38, 0·35, 0·36 and 0·31. Sebening *et al.* (1984) came to the conclusion that for a successful total corrective operation, the ratio of right pulmonary artery and ascending aorta should be at least 0·30.

In our material consisting of normal children the ratio of the internal diameter of the descending aorta and the sum of the size of the left and right pulmonary arteries was 0·60 with a range from 0·41 to 1·00. This was, although not expected, about the same range as that found by Oelert *et al.* (1984) in children with tetralogy of Fallot. They found a range from 0·33 to 1·38 with values lying usually between 0·4 and 0·8 and suggested that children in which this ratio is, at catheterisation in the first year of life, higher than 0·7 should be excluded from primary correction since the size of the pulmonary arteries would be too small for successful total correction. It seems therefore that they only accepted for total corrective operation children with pulmonary arteries of an almost normal size.

Interestingly, our postmortem data concerning the pulmonary and aortic ostia correspond with those obtained *in vivo* using M-mode echocardiography since with this technique identical values were found for the pulmonary ostium but were consistently 2 mm below ours for the aortic ostium (van Meurs *et al.* 1977). With the introduction of two dimensional sector echocardiography it has become possible to assess the diameters of the ascending aorta and pulmonary trunk, but with the limitation that also obtains for M-mode echocardiography that the true diameter of a tubular vessel can only be obtained when the sound beam is perpendicular to the walls of the vessel and traverses the lumen at its midportion (Weyman *et al.* 1978).

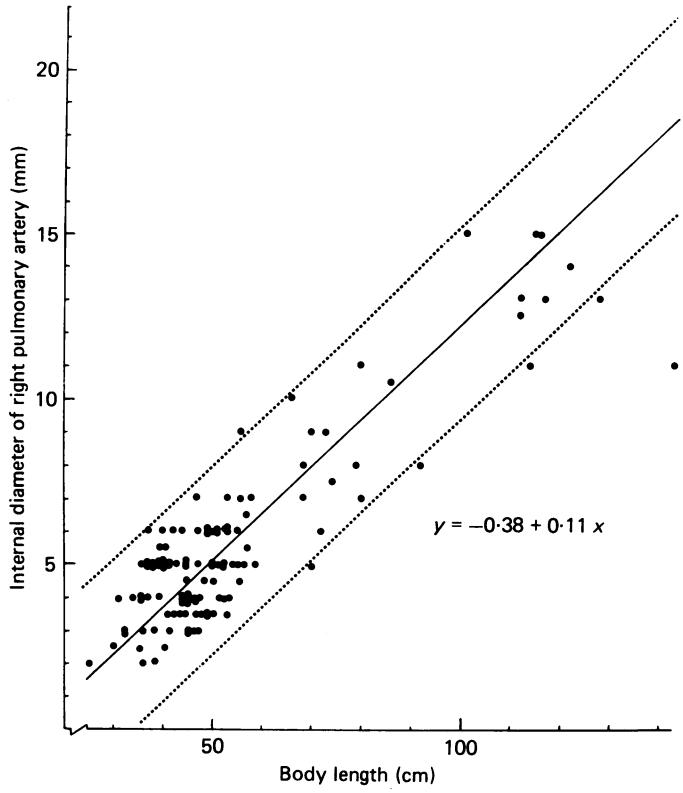

Fig. 4. Relation between internal diameters and right pulmonary artery (mm) and body length (cm); interrupted lines indicate 95% limits.

Cloez *et al.* (1984) pointed out that with this method the internal diameters of the pulmonary trunk and its branches are slightly smaller than the angiographically determined diameters. Using the data from our postmortem material as reference data for estimations in the living one should bear in mind that measurements from two dimensional echocardiograms will probably be underestimated when the sound beam is not going through the centre of the vessel.

Finally, considering the possible further development of the pulmonary arteries in children with tetralogy of Fallot it should be realised that not only the internal diameter of the pulmonary trunk and its branches but also the condition of the arterial walls will determine further development of these vessels. Evaluation of the histological development of the vascular wall of the pulmonary arteries in normal infants and children as well as in those with tetralogy of Fallot will lead to a better definition of normal and pathological conditions of the pulmonary arterial system.

SUMMARY

To provide a better understanding of the operability of the pulmonary arteries in children with tetralogy of Fallot or with pulmonary atresia, we investigated the growth of the internal diameters of the pulmonary arterial tree in fresh postmortem hearts and great arteries of infants and children of ages up to 10 years after birth, who died from non-vascular diseases. Linear correlations were found between, on

the one hand, the internal diameters of the pulmonary ostium, pulmonary trunk and left and right pulmonary artery and, on the other, body length. Based on an approach used in clinical studies we also determined the ratios between the internal diameter of the pulmonary arterial tree and the ascending aorta and also the ratios of the internal diameters of the descending aorta and the sum of the size of the left and right pulmonary arteries. Comparison of the data from the postmortem material with observations on the internal diameters measured with two dimensional (sector) echocardiography echo indicates that the latter may slightly underestimate the true diameters.

The authors are indebted to Professor Dr J. Moll for his critical advice and to Dr J. J. Willemse for the photographs.

REFERENCES

BENEKE, F. W. (1879). *Ueber das Volumen des Herzens und die Weite der Arteria pulmonalis und Aorta ascendens in den verschiedenen Lebensaltern.* Cassel, Germany: Theodor Kay.

BENSON, L. N., SMALLHORN, J. S., FREEDOM, R. M., TRUSLER, G. A. & ROWE, R. D. (1985). Pulmonary valve morphology after balloon dilatation of pulmonary valve stenosis. *Catheterization and Cardiovascular Diagnosis* **11**, 161–166.

BLACKSTONE, E. H., KIRKLIN, J. W., BERTRANOU, E. G., LABROSSE, C. J., SOTO, B. & BARGERON, L. M. (1979). Preoperative prediction from cineangiograms of post-repair right ventricular pressure in tetralogy of Fallot. *Journal of Thoracic and Cardiovascular Surgery* **78**, 542–552.

CLOEZ, J. L., BRUNOTTE, F., ADMANT, P., WORMS, A. M. & PERNOT, C. (1984). Evaluation de l'artère pulmonaire et de ses branches en échocardiographie bidimensionelle dans la tétralogie de Fallot et l'artésie pulmonaire chez le nourrisson. *Archives françaises de pédiatrie* **41**, 307–312.

DAILY, P. O., STINSON, E. B., GRIEPP, R. B. & SHUMWAY, N. E. (1978). Tetralogy of Fallot. Choice of surgical procedure. *Journal of Thoracic and Cardiovascular Surgery* **75**, 338–345.

GUSSENHOVEN, W. J., VAN LEENEN, B. F., KUIS, W., DE VILLENEUVE, V. H., BOM, N. & VAN MEURS-VAN WOEZIK, H. (1983). Comparison of internal diameter of great arteries in congenital heart disease. *British Heart Journal* **49**, 45–50.

KIRKLIN, J. W., BLACKSTONE, E. H., PACIFICO, A. D., BROWN, R. N. & BARGERON, L. M. (1979). Routine primary repair vs two-stage repair of tetralogy of Fallot. *Circulation* **60**, 373–386.

KIRKLIN, J. W., BLACKSTONE, E. H., PACIFICO, A. D., KIRKLIN, J. K. & BARGERON, L. M. (1984). Risk factors for early and late failure after repair of tetralogy of Fallot and their neutralization. *Thoracic and Cardiovascular Surgeon* **32**, 208–214.

LAAS, J., ENGESER, U., STRUCK, E., SAUER, U., BUHLMEYER, K., ZWINGERS, TH. & SEBENING, F. (1984). Tetralogy of Fallot. Development of hypoplastic pulmonary arteries after palliation. *Thoracic and Cardiovascular Surgeon* **32**, 133–138.

OELERT, H., HETZER, R., LUHMER, I., KALLFELZ, H. C. & BORST, H. G. (1984). Criteria for and against primary correction of Fallot's tetralogy. *Thoracic and Cardiovascular Surgeon* **32**, 215–219.

OKU, H., SHIROTANI, H., YOKOYAMA, T., YOKOTA, Y., KAWAI, J., MORI, A., KANZAKI, Y., MAKINO, S., ANDO, F. & SETSUIE, N. (1978). Postoperative size of the right ventricular outflow tract and optimal age in complete repair of tetralogy of Fallot. *Annals of Thoracic Surgery* **25**, 322–328.

SACHS, L. (1973). *Angewandte Statistik.* Berlin, Heidelberg, New York: Springer.

SEBENING, F., LAAS, J., MEISNER, H., STRUCK, E., BUHLMEYER, K. & ZWINGERS, TH. (1984). The treatment of tetralogy of Fallot: early repair or palliation? *Thoracic and Cardiovascular Surgeon* **32**, 201–207.

TUCKER, W. Y., TURLEY, K., ULLYOT, D. J. & EBERT, P. A. (1979). Management of symptomatic tetralogy of Fallot in the first year of life. *Journal of Thoracic and Cardiovascular Surgery* **78**, 494–501.

VAN MEURS-VAN WOEZIK, H. & KLEIN, H. W. (1974). Calibres of aorta and pulmonary artery in hypoplastic left and right heart syndromes: effects of abnormal bloodflow? *Virchows Archiv A. Pathological Anatomy and Histology* **364**, 357–364.

VAN MEURS-VAN WOEZIK, H., KLEIN, H. W. & KREDIET, P. (1977). Normal internal calibres of ostia and great arteries and of aortic isthmus in infants and children. *British Heart Journal* **39**, 860–865.

VAN MEURS-VAN WOEZIK, H. & KREDIET, P. (1982). Measurements of the descending aorta in infants and children: comparison with other aortic dimensions. *Journal of Anatomy* **135**, 273–279.

WEYMAN, A. E., CALDWELL, R. L., HURWITZ, R. A., GIROD, D. A., DILLON, J. C., FEIGENBAUM, H. & GREEN, D. (1978). Cross-sectional echocardiographic characterization of aortic obstruction. I. Supravalvular aortic stenosis and aortic hypoplasia. *Circulation* **57**, 491–497.