Pulmonary Artery Growth after Systemic-to-pulmonary Shunt in Children with a Univentricular Heart and a Hypoplastic Pulmonary Artery Bed

Implications for Fontan Surgery

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SUMMARY

The aim of the study was to investigate the developmental pattern of hypoplastic pulmonary artery (p.a.) bed augmented by systemic-to-pulmonary shunt in children with univentricular heart scheduled for Fontan surgery.

For the study, a highly selected patient cohort was chosen (12 patients aged between 5 and 19 years; mean 9.5 years) with comparable initial morphological conditions of univentricular heart and hypoplastic p.a. bed, who after mandatory systemic-to-pulmonary shunt underwent Fontan procedure at time of normalization of pulmonary artery size. Further selection criteria were: normal pulmonary vascular resistance at time of Fontan procedure, competent a-v valve(s), and globally unimpaired ventricular function.

All patients were grouped according to the preoperative pulmonary flow index (Q_{pi} ; L/min/m² b.s.a.) measured immediately before Fontan operation: Group A: 1.5–2.5; B: 3.0–4.0; C: 4.0–5.0; D: > 6.0, and their cardio-pulmonary hemodynamic situation (Hb, $SA_{sat}\%$, Q_p/Q_s , PAP, R_p/R_s , EDVP, $FS\%$, ventricular diastolic compliance ($VC = EDVP/Q_{pi} + Q_{si}$) as well as the pulmonary artery size and area using standard (Nakata-index, McGoon-ratio) and a self designed computer assisted planimetric area calculation (PPAAI; cm²/m² b.s.a.) analysed.

Each patient underwent 1–3 shunt procedures, the mean shunt patency period for groups A, B, C and D was 12, 8.6, 5.3, and 4.5 years, respectively. The mean Nakata-index (283, 297, 324, 405 in groups A-D) and the McGoon-ratio (2.0, 2.2, 2.8, 3.3 in groups A-D) correlated with the Q_p index, reflecting flow dependent development of pulmonary artery bed. No correlation was found between Q_{pi} and PPAAI (47, 40, 41 and 47 in group A-D). The VC/Q_p relation showed an inversely proportional pattern with values 2.3, 1.0, 0.8, 0.7 for corresponding groups A-D, the lowest VC in group A correlated with

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polyglobulic status (Hb- values; g/dl) : 21.3 in A vs 19.8, 18.0 and 16.5 in B-D) and mean arterial SASat-values (77% in A vs 83%, 84% and 89% in B-D).

In conclusion, in our highly selected patient cohort, the development of p.a. size was strongly flow-dependent, and patients with restrictive pulmonary flow needed an approximately threefold longer time period to normalize their p.a. size compared to those with excessive flow. In patients with restrictive pulmonary flow, the Nakata-index underestimated the degree of development of the pulmonary artery system, probably due to the distortion of the proximal p.a. segment. In consequence, in these patients the normalization of the p.a. bed and thus suitability for the Fontan procedure probably occurred much earlier. Based on our observations and those of others, in patients with excessive flow the normalization of p.a. bed, provided it occurs within 3-4 years, seems not necessarily to be associated with a deterioration of ventricular function. (Jpn Heart J 1998; 39: 671-680)

Key words: Hypoplastic pulmonary artery bed, Fontan procedure

GENERALLY, systemic-to-pulmonary shunt (STPS) is an effective method for augmentation of hypoplastic p.a. bed^{1,4,13)} preparing the pulmonary circulation for definite repair. However, pulmonary artery system supplied by a shunt may have a different growth pattern. This is especially important in the indication policy for a Fontan procedure, as the pulmonary artery size (p.a. index) is reported to be one of the important factors influencing early and late outcome after a definite repair,^{3,20)} and on the other hand, a long standing shunt condition may have adverse effects on myocardial function.¹⁵⁾ Therefore, of essential importance seems to be the question whether the Nakata-index and McGoon-ratio are reliable factors in the assessment of the degree of development of p.a. bed, especially in children with a high potential for distortion of p.a. due to STPS.

Little is known about the factors promoting growth of the p.a. bed and its developmental pattern after STPS. Some early reports^{10,21)} and recently published work²⁰⁾ suggest that one of the most important primary determinant factors promoting growth of the pulmonary vessel is the p.a. flow.

To determine the prognostic value of the p.a. flow as a factor correlating with or determining the p.a. size, we investigated the developmental pattern of the p.a. system in 12 children with univentricular heart and hypoplastic p.a. bed augmented by STPS, with special regard to the relationship between the p.a. flow, p.a. size and the time factor.

For the study, we selected children unified by the comparable morphologic conditions of univentricular heart and hypoplastic p.a. bed, who after mandatory STPS developed a different level of p.a. flow, from restrictive to excessive high, and underwent Fontan procedure at the time of normalization of p.a. diameter,

presenting with globally unimpaired ventricular function and normal pulmonary vascular resistance.

We also tried, in the light of our results, to delineate the interpretational value of the Nakata-index and McGoon-ratio in terms of assessments of suitability for a Fontan procedure, particularly focusing our attention on the relationship between the degree of development of proximal and distal p.a. segments, especially in children with long standing STPS and restrictive p.a. flow.

MATERIALS AND METHODS

Twelve non-consecutive patients aged between 5 and 19 years (mean 9.5 years) with univentricular heart and hypoplastic p.a. bed, who after mandatory STPS underwent successful Fontan procedure during 1980–1993, were chosen for the study. The selection criteria were: normal p.a. diameter, normal pulmonary arteriolar resistance, competent atrioventricular valve(s), and globally unimpaired ventricular function at the time of the Fontan procedure.

In all patients, the following parameters were analysed for preoperative assessment of pulmonary and hemodynamic function: pulmonary-to-systemic flow ratio ($Q_p: Q_s$), pulmonary flow-index (Q_{pi} ; L/min/m² b.s.a.), mean pulmonary artery pressure (PAP mean; mmHg), pulmonary-to-systemic resistance ratio ($R_p: R_s$), Nakata-index (PAI; mm²/m² b.s.a.), McGoon-ratio, planimetrically assessed pulmonary artery area index (PPAAI; cm²/m² b.s.a.), end-diastolic ventricular pressure (EDVP; mmHg), fractional shortening (FS; %), ventricular diastolic compliance ($VC = EDVP/Q_{pi} + Q_{si}$) — based on a modified formula in accordance with Mair *et al.*,¹⁴⁾ as well as hemoglobin (Hb; g/dl) and systemic arterial oxygen saturation values (SA_{sat}; %). In 5 patients lung biopsies were taken intraoperatively, and the lung specimens were analysed and graded according to Heath & Edwards classification.⁹⁾

For measurements of p.a. size preoperative angiograms were evaluated according to the techniques described by Nakata *et al.*¹⁶⁾ and McGoon.¹⁸⁾

In addition to the classical measurements of p.a. size according to Nakata and McGoon, in every patient a defined area of the p.a. tree was calculated using a computer added planimetric procedure developed in our institution according to the following principle: From the pulmonary angiograms of the left and right lung pictures were taken in the phase of the most powerful contrast intensity in systole and magnifications up to A4 international paper format were made. In all patients, both the left and right p.a. system could be reached either by an antegrade route or by unilateral access via a prosthetic shunt. The contours of the p.a. were then outlined in a standard fashion beginning proximally at the main p.a. at the prebranching level and finishing at the subsegmental arteries,

Figure. Planimetric calculation of the pulmonary artery area index (PPAAI). The contours of pulmonary artery are outlined and the vessel area calculated using a computer technique and self developed software (for details see Methods).

whereby the limit for the distal diameter was uniformly set at 2 mm (Figure). The angiographic pictures were then scanned and the outlined pulmonary vessel areas calculated using a computer (PC-4-86 DX 2/66, syquest 110 MB, 20" monitor, HP Scanjet IIC, 300 × 300 dpi, scannersoftware HP Photofinish) and a self-developed software (program language: Visual Basic 3.0 professional). The outlined areas were coloured, and the number of points used for colouring the areas counted and referred to the count of points of a reference circled area. The values were finally given in cm^2 in relation to the body surface area (Figure).

The patients were grouped according to the preoperative pulmonary flow index (Q_{pi} ; $\text{L}/\text{min}/\text{m}^2$ b.s.a.): group A: 1.5–2.5; group B: 3.0–4.0; group C: 4.0–5.0 and group D: > 6.0. The preoperative pulmonary and cardiac function were analysed and intraindividually compared. Postoperatively, the clinical status was assessed in the early postoperative phase by the level of central venous pressure and later by the presence of venous congestion symptoms.

RESULTS

In Table I, data are presented concerning diagnosis, shunt/patient count, mean shunt patency period, mean age at time of the Fontan procedure as well as the type of Fontan surgery.

Six patients underwent a single shunt procedure, five a Blalock-Taussig shunt (BTS) and one a Waterston shunt (WAT); in five patients a double (5 BTS) and in one patient a triple shunt procedure (2 BTS + 1 WAT) was necessary. The shunt prostheses used were 4 and 5 mm in diameter. The mean shunt/patient count ranged between 1.5–1.6 and was comparable within the groups. The mean

Table I. Preoperative Patient Profiles I

	Group A Qpi: 1.5–2.5 (n = 3)	Group B Qpi: 3.0–4.0 (n = 4)	Group C Qpi: 4.0–5.0 (n = 3)	Group D Qpi > 6.0 (n = 2)
Diagnosis	Holmes (S, D, D), PA DORV (I, D, D), PS TGA (S, D, L), PS	TGA (S, D, L), PS TGA (S, D, D), PS TGA (S, D, L), PA, MA TGA (S, D, L), PS	TGA (S, D, L), PS TGA (S, D, L), PA Holmes (S,D,D), PS	TA, PS TGA (S, D, D), PA
Mean shunt/pt	1, 6 (2; 1; 2)	1, 5 (1; 1; 2; 2)	1, 6 (1; 1; 2 + 1*)	1, 5 (2; 1*)
Mean shunt-patency period (yrs)	12	8, 6	5, 3	4, 5
Mean age at Fontan-op (yrs)	16	9	7	5, 5
Type of Fontan-op	2 × AP-C 1 × TCPC (F)	1 × AP-C 3 × TCPC (F)	3 × TCPC (F)	1 × TCPC 1 × TCPC (F)

*Waterston-shunt; AP-C = atrio-pulmonary connection; DORV = double outlet right ventricle; F = fenestration; Holmes = Holmes heart (dominant left ventricle, right-hand architecture, concordant ventriculoarterial connection); MA = mitral atresia; PA = pulmonary atresia; PS = pulmonary stenosis; Qpi = pulmonary flow index ($\text{L}/\text{min}/\text{m}^2$ b.s.a.); TA = tricuspid atresia; TCPC = total cavo-pulmonary connection; TGA = transposition of the great arteries. Symbols in parentheses relate to the segmental anatomic combination of the heart: viscerotransposition or bronchotransposition situs: I = inverses; S = solitus; ventricular loop: D = normal, L = inverted; relations of the great arteries: aorta to the right (D) or to the left (L) from the pulmonary artery.

shunt patency period was 12, 8.6, 5.3 and 4.5 years for groups A-D, respectively.

The mean age at Fontan procedure was 16 years in group A, the highest, in comparison to 9.0, 7.0 and 5.5 years in groups B, C and D, respectively. Nine patients underwent a total cavo-pulmonary-, and 3 patients an atrio-pulmonary connection. An intraatrial tunnel fenestration was done in 8 cases.

In Table II, data (mean values/absolute terms) are given concerning the Nakata-index, McGoon-ratio, PPAI, PAP mean, Qp: Qs ratio, Rp: Rs ratio, VEDP, VC, FS, as well as SAsat- and Hb-values.

The patients with $\text{Qpi} < 4.0 \text{ L}/\text{min}/\text{m}^2$ had a restrictive, with $\text{Qpi} 4.0\text{--}5.0$ a balanced, and with $\text{Qpi} > 6.0 \text{ L}/\text{min}/\text{m}^2$ an excessive pulmonary blood flow. The mean p.a. pressure was proportional to the Qpi and showed an increasing tendency throughout the groups with values of 13, 15, 15 and 18 mmHg for groups A, B, C and D. No correlation between the Rp: Rs ratio and shunt patency period, mean PAP and Qp: Qs ratio was observed in the groups.

A positive correlation between Qpi and the Nakata-index and McGoon-ratio, but no correlation between Qpi and PPAI was found. There was a strong inverse relationship between the Nakata-index and shunt patency period (Tables I and II).

An evident inverse relationship could be found between the Qpi and ventricular diastolic compliance ($\text{VC} = \text{EDVP}/(\text{Qpi} + \text{Qsi})$). Patients in group A

Table II. Preoperative Patient Profiles II

	Group A Qpi: 1.5–2.5 (n = 3)	Group B Qpi: 3.0–4.0 (n = 4)	Group C Qpi: 4.0–5.0 (n = 3)	Group D Qpi > 6.0 (n = 2)
Nakata-index (mm ² /m ² bsa)	283 (250; 284; 317)	297 (232; 282; 291; 386)	324 (267; 344; 363)	405 (388; 432)
McGoon-ratio	2.0 (1.9; 2.1; 2.1)	2.2 (1.9; 2.0; 2.1; 2.7)	2.8 (2.1; 3.0; 3.5)	3.3 (3.3; 3.4)
PPAA-index (cm ² /m ² bsa)	47 (34; 54; 55)	40 (33; 41; 42; 44)	41 (43; 42; 38)	47 (40; 55)
PAPmean (mmHg)	13 (18; 10; 12)	15 (15; 13; 20; 14)	15 (16; 15; 15)	18 (17; 20)
Qp: Qs	0.7 (0.7; 0.7; 0.8)	0.8 (0.6; 0.8; 0.8; 0.9)	1.1 (1.0; 1.0; 1.3)	2.4 (2.0; 2.9)
Qpi	1.9 (1.6; 1.8; 2.4)	3.5 (3.4; 3.4; 3.5; 3.9)	4.3 (4.2; 4.4; 4.5)	8.2 (6.8; 9.6)
Rp: RS	0.1 (0.04; 0.09; 0.14)	0.16 (0.13; 0.16; 0.18; 0.18)	0.15 (0.09; 0.18; 0.19)	0.08 (0.08; 0.09)
VEDP (mmHg)	11 (10; 10; 11)	9 (5; 8; 10; 14)	7 (6; 7; 8)	8 (8; 8)
VC	2.3 (1.7; 2.4; 2.7)	1.0 (0.6; 1.1; 1.2; 1.35)	0.8 (0.7; 0.7; 1.0)	0.7 (0.6; 0.8)
FS (%)	29 (28; 29; 30)	37 (32; 36; 39; 42)	30 (30; 30; 31)	30 (28; 32)
Hb (g/dl)	21 (20; 21; 21)	19 (19; 19; 20; 21)	18 (17; 18; 19)	16 (17; 15)
SAsat (%)	77 (72; 80; 80)	83 (81; 80; 82; 84)	84 (82; 85; 85)	89 (85; 94)

FS = fractional shortening; Hb = hemoglobin concentration; PPAA = planimetric pulmonary artery area; PAP = pulmonary artery pressure; Qp: Qs = pulmonary-to-systemic flow ratio; Qpi = pulmonary flow-index (L/min/m² b.s.a.); Rp: Rs = pulmonary-to-systemic resistance ratio; SAsat = systemic artery oxygen saturation; VC = ventricular diastolic compliance; VEDP = ventricular enddiastolic pressure.

Table III. Lung Biopsy Data and Postoperative Outcome

	Group A Qpi: 1.5–2.5 (n = 3)	Group B Qpi: 3.0–4.0 (n = 4)	Group C Qpi: 4.0–5.0 (n = 3)	Group D Qpi > 6.0 (n = 2)
CVP (mmHg)	22 (21; 22; 23)	16 (13; 16; 16; 19)	15 (13; 16; 16)	12 (10; 14)
Lung biopsy*	1 × grade II (III) 1 × grade I	1 × grade 0	1 × grade I 1 × grade II (IV)	
Outcome	venous congestion lethal	no 1 (bleeding)	no 1 (cardiac failure)	no

CVP = central venous pressure (mean values for the first three postop days); LA = left atrium; Qpi = pulmonary flow-index (L/min/m² b.s.a.); RA = right atrium; R-L = right-to-left.

*acc. to Heath and Edwards classification,⁹⁾ in brackets the highest grade among five specimens taken routinely intraoperatively.

showed the highest mean VEDP accompanied by the lowest ventricular compliance, highest Hb- and lowest SAsat-values.

Intraoperatively taken lung biopsies revealed higher degrees of pulmonary vascular changes in 2 out of 5 patients (Table III).

As presented in Table III, in the early postoperative period the level of the central venous pressure was inversely proportional to the preoperative pulmonary flow- and size- index, with the highest mean value of 22 mmHg in group A and the lowest mean value of 12 mm Hg in group D. No difference was observed with regard to the postoperative catecholamine demand and mechanical ventila-

tion time (except one non-survivor). The duration of chest tube drainage for pleural effusions was slightly longer in group A than in other groups. Two patients died, one in group A due to a coagulation disorder and bleeding complications, and one patient in group C due to cardiac failure. The latter was a 6-year-old patient who after a previous Waterston shunt underwent a total cavo-pulmonary connection with baffle fenestration and could not be weaned from cardiopulmonary bypass (CPB) due to low output syndrome. By suspicion of a CPB-induced increase in pulmonary vascular resistance, the patient was supported by a mechanical circulatory system (ECMO), and finally died due to multiple organ system failure. The lung biopsy taken intraoperatively revealed in four of five specimens grade II and in one grade IV changes according to the Heath and Edwards classification.

DISCUSSION

Although the Nakata-index is reported to be a nonpredictor of operative mortality,^{2,7)} it seems to be a factor influencing postoperative hemodynamics and thus the early and late outcome in patients receiving a Fontan — type of circulation.^{3,5,20)}

The fact that the Fontan procedure can be performed in patients with a Nakata-index as low as $100 \text{ mm}^2/\text{m}^2$ or less (the lowest value published by Bridges²⁾ was $48 \text{ mm}^2/\text{m}^2$) and with restrictive p.a. flow with Qp: Qs values as low as 0.2: 1.0^{11,17)} suggests that in patients with hypoplastic p.a. bed, generally, the potential for an increase in pulmonary blood flow capacity is high enough to tolerate Fontan circulation but not high enough to guarantee optimal postoperative hemodynamics.

The investigations of Fontan³⁾ and Knott-Craig¹¹⁾ suggest that the cut-off point of the Nakata-index below which the probability for death or take down of Fontan circulation, low cardiac output or persistent pleural effusions increases significantly, is supposed to be approximately $200 \text{ mm}^2/\text{m}^2$.

Therefore, it seems logical that in patients with initially restrictive p.a. flow augmented by STPS, normalization of p.a. size (Nakata-index) should be strived for in order to achieve the best postoperative hemodynamics of Fontan circulation, provided that the adverse effects of the shunt procedure do not occur.

According to the suggestions of Senzaki,²⁰⁾ the pulmonary circulation can be considered as an electrical circuit, and in this analogy, pulmonary artery size as expressed by the Nakata-index (PAI) is the product of pulmonary artery flow (Qp), compliance (Cp), and resistance (Rp), as shown by the simplified formula $\text{PAI} = \text{Qp} \times \text{Rp} \times \text{Cp}$. If resistance (Rp) and ventricular function, as in our patient cohort within normal limits (Table II), can be considered as negligible, the

size of the pulmonary artery can hypothetically be represented by flow (Q_{pi}) and compliance (C_p). We could fully confirm this hypothesis and show that the development of the p.a. diameter is strongly flow-dependent, and in consequence that the pulmonary flow index (Q_{pi}) is of prognostic value in the indication policy for Fontan repair.

In patients with excessive p.a. flow, normalization of the p.a. size generally occurs within a relatively short period of time with no increased risk for deterioration of ventricular function. According to data published by Kuroda,¹²⁾ there is no significant difference in the enddiastolic-volume index, ventricular mass index or ventricular mass/enddiastolic volume ratio between patients with restrictive ($Q_p: Q_s < 1.0$) and increased ($Q_p: Q_s = > 1.0$) pulmonary blood flow during the first 3 years after the shunt procedure. Gewillig,⁶⁾ based on investigations in 8 patients with tricuspid atresia who remained palliated by a shunt, observed after a 3-year-shunt period a decrease in the left ventricular wall thickness related to enddiastolic dimension, suggesting ventricular dilation, but no significant change in the load-independent index of contractility (rate corrected velocity of shortening/endsystolic meridional stress), suggesting no alteration of left ventricular performance.

In patients with restrictive p.a. flow normalization of p.a. size is possible within a time period approximately threefold longer than in those with excessive p.a. flow, with a risk for development of cyanosis-related deterioration of ventricular function⁸⁾ and pulmonary vascular obstructive disease.¹⁵⁾ We found that in these patients the Nakata-index is not a reliable factor in the assessment of the degree of development of p.a. size, most probably due to a high potential for shunt-related distortion of the proximal segment of the p.a.¹⁵⁾

Linear correlation between the Nakata-index and McGoon-ratio and pulmonary flow index, but no correlation between planimetrically measured p.a. size and p.a. flow index suggest that the Nakata-index and McGoon-ratio underestimate and also do not consider the degree of development of distal p.a. bed, possibly also the flow capacity. This is especially true for the Nakata-index since it is calculated similar to our planimetrically calculated p.a. area index in relation to the body surface area.

According to our planimetric measurements, normalization of the p.a. diameter (mainly that of the distal segments) is supposed to occur earlier than the Nakata-index suggests. In our opinion, the indexed cross-sectional area of the lower lobe branch of the right and left p.a., as proposed by Reddy¹⁹⁾ is probably a more appropriate measure to assess the pulmonary artery growth expressing more adequately the degree of development of the p.a. bed.

In conclusion, patients who despite STPS still have a hypoplastic p.a. bed and restrictive p.a. flow remain a matter of concern in terms of adequate pallia-

tion policy and timing for the Fontan procedure. Development of the p.a. bed is strongly flow dependent, however, the Nakata-index/McGoon-ratio may be not reliable factors in the assessment of suitability for the Fontan procedure in children with STPS. "Lower" Nakata-index/McGoon-ratio associated with excessive or balanced p.a. flow may not be a risk factor for the Fontan procedure in these children.

Our investigations suggest that frequent monitoring of the development of the p.a. size and its tendency, with special regard to the distal p.a. segments, p.a. flow (Q_{pi}) and the compliance (C_p), is necessary. In patients with restrictive pulmonary flow and lacking a tendency to increase p.a. diameter, a further generous shunt should probably be implanted for acceleration of p.a. growth.⁽¹¹⁾ Alternatively, the bidirectional Glenn shunt should be taken into consideration, also in patients with unimpaired ventricular function. The decision for early conversion into a Glenn shunt can be supported by the fact that the benefit from reducing the volume overload on the singular chamber may be of greater importance than the disadvantage of lacking an increase in p.a. diameter. On the other hand, further investigations are necessary to determine whether patients with restrictive p.a. flow and good ventricular function will benefit more from the bidirectional Glenn shunt than from STPS in terms of augmentation of p.a. bed, and thus, long term outcome after a subsequent Fontan procedure.

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