POTENTIALITY OF CONSTRUCTION OF AN AKINETIC SEPTUM IN SINGLE VENTRICLE AS A RADICAL CORRECTION

Part II: Pre- and Post-operative Efficiency of Cardiac Performance

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Construction of the interventricular septum has been thought to be a radical correction for single ventricle and a possibility of its success was analyzed by reconstructing single ventricle with the data obtained in the normal canine hearts (Part I).

The possibility was discussed in term of physical efficiency of cardiac performance required in the post-correction single ventricle, namely by 1) myocardial fiber shortening. 2) diastolic and systolic volume ratio of the ventricles. 3) stroke volume and 4) radial and tangential forces.

The circumferential fiber shortening was within normal limits (18%), when the septum was constructed with an akinetic prosthesis where the circumference perpendicular to the long axis was equally divided into 2 in length. However, ventricular volumes and stroke volumes were larger in the systemic (left) ventricle than in the venous (right). When the septum was constructed at the rising points of the septum, the ventricular volume ratio became normal. However the circumferential fiber shortening was beyond normal limit (35%) and the right ventricular stroke volume was much larger than those of the left. Thereby, it was concluded that the septum should be constructed somewhere between the midpoint and the rising points of the septum in the circumference, namely 8 per cent of the circumference in length from the midpoint toward the left.

CONSTRUCTION of the interventricular septum in single ventricle would bring the following hemodynamic alterations: 1. Prevention of mixing of venous and arterial blood. 2. Efficiency

in cardiac performance. 3. Correction of associated anomaly or anomalies (for example, correction of pulmonary stenosis).

This part of this study is to determine physical efficiency of the single ventricle when an akinetic septum was constructed, and to discuss a possibility of its success as radical correction for single ventricle in term of the physical efficiency of the corrected single ventricle.

To discuss the possibility, the following

Key Words:

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Fig.1. Estimated Septum and Septum 20% Shorter in the Long Axis.

A longitudinally-divided half of the septum was plotted with solid line, which was estimated by the ratios obtained in Part I of this study. The septum represented with a dotted line was 20% shorter in the long axis.

assumptions were made:

- 1) Stroke volume for the systemic circulation is 45.00 ml. with systemic blood pressure of 120/80 mmHg.
- 2) Circumferential fiber shortening of the myocardium is uniform and 18 per cent.
- 3) Shortening of the apex-base axis (the long axis) is 10 per cent on systole.
- 4) Circumferential changes of a plane (the cross-section) perpendicular to the long axis are identical in the normal canine hearts (part 1) and the heart of single ventricle.
- 5) Hypertension of the pulmonary artery was corrected after the construction of the new septum, if present.
- 6) The single ventricle was circular on cross-section and the systemic ventricle in the corrected single ventricle became circular.
- 7) The formalin-fixed normal hearts with intraluminal pressures of 15 cm H₂O for the right ventricle and of 30 cm H₂O for the left were representative of the diastolic phase in dimension.
- 8) The thickness of the wall was uniform and was neglected.

The physical works of the single ventricle will be discussed in the following situations:

- 1) Single ventricle before the construction of the septum (Abbreviated as V).
- 2) Postoperative single ventricle in which an akinetic septum was constructed as to divide the circumference equally into the right (low-pressure) and left (high-pressure) free ventricular

walls in length (abbreviated as V_N).

- 3) Single ventricle in which an akinetic septum was constructed by anchoring it where the right and left free ventricular walls fell in the normal ratio in length (abbreviated as V_M).
- 4) Single ventricle in which an akinetic septum (20 per cent shorter in the long axis) was constructed by anchoring it where the right and left free ventricular walls were in the normal ratio in length (abbreviated as V_P).
- 5) Normal ventricle equivalent to the constructed systemic ventricle in the single ventricle (abbreviated as V_u).

- 1) Performance of single ventricle before the construction of the septum (V)

It was simply assumed that the single ventricle must expel a volume twice as much as did the normal systemic ventricle and, therefore, that single ventricle must expel 90 ml. at each stroke with pressure of 120/80 mmHg as the normal stroke volume was assumed 45 ml.

Relation of the radii of the single ventricle (systolic radius: r_S , diastolic: r_D) was as follow when the circumferential fiber shortening was 18 per cent.

$$\frac{2\pi(r_D - r_S)}{2\pi r_D} = 0.18$$

$$\therefore r_S = 0.82r_D$$

As discussed in the first paper of the study the average long axis was 5.39 cm and the maximal

total circumference was 21.04 cm in the 7 hearts examined. Therefore a ratio of the radius (r_D) and the long axis (L_D) was

$$2r_D : L_D = \frac{21.04}{\pi} : 5.39$$

$$L_D = \frac{5.39 \times 2 \times \pi}{21.04} r_D = 1.61 r_D$$

As the assumed shortening of the long axis was 10% on systole, the long axes on diastole (L_D) and systole (L_S) were

$$L_S = 0.9 L_D$$

The ratios (α) of the circumferences at the 10 cross sections to the maximum one were tabulated in table I (They were obtained in Fig. 1 in Part I). The volumes of the single ventricle in diastole (V_D) and systole (V_S) were calculated by dividing equally the single ventricle into 10 cross sections perpendicular to the long axis and by adding ventricular areas of these 10 cross sections as shown next.

$$\begin{aligned} V_D &= \pi(\alpha_5 r_D)^2 \times 0.1 \times L_D + \dots \\ &\quad + \pi(\alpha_{95} r_D)^2 \times 0.1 \times L_D \\ &= 0.1 \times \pi \times L_D \times r_D^2 \times \sum \alpha_i^2 \quad (L_D = 1.61 r_D) \\ &= 0.16 \times \pi \times r_D^3 \times \sum \alpha_i^2 \\ V_S &= 0.1 \times \pi \times 0.9 \times 1.61 \times r_D \times (0.82 r_D)^2 \\ &\quad \times \sum \alpha_i^2 \end{aligned}$$

As the stroke volume of the single ventricle was 90 ml.

$$\begin{aligned} V_D - V_S &= 0.16 \pi r_D^3 \sum \alpha_i^2 - 0.9 \times 1.6 \pi \times 0.82^2 \\ &\quad \times r_D^3 \times \sum \alpha_i^2 = 90 \\ 0.16 \pi r_D^3 \cdot \sum \alpha_i^2 (1 - 0.9 \times 0.82^2) &= 90 \\ 1.37 r_D^3 &= 90 \\ r_D &= 4.03 \text{ (cm)} \end{aligned}$$

Then,

$$\begin{aligned} r_S &= 0.82 r_D = 3.30 \text{ (cm)} \\ L_D &= 1.61 r_D = 6.49 \text{ (cm)} \\ L_S &= 0.9 L_D = 5.89 \text{ (cm)} \\ V_D &= 0.1 \times 3.14 \times 6.49 \times 4.03^2 \times 7.07 \end{aligned}$$

$$= 230.68 \text{ (cm}^3\text{)}$$

$$\begin{aligned} V_S &= 0.1 \times 3.14 \times 5.84 \times 3.30^2 \times 7.07 \\ &= 139.19 \text{ (cm}^3\text{)} \end{aligned}$$

Surface areas of the single ventricle (diastolic: A_D , systolic: A_S) were calculated as follows.

$$\begin{aligned} A_D &= (2\pi\alpha_5 r_D \times 0.1 L_D + \dots + 2\pi\alpha_{95} r_D \\ &\quad \times 0.1 L_D) + \pi(\alpha_{100} r_D)^2 \\ &= 2\pi r_D \cdot \sum \alpha_i \times 0.1 L_D + \pi(\alpha_{100} r_D)^2 \\ &= 2 \times 3.14 \times 4.03 \times 7.98 \times 0.1 \times 6.49 \\ &\quad + 3.14 \times 0.93^2 \times 4.03^2 \quad (\alpha_{100} = 0.93, \\ &\quad \text{from Fig. 1 in part I}) \\ &= 175.10 \text{ (cm}^2\text{)} \end{aligned}$$

$$\begin{aligned} A_S &= 2\pi r_S \cdot \sum \alpha_i \times 0.1 L_S + \pi(\alpha_{100} r_S)^2 \\ &= 2 \times 3.14 \times 3.30 \times 7.98 \times 0.1 \times 5.84 \\ &\quad + 3.14 \times 0.93^2 \times 3.30^2 \\ &= 126.11 \text{ (cm}^2\text{)} \end{aligned}$$

Ejection fraction (EF) was

$$EF = \frac{230.68 - 139.19}{230.68} \times 100 = 39.27 \text{ (\%)}$$

Total radial forces (diastolic: F_D , systolic: F_S) were calculated with an assumption that the single ventricle had expelled its whole stroke volume when the blood pressure reached its maximum (120 mmHg) (1).

$$\begin{aligned} F_D &= A_D \times P_D \times 1332 \\ &= 175.10 \times 80 \times 1332 \\ &= 1.87 \times 10^7 \text{ (dyne)} \\ F_S &= A_S \times P_S \times 1332 \\ &= 126.11 \times 120 \times 1332 \\ &= 2.02 \times 10^7 \text{ (dyne)} \end{aligned}$$

where P_D and P_S were diastolic and systolic blood pressures, respectively.

Tangential force (T) was defined (2) as

$$\begin{aligned} P \cdot \pi r^2 &= 2\pi r \cdot T \\ \therefore T &= \frac{r}{2} P \end{aligned}$$

TABLE I DIMENSIONAL RATIOS OF THE NORMAL HEART

%distance from apex	α	α^2	β	γ	K	r_{MD}	$(\frac{\gamma}{1-K}r_D)^2$	γ^2	$\frac{K}{1-K}$	$\gamma^2 \frac{K}{1-K}$	$\gamma^2 (\frac{K}{1-K})^2$
95	0.99	0.97	0.34	0.32	0.47	2.42	5.86	0.10	0.89	0.09	0.08
85	1.00	1.00	0.33	0.33	0.47	2.50	6.25	0.11	0.89	0.10	0.09
75	1.00	1.00	0.34	0.33	0.47	2.50	6.25	0.11	0.89	0.10	0.09
65	0.99	0.97	0.34	0.33	0.48	2.54	6.45	0.11	0.92	0.10	0.09
55	0.96	0.91	0.36	0.34	0.48	2.62	6.86	0.12	0.92	0.11	0.10
45	0.90	0.82	0.29	0.35	0.46	2.62	6.86	0.13	0.85	0.11	0.09
35	0.81	0.66	0.42	0.35	0.43	2.46	6.05	0.12	0.75	0.09	0.07
25	0.69	0.48	0.50	0.35	0.37	2.26	5.11	0.12	0.59	0.07	0.04
15	0.49	0.24	0.72	0.37	0.21	1.89	3.52	0.13	0.27	0.04	0.01
5	0.16	0.03	1.00	0.21	0	0.85	0.72	0.04	0	0	0
Total	7.98	7.07	4.74	3.28	3.84	22.66	53.93	1.09	6.97	0.81	0.66

The ratios above were obtained in Fig.1, Fig.2 and Fig.3 in Part I.

- α : ratio of the circumference (the right and left free ventricular walls) at a given cross-section (perpendicular to the long axis) to the maximum circumference.
 β : ratio of the left free ventricular wall (WLF) to the circumference.
 γ : ratio of WLF to the maximum circumference.
K: ratio of the septal length (S) to the left ventricular circumference.
 r_{MP} : radius of the systemic ventricle on diastole (V_{MD}) in the corrected single ventricle in which an akinetic septum was anchored where the right and left free ventricular walls were in the normal ratio, and was equal to $\frac{\gamma}{1-K} r_D$.

TABLE II CIRCUMFERENCE, RADIUS, AND AREA OF THE CROSS-SECTION IN THE CORRECTED SINGLE VENTRICLE (V_N), IN WHICH THE CIRCUMFERENCE WAS EQUALLY DIVIDED INTO TWO IN LENGTH

%distance	Total circumference (cm)		Radius (cm)		Area (cm ²)			
	Diastole	Systole	Diastole	Systole	LV		RV	
					Diastole (A_{NLD})	Systole (A_{NLS})	Diastole (A_{NRD})	Systole (A_{NRS})
95	25.06	20.55	3.27	2.91	33.6	26.6	14.5	10.5
85	25.31	20.75	3.30	2.94	34.2	27.1	14.5	11.0
75	25.31	20.75	3.30	2.94	34.2	27.1	14.5	11.0
65	25.06	20.55	3.27	2.91	33.6	26.6	14.5	10.5
55	24.30	19.93	3.17	2.82	31.6	25.0	13.8	9.6
45	22.78	18.68	2.97	2.64	27.7	21.9	11.8	8.5
35	20.50	16.81	2.67	2.38	22.4	17.8	8.8	7.3
25	17.46	14.32	2.28	2.03	16.3	12.9	6.8	5.3
15	12.40	10.17	1.62	1.44	8.2	6.51	3.2	2.3
5	4.05	3.32	0.53	0.47	0.9	0.69	2.3	0.2
Total	202.23	165.83	26.38	23.48	242.7	192.2	102.7	76.2

Diastolic and systolic total circumferences were $2\pi r_D \times \alpha$ and $0.82 \cdot \alpha \cdot 2\pi r_D$, respectively.

Radii were $\frac{\alpha(\pi+2)}{2\pi} r_D$ and $(1-0.11)\frac{\alpha(\pi+2)}{2\pi} r_D$, respectively.

LV: high-pressure (left or systemic) ventricle.

RV: low-pressure (right or venous) ventricle.

A_{NLD} and A_{NLS} : cross-sectional areas of the left ventricle, diastolic and systolic, respectively.

A_{NRD} and A_{NRS} : those of the right ventricle.

Total tangential forces (diastolic : T_D , systolic : T_S)

$$\begin{aligned}
 T_D &= \left(\frac{1}{2} P_D \cdot \alpha_5 r_D \times 2\pi \alpha_5 r_D \times 0.1 L_D + \dots \right. \\
 &\quad \left. + \frac{1}{2} P_D \cdot \alpha_{95} r_D \times 2\pi \alpha_{95} r_D \times 0.1 L_D \right) \times \\
 &\quad \times 1332 \\
 &= \pi \cdot r_D^2 \cdot P_D \times 0.1 L_D \times 1332 \times \Sigma \alpha_i^2 \\
 &= 3.14 \times 4.03^2 \times 80 \times 0.1 \times 6.49 \times 1332 \times 7.07 \\
 &= 2.5 \times 10^7 \text{ (dyne)} \\
 T_S &= \pi \cdot r_S^2 \cdot P_S \times 0.1 L_S \times 1332 \times \Sigma \alpha_i^2 \\
 &= 2.2 \times 10^7 \text{ (dyne)}
 \end{aligned}$$

In calculating the total tangential forces (diastolic : T_D , systolic : T_S), the cross-sectional area at the end of the long axis was omitted

because it was thought that most of the last cross section would not contribute to development of the tension as the last cross section was consisted of the fibrous tissue (mainly by the mitral cusps).

II) Post-operative performance of the single ventricle in which an akinetic septum was constructed as to divide the circumference equally into two (V_N)

An akinetic septum was assumed to be constructed by anchoring it at the midpoints of the cross-sectional circumference of the single ventricle as to divide equally the cross-sectional area into two, being resulted in that the free walls of the right (venous or low-pressure) and left (systemic or high-pressure) ventricles were equal in length. A size of the septal prosthesis employed was identical to the diameter of the circumference in length. Therefore, the radii (diastolic : r_{ND} systolic : r_{NS}) of the systemic ventricle (pump ventricle) were obtained from

TABLE III DIMENSIONAL VALUES OF THE CORRECTED SINGLE VENTRICLE ON SYSTOLE (SHORTENING : 35%) IN WHICH AN AKINETIC SEPTUM (20% SHORTER IN THE LONG AXIS) WAS WHERE THE SEPTUM WAS RISEN FROM THE CIRCUMFERENCE IN THE NORMAL HEART.

% distance LV Circumf. from apex	(cm)	W_{LF-MS} (35% shortened)	r_{MS}	r^2_{MS}	A'_{MS} (cm ²)	W_{RF-S}	φ	Radius of C_M RV (cm)	(cm ²)
95	12.45	5.27	1.98	3.92	12.34	10.09	97.19	2.34	6.3
85	12.83	5.43	2.04	4.16	13.11	11.02	97.11	2.47	8.0
75	12.83	5.43	2.04	4.16	13.11	10.64	97.11	2.44	7.1
65	13.14	5.43	2.09	4.37	13.75	10.53	96.31	2.44	6.2
55	13.55	5.60	2.16	4.67	14.62	10.00	96.31	2.40	5.0
45	13.31	5.76	2.12	4.49	14.10	9.13	97.78	2.29	2.3
35	12.44	5.76	1.98	3.92	12.32	7.92	99.33	2.09	2.1
25	10.96	5.76	1.75	3.06	9.56	5.76	99.68	1.85	3.0
15	8.57	6.08	1.36	1.85	5.85	2.35	99.12	1.50	5.0
5	3.46	3.46	0.55	0.30	0.95	0.00	0.00	0.00	0.0
Total	113.54	53.98	18.07	34.90	109.71	—	—	—	45.0

LV. circumf.: systemic ventricular circumference

r_{MS} : radius of the systemic ventricle on systole

A'_{MS} : cross-sectional area of the systemic ventricle

W_{RF-S} : length of the low-pressure free ventricular wall

W_{LF-MS} : length of the systemic free ventricular wall

φ : a half of an opening angle for the septum in the low-pressure ventricle (Fig.6 in Part I).

Radius of RV.: radius of the low-pressure ventricle

C_M : cross-sectional area of the low-pressure ventricle.

TABLE IV VALUES FOR DETERMINING THE VOLUMES OF THE VENTRICLE IN WHICH AN AKINETIC SEPTUM WAS WHERE THE RIGHT AND LEFT FREE VENTRICULAR WALLS WERE IN THE NORMAL RATIO IN LENGTH

% distance of long axis	K'	$\gamma \cdot \frac{K(K'-1)+1}{1-K}$	$(\gamma \cdot \frac{K(K'-1)+1}{1-K})^2$	$\gamma^2 \cdot \frac{KK'}{1-K}$	$\gamma^2 \cdot (\frac{KK'}{1-K})^2$	$\gamma \cdot (\frac{KK'}{1-K} + 0.47)$	$\gamma^2 (\frac{KK'}{1-K} + 0.47)^2$	$\gamma \cdot \frac{KK'}{1-K}$
95	1.00	0.60	0.36	0.09	0.08	0.43	0.19	0.30
85	1.00	0.62	0.38	0.10	0.08	0.45	0.20	0.29
75	1.00	0.62	0.38	0.10	0.09	0.45	0.20	0.30
65	1.00	0.63	0.40	0.10	0.09	0.46	0.21	0.30
55	0.91	0.63	0.40	0.10	0.08	0.45	0.20	0.29
45	0.83	0.60	0.36	0.09	0.06	0.41	0.17	0.25
35	0.57	0.50	0.25	0.05	0.02	0.32	0.10	0.15
25	0	0.35	0.12	0	0	0.16	0.03	0
15	0	0.37	0.14	0	0	0.17	0.03	0
5	0	0.21	0.04	0	0	0.10	0.01	0
Total	—	5.13	2.83	0.63	0.50	3.40	1.34	1.88

K' : ratio of the cross-sectional length of the septum 20% shorter in the long axis to that of the septum (Fig.1)

TABLE V CROSS-SECTIONAL DIMENSIONS OF BOTH THE VENTRICLES IN THE CORRECTED SINGLE VENTRICLE IN WHICH AN AKINETIC SEPTUM WAS 20% SHORTER IN THE LONG AXIS AND ANCHORED WHERE BOTH THE FREE VENTRICULAR WALLS WERE IN THE NORMAL RATIO

% Distance	Radius (cm)				Free RV wall (cm)		Area (cm ²)			
	LV		RV				LV		RV	
	Diast.	Syst.	Diast.	Syst.	Diast.	Syst.	Diast.	Syst.	Diast.	Syst.
95	2.26	1.54	3.25	1.65	15.53	6.83	16.0	7.4	24.2	1.5
85	2.33	1.59	3.47	1.74	16.96	7.46	17.0	7.9	28.1	1.5
75	2.33	1.59	3.40	1.68	16.37	7.20	17.0	7.9	27.8	1.3
65	2.36	1.62	3.39	1.70	16.20	7.13	17.5	8.2	26.8	0.5
55	2.41	1.64	3.29	1.67	15.39	6.77	18.2	8.4	23.1	0.9
45	2.35	1.56	3.04	1.46	14.05	6.18	17.3	7.6	19.2	0
35	2.16	1.37	2.62	1.42	12.18	5.36	14.6	5.9	14.5	0.9
25	1.75	0.96	1.75	0.96	8.86	3.90	9.6	2.9	8.5	1.4
15	1.49	0	0	0	3.61	0	7.0	0	0	0
5	0.85	0	0	0	0	0	2.3	0	0	0
Total	—	—	—	—	—	—	136.5	56.2	172.2	8.0

LV: high-pressure ventricle

RV: low-pressure ventricle

TABLE VI DIMENSIONAL VALUES OF THE NORMAL VENTRICLES

% distance	Diastole					Systole				
	LV circumf. (cm)	LV radius (cm)	RV free wall (cm)	LV area (cm ²)	RV area (cm ²)	LV circumf. (cm)	LV radius (cm)	RV free wall (cm)	LV area (cm ²)	RV area (cm ²)
95	15.28	2.42	15.53	18.4	22.9	12.53	2.00	12.73	12.6	20.9
85	15.75	2.50	16.96	19.6	27.8	12.92	2.06	13.91	13.3	18.5
75	15.75	2.50	16.37	19.6	25.7	12.92	2.06	13.42	13.3	18.2
65	16.06	2.54	16.20	20.3	24.5	13.17	2.10	13.28	13.9	16.0
55	16.56	2.62	15.39	21.6	22.0	13.58	2.16	12.62	14.7	15.5
45	16.41	2.62	14.05	21.6	17.6	13.46	2.14	11.52	14.4	12.7
35	15.54	2.46	12.18	19.0	13.2	12.74	2.03	9.99	12.9	8.2
25	14.06	2.26	8.86	16.0	7.3	11.53	1.84	7.27	10.6	5.1
15	11.85	1.89	3.61	11.2	0	9.69	1.54	2.96	9.5	0.9
5	5.32	0.85	0	2.3	0	4.36	0.69	0	1.5	0
Total	142.58	—	—	169.5	161.0	116.90	—	—	114.6	116.0

LV: high-pressure ventricle

RV: low-pressure ventricle

LV radius was equal to $\frac{\gamma}{1-K}r_D$

the radii of the single ventricle (r_D , r_S) as follows,

$$2\pi r_{ND} = 2\pi r_D \times \frac{1}{2} + 2\pi r_D$$

$$r_{ND} = \frac{\pi + 2}{2\pi} r_D = 0.82r_D = 3.30(\text{cm})$$

TABLE VII PERFORMANCES OF THE SINGLE VENTRICLE AND THE CONSTRUCTED VENTRICLES IN THE SINGLE VENTRICLE

	Radius ($\times r_D$)	Volume (ml)				EF (%)	circumf. shorten- ing (%)	Radial force ($\times 10^7$ dyne)		Tangential force ($\times 10^7$ dyne)	
		Left		Right				Diast.	Syst.	Diast.	Syst.
		Diast.	Syst.	Diast.	Syst.						
V	1.00	230*	139*	—	—	39	18	1.87	2.02	2.5	2.2
V_N	0.82	157	112	67	45	29	18	1.46 (2.39)	1.75 (3.07)	1.67 (1.02)	1.79 (1.02)
V_M	0.65	110	64	104	26	42	35	1.14 (1.84)	1.20 (2.50)	1.17 (0.73)	1.02 (0.49)
V_P	0.63	85	40	102	5	53	53	1.01 (1.58)	0.95 (2.11)	0.91 (0.58)	0.64 (0.30)
V_u	0.79	110	67	104	68	41	18	1.18	1.28	1.22	1.11

*: volume of single ventricle

(see the text for details)

Its volume (diastolic : V_{ND}) was

$$\begin{aligned} V_{ND} &= \Sigma \pi (\alpha_i r_{ND})^2 \times 0.1 \times L_D \\ &= 3.14 \times 0.82^2 \times 4.03^2 \times 7.07 \times 0.1 \times 6.49 \\ &= 157.33 \text{ (cm}^3\text{)} \end{aligned}$$

As the constructed septum was non-contractile, the contractile portion was only the free ventricular wall in the systemic ventricle and its ratio to the systemic (left) ventricular circumference was

$$\frac{\left(\frac{2\pi r_D}{2} + 2r_D \right) - 2r_D}{\frac{2\pi r_D}{2} + 2r_D} = \frac{\pi}{\pi + 2} = 0.61 \text{ (\%)}$$

With 10% shortening of the long axis, circumferential fiber shortening of the systemic ventricle to expel 45 ml. of stroke volume was calculated as follows

$$\begin{aligned} V_{ND} - V_{NS} &= 157.33 - 0.1\pi \times r_{NS}^2 \times L_S \cdot \Sigma \alpha_i^2 \\ &= 45.00 \\ r_{NS}^2 &= 8.67 \\ r_{NS} &= 2.94 \end{aligned}$$

On the other hand relationship of the radii of

the systemic ventricle in systole (r_{NS}) and diastole (r_{ND}) was expressed by

$$r_{NS} = \frac{2\pi r_{ND}(1 - 0.61X)}{2\pi}$$

$$\therefore r_{NS} = (1 - 0.61X)r_{ND}$$

Then

$$2.94 = (1 - 0.61X) \times 3.30$$

$$\therefore X = 0.18$$

Where X was circumferential fiber shortening rate of the contractile portion.

The volume of the systemic ventricle on systole (V_{NS}) was then,

$$\begin{aligned} V_{NS} &= 0.1 \times L_S \times \Sigma \pi (\alpha_i r_{NS})^2 \\ &= 0.1 \times 0.9 \times 6.49 \times 3.14 \times 8.67 \times 7.07 \\ &= 112.40 \text{ (cm}^3\text{)} \end{aligned}$$

Ejection fraction (EF) was

$$EF = \frac{157.33 - 112.40}{157.33} \times 100 = 28.6 \text{ (\%)}$$

Eighteen per cent shortening of the left free ventricular wall will be equal to 11% of the total circumference of the systemic ventricle ($0.61 \times 0.18 = 0.11$), and the radius of the

systemic ventricle in systole will be $0.73 r_D (r_{NS} = (1 - 0.61 \times 0.18) \times 0.82 r_D)$.

Surface areas (A_{ND} , A_{NS}) were

$$\begin{aligned} A_{ND} &= 2\pi r_{ND} \times 0.1 L_D \times \Sigma \alpha_i + \pi(\alpha_{100} r_{ND})^2 \\ &= 2 \times 3.14 \times 3.30 \times 0.1 \times 6.49 \times 7.98 \\ &\quad + 3.14 \times 0.93^2 \times 3.30^2 \\ &= 136.90 \text{ (cm}^2\text{)} \end{aligned}$$

$$\begin{aligned} A_{NS} &= 2\pi r_{NS} \times 0.1 L_D \times 0.9 \times \Sigma \alpha_i \\ &\quad + \pi(\alpha_{100} r_{NS})^2 \\ &= 109.62 \text{ (cm}^2\text{)} \end{aligned}$$

Total radial forces (F_{ND} , F_{NS}) were

$$\begin{aligned} F_{ND} &= A_{ND} \times P_D \times 1332 \\ &= 136.90 \times 80 \times 1332 \\ &= 1.46 \times 10^7 \text{ (dyne)} \end{aligned}$$

However, in this ventricle the contractile portion was 61% and, if this calculated force was produced only by the contractile portion, the force (F_{ND-C}) the contractile portion per unit must produce would be as follows

$$\begin{aligned} F_{ND-C} &= 1.46 \times 10^7 \times \frac{1}{0.61} \\ &= 2.39 \times 10^7 \text{ (dyne)} \end{aligned}$$

In systole the contractile portion will become

$$\frac{0.61(1 - 0.18)}{1 - 0.61 \times 0.18} = 0.57$$

Therefore,

$$\begin{aligned} F_{NS} &= A_{NS} \times P_S \times 1332 \\ &= 109.62 \times 120 \times 1332 \\ &= 1.75 \times 10^7 \text{ (dyne)} \end{aligned}$$

and,

$$\begin{aligned} F_{NS-C} &= 1.75 \times 10^7 \times \frac{1}{0.57} \\ &= 3.07 \times 10^7 \text{ (dyne)} \end{aligned}$$

Strictly speaking, the area of the last section should also be disregarded from this calculation because it was consisted of the non-contractile tissue. However, this fact was neglected with a

reason that this part has not been neglected in this kind of the studies by others. It should also be taken into consideration in calculating F_{ND-C} and F_{NS-C} that thickness of the ventricular wall would be increased on systole.

Total tangential forces (diastolic : T_{ND} , systolic : T_{NS}) were as follows:

$$\begin{aligned} T_{ND} &= \pi \times P_D \times \Sigma \alpha_i^2 \times r_{ND}^2 \times 0.1 \times L_D \times 1332 \\ &= 3.14 \times 80 \times 7.07 \times 3.30^2 \times 0.1 \times 6.49 \\ &\quad \times 1332 \\ &= 1.67 \times 10^7 \text{ (dyne)} \end{aligned}$$

$$\begin{aligned} T_{NS} &= \pi \times P_S \times \Sigma \alpha_i^2 \times r_{NS}^2 \times 0.1 \times 0.9 \times L_D \\ &\quad \times 1332 \\ &= 3.14 \times 120 \times 7.07 \times 2.94^2 \times 0.1 \times 0.9 \\ &\quad \times 6.49 \times 1332 \\ &= 1.79 \times 10^7 \text{ (dyne)} \end{aligned}$$

As the contractile portion was 61% on diastole and 57% on systole, the energies (diastolic : T_{ND-C} , systolic : T_{NS-C}) that were consumed to produce the tensions were

$$\begin{aligned} T_{ND-C} &= 1.67 \times 10^7 \times 0.61 \\ &= 1.02 \times 10^7 \text{ (dyne)} \\ T_{NS-C} &= 1.79 \times 10^7 \times 0.57 \\ &= 1.07 \times 10^7 \text{ (dyne)} \end{aligned}$$

It was thought that an amount of the contractile tissue had nothing to do with to produce a certain tension, if the non-contractile portion was rigid. It was, then, postulated that the less an amount of the contractile tissue was, the less the energy which was consumed to develop a certain tension.

To determine the right ventricular volumes (diastolic : V_{NRD} , systolic : V_{NRS}), planimetry was made on the drawings described in the first part of this study (Fig. 6 in part I) and the values obtained were tabulated in Table II. Namely the free wall of the right ventricle was assumed to shape circular on cross-section because of the least surface tension. In this heart the free walls of the right and left ventricles were divided equal in length so that the radii of the ventricles were

also identical ($= \frac{\alpha(\pi + 2)}{2\pi} r_D$), and the septal length was $\alpha \times 2r_D$.

The opening angle (2θ) for the septum in the left ventricle was $\frac{2}{\pi + 2} \times 360^\circ = 140^\circ$. The circle

of the right ventricle was determined by three factors, i.e., 2 crossing points of the circles of both the ventricles and the radius of the right ventricle. The total circumferences at planes every 10% distance in the long axis and the areas of right and left ventricles were planimetric on the drawings (Table II). The left ventricular volume, which was known by calculation, was also measured to reconfirm the measurement of the right ventricular volume. (The long axes were identical in the right and left ventricle.)

$$\begin{aligned} V_{NRD} &= 0.1 \times L_D \times \Sigma A_{NRDi} \\ &= 0.1 \times 6.94 \times 102.7 \\ &= 66.7 \text{ (ml)} \end{aligned}$$

$$\begin{aligned} V_{NRS} &= 0.1 \times 0.9 \times L_D \times \Sigma A_{NRSi} \\ &= 0.1 \times 0.9 \times 6.49 \times 76.2 \\ &= 44.5 \text{ (ml)} \end{aligned}$$

$$\begin{aligned} V_{NLD} &= 0.1 \times L_D \times \Sigma A_{NLDi} \\ &= 0.1 \times 6.49 \times 242.7 \\ &= 157.5 \text{ (ml)} \end{aligned}$$

$$\begin{aligned} V_{NLS} &= 0.1 \times 0.9 \times L_D \times \Sigma A_{NLSi} \\ &= 0.1 \times 0.9 \times 6.49 \times 192.2 \\ &= 112.3 \text{ (ml)} \end{aligned}$$

Then stroke volume of the right ventricle was

$$\begin{aligned} V_{NRD} - V_{NRS} &= 66.7 - 44.5 \\ &= 22.2 \text{ (ml)} \end{aligned}$$

III) Performance of the single ventricle in which an akinetic septum was constructed by anchoring it where the right and left free ventricular walls fell in the normal ratio (V_N).

In this heart the septum was postulated to be fixed where the cross-sectional circumference of the single ventricle was divided into the right and left free ventricular walls in such a manner as the normal heart was (Fig. 3 in Part I). The size of the septum was equal to the diameter of the circumference or to the septum estimated by the ratios obtained, as the diameter and the estimated septum were almost equal as shown in Fig. 8

in Part I.

The free left ventricular wall (W_{LF}) was calculated as follows (Table I):

$$W_{LF} = \gamma \cdot 2\pi r_D$$

The septal length (S) was expressed by

$$\frac{S}{S + W_{LF}} = K$$

$$\therefore S = \frac{K}{1 - K} \quad W_{LF} = \frac{K}{1 - K} \gamma 2\pi r_D$$

where K was a ratio of the septal length (S) to the left ventricular circumference and was obtained in Fig. 2 in Part I. Gamma (γ) was a product of ratio (α) of the circumference to the maximum circumference and ratio (β) of the left free ventricular wall (W_{LF}) to the circumference (Table I). Then the circumference of the new systemic ventricle was

$$\begin{aligned} W_{LF} + S &= \gamma 2\pi r_D + \frac{K}{1 - K} \gamma 2\pi r_D \\ &= \frac{1}{1 - K} 2\pi \gamma r_D \end{aligned}$$

The diastolic radius (r_{MD}) would be

$$r_{MD} = \frac{1}{1 - K} \gamma r_D$$

And a summation of the radii at planes every 10% distance ratio in the long axis (Σr_{MDi}) was, then,

$$\Sigma r_{MDi} = 22.66$$

The cross-sectional area (A'_M) was

$$A'_M = \pi \left(\frac{1}{1 - K} \gamma r_D \right)^2$$

Therefore the diastolic volume (V_{MD}) would be

$$\begin{aligned} V_{MD} &= 0.1 \times L_D \times \Sigma \pi \left(\gamma_i r_{Di} \frac{1}{1 - K_i} \right)^2 \\ &= 0.1 \times L_D \times \pi \times \Sigma \left(\frac{\gamma_i}{1 - K_i} r_{Di} \right)^2 \end{aligned}$$

$$= 0.1 \times 6.49 \times 3.14 \times 53.93$$

(From Table I)

$$= 109.90 \text{ (ml)}$$

Only the left free ventricular wall (W_{LF}) would contract on systole and circumferential shortening of W_{LF} was assumed to be x . Then y was put as follow:

$$y = 1 - x$$

Then the length of W_{LF} on systole was

$$y \cdot \gamma \cdot 2\pi r_D$$

The septal length on systole was

$$\frac{K}{1-K} \cdot \gamma \cdot 2\pi r_D$$

The systolic left ventricular circumference was, then,

$$\begin{aligned} y \cdot \gamma \cdot 2\pi r_D + \frac{K}{1-K} \gamma \cdot 2\pi r_D \\ = \gamma \cdot 2\pi r_D \left(y + \frac{K}{1-K} \right) \end{aligned}$$

The radius (r_{MS}) on systole was

$$2\pi r_{MS} = \gamma \cdot 2\pi r_D \left(y + \frac{K}{1-K} \right)$$

$$r_{MS} = \gamma \cdot \left(y + \frac{K}{1-K} \right) r_D$$

Its volume on systole (V_{MS}) was (Table III)

$$\begin{aligned} V_{MS} &= 0.1 \times 0.9 \times L_D \times \Sigma \pi r_{MSi}^2 \\ &= 0.1 \times 0.9 \times L_D \times \Sigma \pi \left[\gamma_i \left(y + \frac{K_i}{1-K_i} \right) r_D \right]^2 \\ &= 29.79 \times \Sigma \gamma_i^2 \left[y^2 + 2 \frac{K_i}{1-K_i} y + \frac{K_i^2}{(1-K_i)^2} \right] \end{aligned}$$

As stroke volume was 45.00 ml,

$$\begin{aligned} V_{MD} - V_{MS} &= 109.90 - 29.79 \times \Sigma \gamma_i^2 \left[y^2 \right. \\ &\quad \left. + 2 \frac{K_i}{1-K_i} y + \frac{K_i^2}{(1-K_i)^2} \right] \end{aligned}$$

$$= 45.00$$

$$\Sigma \gamma_i^2 y^2 + \Sigma 2\gamma_i^2 \frac{K_i}{1-K_i} y + \Sigma \gamma_i^2 \frac{K_i^2}{(1-K_i)^2}$$

$$= \frac{109.90 - 45.00}{29.79}$$

$$= 2.18$$

$$1.09y^2 + 1.62y - 1.52 = 0$$

$$y = \frac{-1.62 \pm \sqrt{1.62^2 + 4 \times 1.09 \times 1.52}}{1.09 \times 2}$$

$$= \frac{-1.62 \pm 3.04}{2.18}$$

As range of y was $1 > y > 0$,

$$y = \frac{1.42}{2.18} = 0.65$$

Then

$$x = 1 - 0.65 = 0.35$$

Therefore the left free ventricular wall must contract 35% to expel 45.00 ml. at contraction. Then, the systolic radius (r_{MS}) became

$$r_{MS} = \gamma \left(0.65 + \frac{K}{1-K} \right) r_D$$

The volume on systole (V_{MS}) was then

$$\begin{aligned} V_{MS} &= 0.1 \times 0.9 \times L_D \times \Sigma A'_{MSi} \\ &= 0.1 \times 0.9 \times 6.49 \times 109.71 \\ &= 64.08 \text{ (ml)} \end{aligned}$$

Ejection fraction (EF) was

$$EF = \frac{109.90 - 64.08}{109.90} \times 100$$

$$= 41.7 \text{ (\%)}$$

Surface areas (diastolic : A_{MD} , systolic : A_{MS}) were

$$\begin{aligned}
 A_{MD} &= \Sigma(2\pi r_{MDi}) \times 0.1 \times L_D \\
 &\quad + \pi \left(\frac{\gamma_{100}}{1 - K_{100}} r_D \right)^2 \\
 &= 2 \times 3.14 \times 22.66 \times 0.1 \times 6.49 \\
 &\quad + 3.14 \times \left(\frac{0.30}{1 - 0.43} \times 4.03 \right)^2 \\
 &= 106.68 \text{ (cm}^2\text{)}
 \end{aligned}$$

$$\begin{aligned}
 A_{MS} &= \Sigma(2\pi r_{MSi}) \times 0.1 \times 0.9 \times L_D + \pi r_{MS-100}^2 \\
 &= 113.54 \times 0.1 \times 0.9 \times 6.49 + 3.14 \times 1.69^2 \\
 &= 75.29 \text{ (cm}^2\text{)}
 \end{aligned}$$

where α_{100} was 0.93 (Fig. 1 in Part I) and β_{100} was 0.32 (Fig. 3 in Part I). Thus, γ_{100} became 0.30. K_{100} was 0.43 (Fig. 2 in Part I). Then r_{MS-100} was calculated as follows:

$$\begin{aligned}
 r_{MS-100} &= \gamma_{100} \left(y + \frac{K_{100}}{1 - K_{100}} \right) r_D \\
 &= 0.30 \times \left(0.65 + \frac{0.43}{1 - 0.43} \right) \times 4.03 \\
 &= 0.30 \times (0.65 + 0.75) \times 4.03 \\
 &= 1.69
 \end{aligned}$$

Total radial forces (F_{MD} , F_{MS}) were

$$\begin{aligned}
 F_{MD} &= A_{MD} \times P_D \times 1332 \\
 &= 106.68 \times 80 \times 1332 \\
 &= 1.14 \times 10^7 \text{ (dyne)} \\
 F_{MS} &= A_{MS} \times P_S \times 1332 \\
 &= 75.29 \times 120 \times 1332 \\
 &= 1.20 \times 10^7 \text{ (dyne)}
 \end{aligned}$$

As the akinetic septum was 38% of the left ventricle on diastole (3.84×0.1 from Table I), the force (F_{MD-C}) the contractile portion must produce would be as follows:

$$\begin{aligned}
 F_{MD-C} &= 1.14 \times 10^7 \times \frac{1}{1 - 0.38} \\
 &= 1.84 \times 10^7 \text{ (dyne)}
 \end{aligned}$$

On systole the contractile portion (W_{LF-MS}) in the left ventricle was obtained from Table III.

$$\frac{W_{LF-MS}}{\text{Lt. vent. circumf.}} = \frac{53.98}{113.54} = 0.48$$

Therefore the force of the contractile portion on systole (F_{MS-C}) was

$$\begin{aligned}
 F_{MS-C} &= 1.20 \times 10^7 \times \frac{1}{0.48} \\
 &= 2.50 \times 10^7 \text{ (dyne)}
 \end{aligned}$$

Total tangential forces (T_{MD} , T_{MS}) were

$$\begin{aligned}
 T_{MD} &= \frac{1}{2} \Sigma r_{MDi} \times P_D \times 2\pi \times \Sigma r_{MDi} \times 0.1 \\
 &\quad \times L_D \times 1332 \\
 &= \pi \times P_D \times \Sigma r_{MDi}^2 \times 0.1 \times L_D \times 1332 \\
 &= 1.17 \times 10^7 \text{ (dyne)} \\
 T_{MS} &= \pi \times P_S \times \Sigma r_{MSi}^2 \times 0.1 \times 0.9 \times L_D \times 1332 \\
 &= 3.14 \times 120 \times 34.90 \times 0.1 \times 0.9 \times 6.49 \\
 &\quad \times 1332 \\
 &= 1.02 \times 10^7 \text{ (dyne)}
 \end{aligned}$$

The energies that the contractile portion must expend to produce the tensions (T_{MD-C} , T_{MS-C}) would be

$$\begin{aligned}
 T_{MD-C} &= T_{MD} \times 0.62 \\
 &= 1.17 \times 10^7 \times 0.62 \\
 &= 0.73 \times 10^7 \text{ (dyne)} \\
 T_{MS-C} &= T_{MS} \times 0.48 \\
 &= 1.02 \times 0.48 \\
 &= 0.49 \times 10^7 \text{ (dyne)}
 \end{aligned}$$

The diastolic volume of the right ventricle was identical to that of $V_{\mu D}$ on diastole. The volume on systole was calculated (Table III) as follows:

$$\begin{aligned}
 V_{NRS} &= 0.1 \times 0.9 \times L_D \times \Sigma C_{Mi} \\
 &= 0.1 \times 0.9 \times 6.49 \times 45.0 \\
 &= 26.3 \text{ (ml)}
 \end{aligned}$$

where C_M was determined by planimetry on the drawings that were obtained with the equations described earlier (Fig. 6 in Part I)

IV) Performance of the single ventricle in which an akinetic septum (20% shorter in the long axis) was constructed by anchoring it where the right and left free ventricular walls were in the normal relationship in length (V_P).

In the previous experiments of relacing the septum in normal canine heart, it was found that one of the most important functions of the septum seemed to divide the ventricular cavity into two ventricles which were in the normal volume ratio. To retain the normal ratio it was necessary to shorten 20% the long axis of the septal defect resulted from the septal resection to design a new septum, because of non-contracility of the septal prosthesis on systole.

In this section performance of the heart will be determined, in which an akinetic septum was anchored where the cross-sectional circumference of the single ventricle was divided into the right and left free ventricular walls in the normal ratio found in the normal hearts.

To design the septal prosthesis in which the long axis was 20% shorter, cross-sectional lengths of the septum were calculated at every 10% apex-base distance, by the ratios obtained in Fig. 2 and Fig. 3 in Part I, and a half of it was plotted by a solid line in Fig. 1. Then the longitudinal length of the septum was shortened 20% in the long axis and shown with a dotted line. The shortening of 20% in the long axis of the septum would be equal to 18% of shortening in the long axis of the single ventricle, as in the hearts from which the data were obtained the septum was approximately 10% shorter than the left ventricle (or the long axis). It was, however, unknown how much of shortening in the single ventricle would occur on suturing this size of the new septum. It was also unknown how much distortion would be resulted in the spacial relationship. Then it was assumed in this study that the single ventricle resulted in 9% shortening in the long axis (18% divided by 2) and that the significant spacial distortion did not occur in the single ventricle.

Cross-sectional length of the septum 20% shorter in the long axis would be expressed as follows,

$$y'' = \frac{KK'}{1-K} \gamma 2\pi r_D$$

where K' (in Table IV) was ratio of the cross-sectional length of the 20%-decreased septum to that (K) of the septum.

W_{LF} was as follow, as shown earlier in the

study

$$W_{LF} = \gamma 2\pi r_D$$

Therefore, the diastolic radius (r_{PD}) of the systemic ventricle was

$$\begin{aligned} 2\pi r_{PD} &= \frac{KK'}{1-K} \cdot \gamma \cdot 2\pi r_D + \gamma 2\pi r_D \\ &= \gamma 2\pi r_D \frac{K(K' - 1) + 1}{1-K} \end{aligned}$$

$$\therefore r_{PD} = \gamma \frac{K(K' - 1) + 1}{1-K} r_D$$

The volume on diastole (V_{PD}) was (Table IV)

$$V_{PD} = 0.1 \times 0.91 \times L_D$$

$$\begin{aligned} &\times \sum \pi \left[\gamma_i \frac{K_i(K'_i - 1) + 1}{1 - K_i} r_D \right]^2 \\ &= 0.1 \times 0.91 \times L_D \times \pi \times r_D^2 \\ &\times \sum \pi \left[\gamma_i^2 \frac{K_i(K'_i - 1) + 1}{1 - K_i} \right]^2 \\ &= 0.1 \times 0.91 \times 6.49 \times 3.14 \times 4.03^2 \times 2.83 \\ &= 85.23 \text{ (ml)} \end{aligned}$$

If the shortening of the long axis on systole remained unchanged after construction of the septum, difference of the long axis would be only 1% in cardiac cycle, as the long axis had already been shortened 9% on diastole. The volume on systole (V_{PS}) would be then,

$$V_{PS} = 0.1 \times 0.9 \times L_D$$

$$\times \sum \pi \left[\gamma_i \left(\frac{K_i K'_i}{1 - K_i} + X \right) r_D \right]^2$$

where X' was shortening ratio of the free left ventricular wall and X was ratio of the wall on systole to that on diastole. Then

$$X + X' = 1$$

As the stroke volume was 45.00 ml (Table IV).

$$V_{PD} - V_{PS} = 85.23 - 0.1 \times 0.9 \times L_D$$

$$\times \Sigma \pi \left[\gamma_i \frac{K_i K'_i}{1 - K_i} + X \right] r_D^2$$

$$= 45.00$$

$$\Sigma \gamma_i^2 \left(\frac{K_i K'_i}{1 - K_i} + X \right)^2 = 1.35$$

$$\Sigma \gamma_i^2 X^2 + 2 \Sigma \gamma_i^2 \frac{K_i K'_i}{1 - K_i} X + \Sigma \gamma_i^2 \left(\frac{K_i K'_i}{1 - K_i} \right)^2$$

$$= 1.35$$

$$1.09X^2 + 1.26X - 0.83 = 0$$

$$X = \frac{-1.26 \pm \sqrt{5.21}}{2.18}$$

$$= \frac{-1.26 \pm 2.28}{2.18}$$

X should be $1 > X > 0$, then

$$X = \frac{1.02}{2.18} = 0.47$$

then

$$X' = 1 - X = 1 - 0.47 = 0.53$$

Therefore the left free ventricular wall must contract 53% to expel 45 ml as a stroke volume. The systolic volume (V_{PS}) turned out to be 40.07 ml.

Surface areas (A_{PD} , A_{PS}) were

$$A_{PD} = \Sigma (2\pi r_{PDi}) \times 0.1 \times 0.91 \times L_D + r_{PD-100}^2$$

$$= 2 \times 3.14 \times 4.03 \times 5.13 \times 0.1 \times 0.91$$

$$\times 6.49 + 3.14 \times 0.60^2 \times 4.03^2$$

$$= 95.04 \text{ (cm}^2\text{)}$$

$$A_{PS} = \Sigma (2\pi r_{PSi}) \times 0.1 \times 0.9 \times L_D + \pi r_{PS-100}^2$$

$$= 2 \times 3.14 \times 3.40 \times 4.03 \times 0.1 \times 0.9$$

$$\times 6.49 + 3.14 \times 0.43^2 \times 4.03^2$$

$$= 59.69 \text{ (cm}^2\text{)}$$

where r_{P-95} was used as r_{P-100} , and r_{PS} was equal to $\gamma \cdot \left(\frac{KK'}{1 - K} + X \right) r_D$.

Ejection fraction (EF) was

$$EF = \frac{85.23 - 40.07}{85.23} \times 100 = 53 \text{ (\%)}$$

Total radial forces (F_{PD} , F_{PS}) were

$$F_{PD} = A_{PD} \times P_D \times 1332$$

$$= 95.04 \times 80 \times 1332$$

$$= 1.01 \times 10^7 \text{ (dyne)}$$

$$F_{PS} = A_{PS} \times P_S \times 1332$$

$$= 59.69 \times 120 \times 1332$$

$$= 0.95 \times 10^7 \text{ (dyne)}$$

Ratio of the non-contractile portion in the diastolic systemic ventricular surface area would be

$$\frac{\Sigma \left(\gamma_i \frac{K_i K'_i}{1 - K_i} 2\pi r_D \right)}{\Sigma \left(\gamma_i \frac{K_i K'_i}{1 - K_i} 2\pi r_D + \gamma_i 2\pi r_D \right)}$$

$$= \frac{1.88}{1.88 + 3.28} = 0.36$$

As the free ventricular wall contracts 53%, the ratio on systole would be

$$\frac{\Sigma \gamma_i \frac{K_i K'_i}{1 - K_i}}{\Sigma \gamma_i \frac{K_i K'_i}{1 - K_i} + (1 - 0.53) \Sigma \gamma_i}$$

$$= \frac{1.88}{1.88 + 0.47 \times 3.28} = 0.55$$

Therefore the forces (F_{PD-C} , F_{PS-C}) the contractile portion must produce would be

$$F_{PD-C} = 1.01 \times 10^7 \times \frac{1}{1 - 0.36}$$

$$= 1.58 \times 10^7 \text{ (dyne)}$$

$$F_{PS-C} = 0.95 \times 10^7 \times \frac{1}{1 - 0.55}$$

$$= 2.11 \times 10^7 \text{ (dyne)}$$

Total tangential forces (T_{PD} , T_{PS}) were

$$\begin{aligned} T_{PD} &= \frac{1}{2} \sum r_{PDi} \times P_D \times 2\pi \times \sum r_{PDi} \times 0.1 \\ &\quad \times L_D \times 1332 \\ &= 3.14 \times 80 \times 4.03^2 \times 2.83 \times 0.1 \times 0.91 \\ &\quad \times 6.49 \times 1332 \\ &= 0.91 \times 10^7 \text{ (dyne)} \\ T_{PS} &= \pi \times P_S \times \sum r_{PSi}^2 \times 0.1 \times 0.9 \times L_D \times 1332 \\ &= 3.14 \times 120 \times 4.03^2 \times 1.34 \times 0.1 \times 0.9 \\ &\quad \times 6.49 \times 1332 \\ &= 0.64 \times 10^7 \text{ (dyne)} \end{aligned}$$

The energies the contractile portion must produce to develop the tensions (T_{PD-C} , T_{PS-C}) would be

$$\begin{aligned} T_{PD-C} &= T_{PD} \times 0.64 = 0.91 \times 10^7 \times 0.64 \\ &= 0.58 \times 10^7 \text{ (dyne)} \\ T_{PS-C} &= T_{PS} \times 0.47 = 0.64 \times 10^7 \times 0.47 \\ &= 0.30 \times 10^7 \text{ (dyne)} \end{aligned}$$

The cross-sectional areas of the right ventricle were measured with planimetry on the drawings described in Part I (Fig. 6 in Part I), and the results were in Table V. The volumes (diastole : V_{PRD} , systole : V_{PRS}) were

$$\begin{aligned} V_{PRD} &= 0.1 \times L_D \times 0.91 \times \sum A_{PDi} \\ &= 0.1 \times 6.49 \times 0.91 \times 172.2 \\ &= 101.70 \text{ (ml)} \\ V_{PRS} &= 0.1 \times L_D \times 0.9 \times \sum A_{PSi} \\ &= 0.1 \times 6.49 \times 0.9 \times 8.0 \\ &= 4.67 \text{ (ml)} \end{aligned}$$

V) Required performance of the normal left ventricle in which stroke volume (45 ml) and circumferential fiber shortening (18%) were identical to the constructed systemic ventricle in the single ventricle.

To facilitate comparisons of the required performances of the systemic ventricles discussed above, a normal left ventricle was constructed, the determinant of which was 45 ml as stroke volume with 18 per cent circumferential fiber

shortening of the myocardium. Then the required performance and the spatial dimension of this ventricle were determined as follows.

The systolic and diastolic volume ($V_{\mu S}$, $V_{\mu D}$) were

$$\begin{aligned} V_{\mu S} &= \sum \pi (\gamma_i r_{\mu Si})^2 \times 0.1 \times 0.9 \times L_D \\ &= \sum \pi [\gamma_i \times (1 - 0.18) r_{\mu Di}]^2 \times 0.1 \\ &\quad \times 1.61 \times 0.9 \times r_{\mu D} \\ &= \pi \times 0.82^2 \times r_{\mu D}^3 \times \sum \gamma_i^2 \times 0.1 \times 1.61 \\ &\quad \times 0.9 \\ V_{\mu D} &= \sum \pi (\gamma_i r_{\mu Di})^2 \times 0.1 \times L_D \\ &= \pi \times r_{\mu D}^3 \times \sum \gamma_i^2 \times 0.1 \times 1.61 \end{aligned}$$

Then,

$$\begin{aligned} V_{\mu D} - V_{\mu S} &= \pi r_{\mu D}^3 \times 0.1 \times 1.61 \times \sum \gamma_i^2 - \pi \\ &\quad \times r_{\mu D}^3 \times 0.82^2 \times 0.1 \times 1.61 \\ &\quad \times 0.9 \times \sum \gamma_i^2 = 45.00 \\ 1.40 r_{\mu D}^3 &= 45.00 \\ r_{\mu D} &= 3.18 \end{aligned}$$

Therefore

$$\begin{aligned} L_D &= 1.61 \times r_{\mu D} = 1.61 \times 3.18 = 5.12 \\ r_{\mu S} &= 0.82 r_{\mu D} = 0.82 \times 3.18 = 2.61 \\ L_S &= 0.9 \times L_D = 0.9 \times 5.12 = 4.61 \end{aligned}$$

where $r_{\mu D}$ and $r_{\mu S}$ were radii of the ventricle, diastolic and systolic, respectively. The other parameters were calculated with the equations described earlier and tabulated in Table VII.

DISCUSSION

To achieve theoretical analysis of feasibility of constructing the septum as a radical correction of single ventricle, it was mandatory to know precise configuration of single ventricle along the axis. However, it was found that such basic studies were quite few. To circumvent this lack it had to be assumed that the circumferences of the cross-sections perpendicular to the long axis changed identically in the normal heart and single ventricle. The size of the single ventricle was determined by stroke volume and circumferential shortening of the myocardium. It was simply assumed that a stroke volume was 90 ml., namely twice as much as 45.00 ml and that the shortening on systole was 18 per cent in

circumference and 10 per cent in long axis. According to *Sonnenblick*³ the myocardial fiber could theoretically shorten approximately 30 per cent of its initial length. However, it would be 15 to 20 per cent under physiologic afterloaded conditions. Klein⁴ stated that the normal value was 18 per cent. The shortening in the long axis was 13 per cent by *Lewis*⁵ and 10 per cent by *Bishop*⁶.

In the single ventricle in which an akinetic septum was constructed where the circumference was equally divided into 2 in length, the circumferential shortening turned out to be 18 per cent, which is normal, to obtain a stroke volume of 45 ml (Table VII). However, the volume (V_{NRD}) of the right ventricle obtained was only 67 ml., compared with 157 ml. of the left ventricular volume (V_{NLD}). In the normal hearts examined in Part I the right ventricular volume on diastole was 58 ml. and the left was 56 ml. A ratio of the left ventricular volume to the right was 0.98 in the normal heart and 2.34 in this corrected single ventricle. In the normal heart (V_u), the left was 110 ml. and the right 104 ml. The ratio was 1.06. Stroke volumes of both the ventricles were 45 ml. for the left and 22 ml. for the right in this corrected ventricle. In the normal heart (V_u), they were 43 ml. for the left and 36 ml. for the right. One of the reasons for the difference in the stroke volumes in the normal heart would be that the volumes measured were those encircled by the external circumference, therefore, including larger volumes of the trabeculae and the papillary muscles in the left ventricle. In Part I of this study ratios of the volumes encircled by the internal circumference to the external circumference were 0.60 for the left, and 0.72 for the right. Then the volumes in V_u turned out to be 25.8 ml. for the left and 25.9 ml. for the right. The stroke volumes of V_N were 45 ml. for the left and 22 ml. for the right and the corrected ones were 27.0 and 15.8 ml respectively. On the other hand, this ventricular volume ratio on diastole was close to normal in the single ventricle in which the septum was anchored where the ratio of the right and left free ventricular walls were in the normal ratio (V_M). However, in this ventricle the myocardium had to contract 35 per cent to expel 45.00 ml. (Table VII). As mentioned earlier, the maximum shortening of the myocardium was theoretically 32 per cent³ and it was reported by *Kitamura*⁷ that the maximum shortening was 28.8 per cent in a patient with ventricular aneurysm. So it

could be stated that the shortening of 35 per cent in V_M was beyond its ability. However, *Rushmer*⁸ reported that main contraction of the septum was not in circumference, but in long axis. If this is taken into consideration, 18% shortening of the left ventricle in circumference as reported in many studies, turned out to be 35% shortening of the free wall and there would not be effect of akinesis of the septum on shortening rate in the corrected single ventricle. It is also conceivable that the akinetic septum did not take a part of a circle as it was assumed that the left ventricle was circular on cross-section. Namely the septum was deviated toward the left so that the right ventricular volume was increased and the left was decreased, being resulted in improvement of the volume ratio. This would happen when right ventricular pressure was elevated. However, *Ishikawa*⁹ reported in measurement of the diameter of myocardial fibers that the response of the septal muscle followed the adaptational behavior of the left ventricle. This statement might support the assumption that the left ventricle would be circular, although this behavior might be due to the structure, itself, of the septum. By echocardiography it was shown that the septal echo and the echo from the left ventricular wall moved essentially in opposite directions. However, it was also suggested that the septum could function differently when the stroke volumes of the two ventricular chambers are unequal!¹⁰ However, recently *Ionescu*¹¹ reported a case of single ventricle in which a new septum was successfully constructed and it was angiocardio-graphically shown to be concave forward the left ventricle.

It is a well-known fact that the myocardial oxygen consumption is related to the intramural tension. There is a lack of equality in "pressure work" and "volume work". According to *Rodbard*¹² an increase of cardiac output by 40 per cent produced increase of only 26 per cent in oxygen utilization. Therefore, the tangential force would be more important than the radial force in respect of cardiac performance. In calculating the tangential forces in this study it was postulated that the less the contractile portion that produces a certain tension was, the less an amount of the energy that was consumed, if the non-contractile portion in non-elastic (rigid). On the contrary, the energy for the radial forces and the contractile portion were thought to be inversely proportional, although an increase of the thickness of the wall on systole was

neglected in these calculations. However, it was suggested by *Rodbard*¹² that the free ventricular wall contributed to the support of the septum by transmitting the tension produced by the right ventricle to the septum. It could be, therefore, happened that in the corrected single ventricle the abnormal volume ratio of the ventricles was improved by deviation of the septum to the left and an amount of the energies consumed for the radial and tangential forces was saved to some extent, especially when the right ventricular hypertension was remained. There is another factor to be considered in cardiac efficiency, that is, the length of the radius of the pump ventricle in the corrected single ventricle.^{1,13} It is well-known that for a ventricle twice as long as another in radius, four times as much tension must be developed within its wall to maintain the same pressure as shown by *Laplace* law.¹⁴ Therefore, the total radial and tangential forces were smaller in V_M and V_P , as the radii were shorter. However, it was necessary for the myocardium to contract more to pump a constant stroke volume because of less amount of the contractile tissue. In these corrected single ventricles the volume ratios of the ventricles were also improved on diastole, but worsened on systole because of increment of the myocardial fiber shortening. In the previous studies¹⁵⁻¹⁷ the author reported that in the replacement of the septum, the prosthesis must be placed as to divide the ventricular volumes in the normal volume ratio. For this it was shown that the prosthesis must be 20 per cent shorter in the long axis. In V_P , in which the septum was 20% shorter in the long axis, the cardiac performances required were obviously beyond the normal limit in the myocardial fiber shortening and the ventricular volume ratio on systole. However, it was found that the septum replaced was 15.6% of the left ventricular surface area and 12.3% of the left ventricular myocardium, including the septum, in weight, although the latter percentage was dependent upon its definition.¹⁸ *Klein*⁴ reported that the myocardial fiber shortening would cover functional defect of myocardial akinesis or dyskinesis by increasing its degree, if a portion of it was below 20% of the left ventricular surface area. That would be why it was unnecessary to consider the myocardial shortening in the previous studies, and a matter to be considered was the volume ratio in the ventricles.

In summary the following parameters were

taken into consideration in seeking feasibility of the septal construction with an akinetic septum: 1) myocardial fiber shortening 2) diastolic and systolic volume ratios of the right and left ventricles 3) stroke volumes 4) radial and tangential forces. It was found that the longer the free wall of the systemic ventricle was in the total circumference, the less the myocardial fiber shortening was required and the more the radial and tangential forces were, to pump a certain volume as a stroke volume with a certain blood pressure. The volume of the low-pressure ventricle would be decreased and the volume of the systemic ventricle would be increased and a stroke volume of the low-pressure ventricle would be lesser because of less shortening. On the other hand if the septum was shifted to the systemic side, namely when the free left ventricular wall was shorter, the fiber shortening must increase to have a constant stroke volume, although the forces required were less, and the stroke volume of the low-pressure ventricle was greatly increased because of the required increased shortening. When the septum was at the midpoints of the circumference, namely, the free wall of the ventricle being 50% of the circumference, the shortening was around the middle of the normal range, but the volume ratios of the ventricles on diastole and systole were outside the limit and the stroke volume ratio was also abnormal for scantiness of the low-pressure ventricle. When the akinetic septum was where the circumference was divided in the normal ratio, namely, the free wall of the systemic ventricle being approximately 35% of the circumference in the main portion of the long axis (Fig. 3 in Part I), the shortening required was beyond its limit and the stroke volume ratio was also so far excess of the low-pressure ventricle. However, the volume ratio on diastole was within the limit. Therefore, if present, it would be somewhere between the midpoint and the rising point of the septum in the circumference, namely, approximately 8% of the circumference $[(50-35) \times \frac{1}{2} = 8]$ from the midpoint toward left on each side, where all the parameters discussed above could be satisfied in the construction of the akinetic septum in the single ventricle as a radial correction. Other possibilities in success might be present in that the single ventricle had been dilated pre-operatively and/or that the excess of the required shortening was compensated by increase of heart rate. It is, of course, necessary for the subjects discussed in this study

to be documented by experiments.

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