Combining all constants results in:

\[
\ln \sigma = \beta + \alpha C \quad (7)
\]

where

\[
\beta = \ln \left(\frac{a}{k}\right) - k, \quad (8)
\]

and

\[
\alpha = k/C_0 \quad (9)
\]

If one assumes that muscle length at zero stress does not vary considerably over a short time in a given muscle,\(^6\) then \(C_0\) would be constant in a first-order approximation and any change of \(\alpha\) due to an intervention should reflect an alteration in the elastic stiffness constant \(k\) that is identical to \(k\) in equation (3). Further, equation (8) demonstrates that intercept \(\beta\) of the logarithmic stress-circumference relation (equation 3) will be influenced by any change in \(k\) and thereby \(\alpha\).

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**Characteristics of Ventricular Function in Single Ventricle**

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**SUMMARY**  Functional characteristics of the single ventricle were studied by means of biplane angiography in 34 patients. Group 1 consisted of 14 patients with normal or increased pulmonary vascular marking on chest film and no pulmonary stenosis. Group 2 included 20 patients with severe angiographic pulmonary stenosis and decreased pulmonary vascular marking. Ventricular volume parameters were calculated according to Simpson's rule and were compared with normal values. The sum of the normal left and right ventricular volumes was assumed to be 100%.

In group 1, ventricular end-diastolic volumes averaged 143 ± 11% and were significantly \((p < 0.001)\) larger than end-diastolic volumes in group 2 (81 ± 4%). The presence or absence of severe pulmonary stenosis affecting pulmonary blood flow was a main factor regulating the ventricular chamber size in single ventricle. In both groups, the ejection fraction of a single ventricle was significantly lower than that of a normal left or right ventricle. Ventricular size and function in patients with a single ventricle should be carefully assessed before ventricular septation surgery.

**THE ANATOMY OF SINGLE VENTRICLE** has been well described,\(^1\) \(^2\) but its functional characteristics have not been reported. Correction of this complicated cardiac anomaly by septation surgery, in which the single ventricle is divided into two chambers, has become a challenge for cardiac surgeons.\(^3\) \(^4\) \(^5\) Therefore, it is important to know the volume and function of the single ventricle before surgical intervention.

We studied the functional characteristics of the single ventricle by analyzing biplane ventricular angiograms in 34 patients with a diagnosis of single ventricle confirmed angiographically or at autopsy.

**Methods**

**Patient Population**

Biplane, large-film angiograms (6 frames/sec) of 34 patients, 20 males and 14 females, ranging in age from 4 months to 12 years, were analyzed. The availability of angiograms of good quality was the sole criterion for patient selection. All patients were diagnosed as having a single ventricle by the definition reported previously.\(^1\) \(^2\) A single ventricle is one ventricle that receives both the tricuspid and mitral valves, or a common atrioventricular (AV) valve. This definition excludes tricuspid and mitral atresia. The angiographic morphology of the single ventricle was classified into three types (I, II and III). Details of this angiographic classification were also previously reported.\(^1\) \(^2\) In brief, type I is identical to the anatomic type A of Van Praagh et al.,\(^1\) type II is comparable to type C, and type III is equivalent to Van Praagh's types B and D.

There were seven, 13 and 14 patients with types I, II and III single ventricle, respectively. Three patients with type I, eight with type II and nine with type III had severe valvular and subvalvular pulmonary stenosis (PS) or pulmonary atresia. In one patient with type I single ventricle, the ventriculotrunical relationship was normal; four other type I patients had a transposition of the great arteries (TGA), and two had a double outlet right ventricle (DORV). Three patients with a type I single ventricle had two AV valves and four patients had a common AV valve. Of
13 patients with a type II single ventricle, six had a normal ventriculotruncal relationship, four had a TGA, and three had a DORV. Ten type II patients had two AV valves and the remaining three had a common AV valve. All 14 type III patients had a DORV and a common AV valve.

Other commonly associated anomalies included absent inferior vena cava withazygos or hemiazygos continuation in four patients, bilateral superior vena cava in six, anomalous pulmonary venous return in three, single atrium or large atrial septal defects in 20, and a right aortic arch in six. Dextrocardia was present in six patients.

Except for the presence of PS, we did not classify the concomitant anomalies present in these patients with single ventricle because, functionally, both systemic and pulmonic venous returns flow into a single ventricle and are ejected into the great arteries, depending on the relative impedance to outflow from the single ventricle into the pulmonary and systemic circulations. In this series, there were no patients with significant AV valve regurgitation or subaortic or aortic stenosis. Thus, the 34 patients were divided into two groups according to the presence or absence of severe PS demonstrated by angiocardioiaphy. Group 1 included 14 patients with no angiographic PS and a normal or increased pulmonary vasculature on plain chest x-ray films. Group 2 included 20 patients who had significant angiographic PS or pulmonary atresia without patent ductus arteriosus, as well as a decreased pulmonary vascular shadow on chest x-ray films. None of the patients had had a shunt or corrective surgery. In group 1, there were four, five and five patients with types I, II and III single ventricle, and in group 2, there were three, eight and nine patients of each type, respectively.

Patients in group 1 were 4 months to 12 years (average 4.1 years). In group 2, 16 patients with PS were 5 months to 10 years old (mean 2.5 years); four patients with pulmonary atresia were 4 months to 7 years old (average 2.3 years). The age difference between groups was not statistically significant (p > 0.05).

**Data Acquisition**

Biplane, large-film angiography was performed at 6 frames/sec in all patients, who were sedated with intramuscular injections of meperidine or ketamine; lidocaine was used for local anesthesia. Frontal and lateral films were obtained. In the majority of patients, two catheters were inserted through the femoral vein and artery, and ventriculography was performed twice by the injection of contrast material through a retrograde transaortic valve catheter and an

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**Figure 1.** Simultaneous recording of filming time and ECG. The film taken during the PR interval was considered to be an end-diastolic view (EDV) and the one taken at the end of the T wave an end-systolic view (ESV). With large-film angiography at 6 frames/sec, analysis of the EDVs and ESVs from a single beat was unfeasible; therefore, a composite analysis from several beats was made.
Ventricular volumes were computed according to Simpson's rule using an ultrasound graf-pen connected to a Hitac 10 computer system. The magnification of the film was corrected in each patient. End-diastolic volume (EDV), end-systolic volume (ESV) and ejection fraction (EF) were calculated and compared with the normal values reported by Graham, Nakazawa and their co-workers. Because most single ventricles could not be angiographically separated into the right and left ventricular compartments, the ventricular volumes were calculated as a "single ventricle." Therefore, the sum of the normal right and left ventricular volumes was assumed to be 100%; this can be expressed as 147.6 × BSA where BSA is body surface area (m²). The calculated volume was corrected by a regression equation. In types II and III single ventricle, the calculated volumes were corrected by the equation \( V_a = 0.856V_c + 2.5 \) (\( r = 0.995; p < 0.001 \)), where \( V_a \) is the actual volume and \( V_c \) the calculated volume. This equation was made primarily for the biplane analysis of the ventricle with right ventricular morphology. For type I single ventricle with left ventricular morphology, we used the regression equation \( V_a = 0.928V_c - 3.8 \). Although there was an associated small outflow tract chamber in type I single ventricle, its volume was small and therefore excluded from the total volume. Ventricular stroke volumes were calculated from the difference between EDV and ESV. The EF was calculated as the ventricular stroke volume divided by EDV.

**Figure 2.** Representative biplane angiograms from one patient with single ventricle from each group. Both patients were 2 years old and had a type III single ventricle with (group 2) or without (group 1) pulmonary stenosis (PS). Top) Group 1 (Gr-1): no PS; dilatation of the ventricular chamber was obvious. Bottom) Group 2 (Gr-2): pulmonary atresia; the ventricular chamber was small. A-P = anteroposterior view; Lat = lateral view.
Table 1. Ventricular Function in Single Ventricle

| Abbreviations: HR = heart rate; SaO2 = arterial oxygen saturation; Hgb = blood hemoglobin; EDP = end-diastolic pressure; EDVs = end-diastolic volumes expressed as a percentage of sum of normal right and left ventricular volumes (147.6/BSA)1-43; SVI = ventricular stroke volume index of single ventricle; EF = ejection fraction of single ventricle.

Results

The mean values of hemodynamic variables in single ventricle are presented in table 1. The mean heart rates for groups 1 and 2 at the time of the study were 118 ± 7 (SEM) and 127 ± 6 beats/min, respectively. The arterial oxygen saturation (SaO2) in room air averaged 76.7 ± 3.0% (range 60.0-89.0%) in group 1, and 71.4 ± 3.7% (range 49.0-89.5%) in group 2. The SaO2 was higher by approximately 5% in group 1 (NS). The blood hemoglobin content differed (p < 0.05) between groups, although the data were available in only eight patients in group 1 and 13 in group 2. The hemoglobin averaged 15.8 ± 0.4 g%, range 12.8-18.8 g%, in group 1, and 17.6 ± 0.6 g%, range 14.7-23.2 g%, in group 2. In group 1, the end-diastolic pressure was 2-16 mm Hg, average 8.4 ± 0.8 mm Hg, and in group 2 it was 0-13 mm Hg, average 6.8 ± 0.6 mm Hg.

EDVs of the single ventricle of both groups were plotted against BSA (fig. 3). The EDV of single ventricle in group 2 was always larger than that of the normal right or left ventricle, but generally smaller than the combined volumes of the normal right and left ventricles. In contrast, the EDV of single ventricle in group 1 was generally larger than that in group 2, and also larger than the sum of the normal right and left ventricular EDVs. When the EDV of single ventricle was expressed as percentage of the combined volumes of the normal right and left ventricular EDVs (100%), EDVs in groups 1 and 2 averaged 143 ± 11% (73-209%) and 81 ± 4% (54-119%), respectively. The difference in EDVs between two groups was statistically significant (p < 0.001).

The %EDV was plotted against the patient’s age in figure 4. In group 1, 11 of 14 patients (79%) had an increase in EDV to more than 125% of normal. This increase was apparent even in patients younger than 2 years of age. In contrast, in group 2, six of the 14 patients (43%) younger than 2 years of age had a ventricular chamber size of less than 75% of normal.

The average ventricular stroke volume index was 80 ± 9 ml/m² in group 1 and 47 ± 3 ml/m² in group 2 (p < 0.005). The EF averaged 0.49 ± 0.02 in group 1 and was not significantly different from that in group 2 (0.54 ± 0.02). In both groups, the average EF of a single ventricle was significantly (p < 0.001) less than that of a normal left (0.63 ± 0.01;19, 20 0.68 ± 0.0121) or right (0.61 ± 0.01;19 0.61 ± 0.0121) ventricle previously reported by Jarmakani, Thanopoulos and their co-workers.19-21 Figure 5 shows the relationship between EF and BSA compared with a normal left ventricular EF. The EF of a single ventricle was generally lower than that of a normal left ventricle, even when corrected for body size.
Discussion

Single ventricle is one of the most complicated cardiac anomalies and is usually associated with other abnormalities. With the increasing interest in total correction (ventricular septation, ventricular septum creation surgery), and in functional correction (right atrial-pulmonary artery bypass surgery), an understanding of the ventricular chamber size and function in single ventricle is important, but few studies have been done.

To make the analysis of ventricular function easier in this complicated cardiac anomaly, all the inflow abnormalities except significant AV valvular insufficiency were neglected in this study because a single ventricle receives blood from both atria. Among the factors affecting after-load of the single ventricle, such as pulmonary and systemic vascular resistance and anatomic stenosis or obstruction, only significant angiographic valvular or subvalvular PS was considered. The patients with subaortic or aortic stenosis were not included in this series.

In this study, biplane, large-film angiograms were used to assess ventricular size and function. Selection of the films at end-diastole and end-systole was based on the simultaneously recorded ECGs. This method had certain limitations. First, end-diastolic and end-systolic views could not be obtained in a single beat, and they had to be composed from the different beats. Second, end-diastolic frames were chosen during the PR interval and end-systolic frames were selected at the end of the T wave. End-diastole usually occurs at the end of the PR interval and end-systole usually occurs before the end of the T wave. Thus, it is likely that some end-diastolic volumes were underestimated and some end-systolic volumes overestimated, which might have resulted in an erroneously low EF in some patients. Cineangiographic evaluation is certainly preferable for this purpose.

When a significant angiographic PS was considered, hemodynamic characteristics in single ventricle could

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Figure 4. The relationship between the end-diastolic volume (EDV) and the patient's age (years) is shown. EDV was expressed as a percentage of normal. The sum of the normal right and left ventricular volumes was considered to be 100% in this study; the normal limit was 75–125%. In group 1 (Gr-1) patients, dilatation of the single ventricle (SV) occurred at an early age. In contrast, in 43% of the patients younger than 2 years of age in group 2 (Gr-2), the ventricular volume was somewhat underdeveloped (less than 75% of normal). The mean EDV of group 1 was significantly larger than that of group 2 (p < 0.001). PS = pulmonary stenosis; PA = pulmonary artery.

Figure 5. The ejection fraction (EF) was plotted against the body surface area (BSA). The EF was generally depressed in single ventricle (SV) when compared with a normal left ventricular EF, but there was no obvious difference in EF between the two groups. The area between the dotted lines was considered to be the normal range for a normal left ventricle. PS = pulmonary stenosis; PA = pulmonary artery; Gr = group.
be roughly separated into two groups. The EDV in group 1 averaged $143 \pm 11\%$ of normal, and increased chamber size was apparent, even in children younger than 2 years of age. This finding explains the occurrence of congestive heart failure in early childhood. In group 1, ventricular EDV in older children was relatively smaller than that in younger children (fig. 4), which may result from a relative decrease in pulmonary blood flow secondary to an increased pulmonary vascular resistance. Also, improvement of congestive heart failure with age might contribute to a decrease in the relative size of the ventricular chamber in surviving older children. In group 2, 43% of patients had a somewhat underdeveloped ventricle of less than 75% of normal.

In this study, neither pulmonary blood flow nor a pulmonary-systemic flow ratio were measured because of the difficulty in obtaining blood samples from the stenosed or obstructed pulmonary artery. However, because the ventricular stroke volume of group 1 was nearly twice that of group 2, and because hemoglobin concentration in group 1 was significantly less than that in group 2, it is quite likely that the pulmonary blood flow was normal or increased in group 1 patients. The increased pulmonary blood flow seemed to be related to the increased ventricular size in group 1 patients. This relationship has been reported in patients with common AV canal.20, 21

The SaO2 depends on the pulmonary and systemic blood flows, the mixed venous and pulmonary venous oxygen saturations, and the degree of mixing and streaming in the single ventricular chamber.24 The SaO2 was approximately 5% higher in group 1 (NS). The pulmonary blood flow is usually limited in patients with severe PS, but blood mixing is usually better in patients with PS than in patients without it.25 Also, the SaO2 may not differ significantly between the patients with and without PS under sedation during cardiac catheterization. However, the difference in SaO2 may become quite apparent when the patient is exercised, as suggested by the higher hemoglobin concentration in group 2 than in group 1.

In our study, patients who had severe angiographic PS associated with a higher blood hemoglobin content had a significantly smaller ventricle than patients without PS. Jarmakani et al.19 showed that right ventricular size was significantly less than normal in patients with severe tetralogy and a hemoglobin level > 16 g%. The EF of a single ventricle was slightly but significantly depressed regardless of the presence or absence of PS. Again, however, our ECG-based method of film selection might yield a somewhat lower EF than actually present. The depressed EF was also reported in patients with tetralogy of Fallot26, 27 and tricuspid atresia.28 The cause of a depressed EF in cyanotic patients is not entirely clear, but chronic hypoxemia seems to play an important role. Graham26 and Jarmakani27 and their co-workers reported that the depressed EF persisted even after corrective surgery was undertaken with a resultant normalized SaO2. Fibrotic myocardial changes in cyanotic patients may also play at least a partial role.29

The assessment of ventricular volume and function in single ventricle may be of great importance in consideration of surgical treatments, particularly when ventricular septation is considered. A detailed experimental study of ventricular septation in dogs has been reported,30 but characteristics of the human single ventricle are different from those of dogs with a normal ventricular volume. Ventricular septation may be indicated in patients with a good EF and an enlarged, normal or nearly normal ventricular volumes compared with combined normal right and left ventricular volumes. Patients with PS and a small ventricular volume may not be suitable candidates for ventricular septation but may be good candidates for a systemic artery-pulmonary artery shunt to increase pulmonary blood flow, with a resultant increase in chamber size.31 Ventricular septation may become feasible after the shunt operation in these patients. We conclude that ventricular size and function should be carefully assessed before surgery in patients with single ventricle.

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