

# Differential atrial filling after Mustard and Senning repairs

## *Detection by transcutaneous Doppler ultrasound*

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**SUMMARY** The dominance of Mustard's operation for transposition of the great arteries has been challenged by the recent revival of Senning's repair because it promises better long-term results in terms of venous obstruction and atrial haemodynamics. These hypotheses were tested by recording jugular venous flow waveforms transcutaneously in 24 postoperative patients with simple complete transposition using a bidirectional Doppler blood velocimeter. Eight patients had undergone Mustard's operation and 16 the Senning alternative; all had previously had a postoperative cardiac catheterisation.

Both groups of patients had similar left ventricular, pulmonary arterial, and systemic venous atrial pressures. No child showed any evidence at catheterisation of either mitral regurgitation or of superior vena caval pathway obstruction. These two findings were endorsed by the transcutaneous Doppler recordings.

Jugular venous flow in normal children exhibits two maxima, one of atrial filling during ventricular systole, the other of ventricular filling occurs once the tricuspid valve has opened. Both operative procedures diminished the size of the former phase, but the Mustard did so more. After Mustard's operation forward flow during the atrial filling phase was absent in approximately half the cardiac cycles recorded, and severely diminished in the rest. By contrast, there was approximately a 90 per cent appearance of atrial filling waves after Senning's operation which also provided significantly better atrial function than Mustard's procedure in terms of peak velocity of blood entering the atrium and total atrial filling. It is therefore concluded that both procedures compromise atrial volume and compliance but Senning's repair to a much lesser extent.

The Senning operation<sup>1</sup> has recently been revived as an alternative form of treatment to the Mustard procedure<sup>2</sup> for the physiological correction of complete transposition of the great arteries by the decussation of venous inflow.<sup>3</sup> This recent challenge to Mustard's procedure was prompted because of the impressive haemodynamics of some children with 16-year-old Senning repairs, showing no signs of venous stenosis. Such obstruction to inferior and superior vena cavae and to the pulmonary veins is an important cause of late morbidity and mortality after Mustard's procedure<sup>4</sup> despite low initial

mortality.<sup>5-7</sup> Patches of pericardium used in Mustard's procedure may become infected, contract, or develop structural defects.<sup>8</sup> Dacron patches were therefore introduced, but though immediate postoperative survival improved, a high proportion of these children subsequently developed obstruction to venous return, requiring surgical revision.<sup>7-9</sup> If the interatrial baffle is too large it can lead to pulmonary venous obstruction; if it is too small the superior or inferior vena caval pathway or both will become stenosed. Despite refinements,<sup>7-10</sup> the interatrial baffle still creates an inherent confinement of atrial movement, a reduced atrial filling capacity, and a potential for venous obstruction and infective endocarditis.

The geometry of the Senning operation is such

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that stenosis of the vena cavae is nearly impossible and pulmonary venous obstruction may be avoided with operative care. Perhaps more importantly, the amount of foreign material used is small, even after a previous atrial septectomy<sup>11</sup>; reconstruction is mainly of living atrial muscle. This has two potential advantages; firstly, the atrium may be expected to grow as the patient grows, and secondly, the atria may function better as each will be contracting against a yielding, compliant partner rather than against a stiff, immobile prosthesis, as in the Mustard procedure. It has already been shown that the large interatrial baffle used in Mustard's procedure dramatically reduces the rate of filling of the systemic venous atrium, probably by serious loss of atrial compliance and volume<sup>12</sup>; this is also manifested in the systemic venous atrial pressure pulse by a steep y descent.<sup>13</sup> Even disregarding the effect of atrial growth, however, the design of the Senning operation (that is, pulmonary venous blood being redirected outside the atrial wall) suggests that not only atrial compliance but also atrial volume should be less compromised than in Mustard's procedure.

We felt that this hypothesis could be tested non-invasively using transcutaneous Doppler ultrasound to measure jugular venous velocity flow patterns which reflect derangements in right heart haemodynamics irrespective of the underlying aetiology.<sup>14</sup> This technique has been used successfully to diagnose asymptomatic superior vena caval pathway obstruction after Mustard's procedure,<sup>12</sup> and it seemed therefore appropriate to apply it to Senning's repair, firstly to screen for obstruction, however unlikely,<sup>3</sup> and secondly to compare compromise of atrial function after the Mustard and Senning procedures.

## Methods

Jugular venous flow velocity recordings were made in 24 patients who had previously been corrected for simple complete transposition of the great arteries at the University Hospital, Leiden. Sixteen (age range 1.7 to 5.6 years, mean 3.6) had Senning and eight (age range 6.0 to 12.6 years, mean 9.8) had Mustard repairs. Patients were tested sequentially at special outpatient clinics. A transcutaneous bi-directional Doppler ultrasound blood velocimeter\* was used, which incorporated a three-lead electrocardiogram and a flow channel, plotting them both onto an integral paper chart recorder. The machine also emits an audible tone whose frequency is proportional to the velocity signal. The transmitter frequency was 7.52 MKz.

Patients were quiet and supine with no pillow

\*Sonicaid Ltd. Model BV381.

and the head turned slightly away from the examiner to expose the jugular vein. The limb leads of the electrocardiograph were attached to the patient and the instrument checked for an appropriate electrocardiographic deflection (showing the p waves in particular) on the recording paper. The external probe was applied to the skin using Aquasonic 100 ultrasound transmission gel.† The probe was placed over the internal jugular vein and directed toward the inferior border of the contralateral scapula. Its position was then adjusted until the signal reached a maximum. When this signal was consistent, reproducible, and pure, that is free from components of flow from adjacent arteries, the electrocardiogram and jugular flow signals were then recorded simultaneously on the chart recorder at a paper speed of 50 mm/s using a foot switch control. Recordings were obtained whenever possible from both left and right jugular veins, after which a recording of the carotid velocity trace was also made to verify by comparison that there was no arterial component in any of the venous flow recordings. Zero flow was recorded routinely and regularly as a reference level and both venous and arterial forward flows were displayed as positive deflections by the appropriate use of the reversal switch, standard to this instrument.

Areas under flow velocity curves were calculated as follows. First, the original traces were photocopied. Second, areas were then measured both by planimetry (Allbrit Planimeter‡) and by weighing (Stanton CL4D§) each carefully dissected photocopied flow velocity waveform. The latter method was found to be considerably more accurate and reproducible than planimetry. Values for each patient are the means of seven to 20 cardiac cycles, depending upon availability. Only those cardiac cycles showing both atrial and ventricular filling waves were selected for this portion of the study.

All patients had previously undergone a standard postoperative cardiac catheterisation to assess their haemodynamic status.

## Results

### POSTOPERATIVE CARDIAC CATHETERISATIONS

These data are summarised in Table 1. Patients in the Mustard and Senning groups could not be distinguished from one another by pressures in the left ventricle, pulmonary artery, or systemic venous atrium, or by the left ventricle to pulmonary artery pressure gradient. Additionally, none of these four

†Parker Laboratories, New Jersey, USA.

‡Stanley and Co, London.

§Stanton Ltd, London.

variables was found to correlate with any of the height or area ratios derived from the velocity traces.

There was no evidence of mitral regurgitation in any of the children.

Table 1 Postoperative catheterisation results in patients corrected for transposition

	LV (mmHg)	PA (mmHg)	LV-PA gradient (mmHg)	Systemic venous atrium (mmHg)
Mustard	32.9 ± 3.1	23.0 ± 2.2	9.9 ± 2.7	5.8 ± 1.1
Senning	34.6 ± 2.9	21.9 ± 0.9	12.8 ± 3.0	7.5 ± 0.8
	NS	NS	NS	NS

Values are means and standard errors. NS, not significant.

#### DIAGNOSIS OF SUPERIOR VENA CAVAL PATHWAY OBSTRUCTION

Criteria for the non-invasive diagnosis of superior vena caval pathway obstruction using transcutaneous bidirectional Doppler ultrasound recordings from the jugular vein have already been published<sup>12</sup> and Doppler recordings taken from children of both the groups in this study were similarly examined for signs of obstruction. No such signs were apparent in any of the children and this finding was supported by data obtained from each of the children at postoperative cardiac catheterisation. No gradient higher than 1 mmHg between the superior vena cava and the systemic venous atrium was found in any of the children from the Mustard group, and none higher than 4 mmHg found in the Senning group (the two in this group with a 4 mmHg gradient showed no signs of azygos filling during a superior vena caval angiogram).

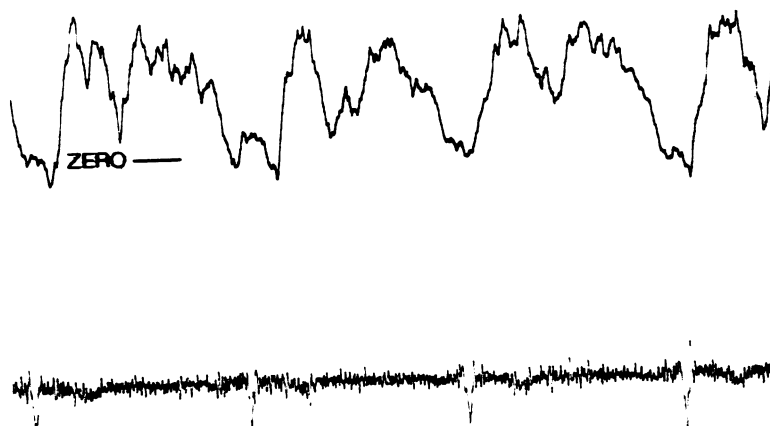
#### COMPARISON OF ATRIAL FUNCTION AFTER MUSTARD AND SENNING PROCEDURES

A typical example of the jugular venous flow velocity trace seen before the current study in a number of normal children is shown in Fig. 1. Similar patterns have been observed by other workers.<sup>4-16</sup> These patterns are characterised by two waves of forward flow. The first, of atrial filling during ventricular systole, is the result of a combination of atrial relaxation and tricuspid descent. The second, in ventricular diastole, reflects filling of the ventricle once the tricuspid valve has opened. The two maxima of forward flow are followed by a wave of reduced or reverse flow coinciding with and probably caused by the atrial systole of the next cardiac cycle.

The pattern seen in most post-Mustard cases is shown in Fig. 2a. It is characterised by a partial or total loss of the forward flow wave in ventricular systole and by no reversal of flow during atrial systole. A typical jugular flow pattern seen in post-Senning cases is shown in Fig. 2b. Forward flow velocity in ventricular systole was also reduced compared with normals but much less so than in the post-Mustard cases, with definite ventricular systolic maxima seen in most or all cardiac cycles. When the relative incidence of atrial filling waves over the entire record of cardiac cycles for each patient was measured and means calculated for each group, the results showed that atrial filling waves were significantly more frequent after Senning's procedure than after the Mustard alternative (Table 2).

The jugular venous velocity waveforms were then analysed in two further ways, as shown in Fig. 3. Mean relative height and area ratios for post-Mustard and post-Senning patients are presented

Fig. 1 Jugular venous flow in a normal child. Flow towards the heart is depicted as above the zero line. There are two maxima of forward flow, the first during ventricular systole is of atrial filling. The second, in ventricular diastole, occurs once the tricuspid valve has opened.



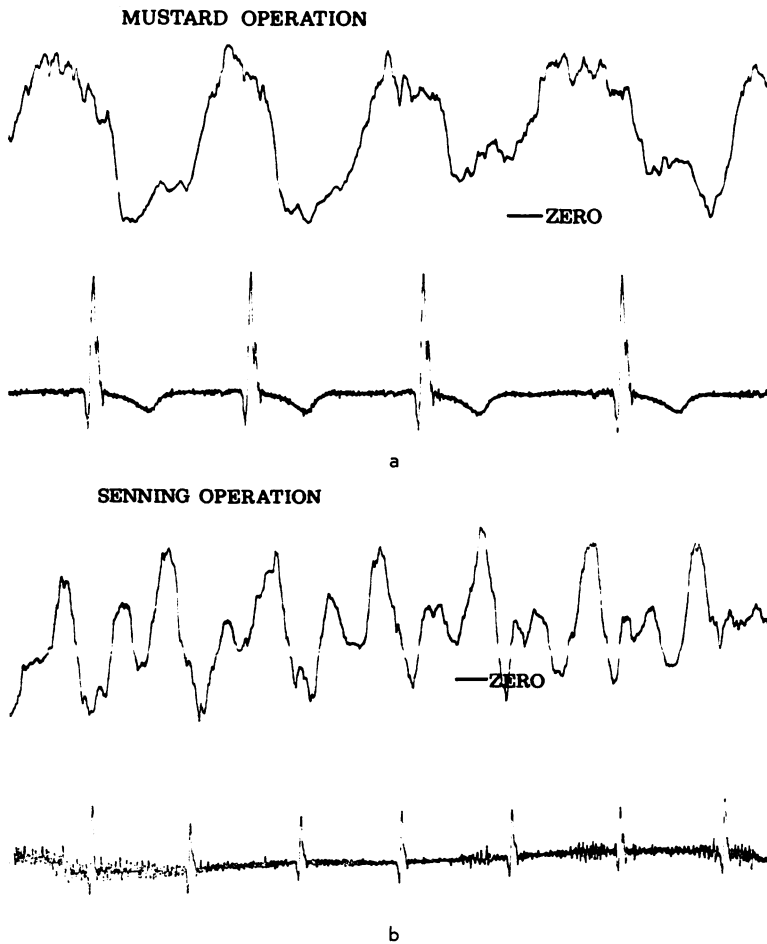


Fig. 2 Typical jugular venous flow velocity recordings in patients after surgical correction of transposition of the great arteries. Flow towards the heart is depicted as above the zero lines. Fig 2a shows that after Mustard's procedure forward flow during ventricular systole (atrial filling phase) is almost or entirely lost. Fig 2b shows that though atrial filling is not as good in Senning's repair as in normal children, it is substantially better than in Mustard's procedure in terms of its incidence, rate, and volume.

in Table 3. These results show that the relative height ratio is significantly higher ( $p < 0.05$ ) for Senning's operation (0.613) than for Mustard's procedure (0.455). The difference between the area ratios was even more pronounced, with the value for Senning's operation (0.436) significantly higher than the value for Mustard's procedure (0.226).

### Discussion

The results have indicated that atrial filling characteristics after the Mustard and Senning procedures are qualitatively and quantitatively different. The data give no information on the relative ventricular filling characteristics. As the two groups of patients were statistically inseparable, however, in terms of their left ventricular and pulmonary arterial pressures (and their mean difference) it may be assumed that their ventricular function was similar.

The dominant factor producing forward jugular flow in ventricular systole is uncertain. There is some evidence<sup>14</sup> that in patients without transposition, tricuspid descent with a closed tricuspid valve is more important than atrial relaxation in promoting systolic superior vena caval flow. In post-Mustard patients the mitral valve may well be restrained from normal descent by the baffle. This, in combination with reduced atrial volume and compliance, tends synergistically to diminish forward venous flow in ventricular systole.

The fact that there was no clinical or angiographic evidence of mitral regurgitation in any of the patients is supported by the ultrasonic results. Tricuspid regurgitation in patients without transposition creates retrograde jugular venous and superior vena caval flow during ventricular systole<sup>14 17 18</sup> and similar results would have been expected in patients in the current study if mitral

regurgitation were present after Mustard's or Senning's procedure.

The inequality of the mean ages of the two groups examined in this study was because the Mustard operation was largely discontinued in Leiden some time ago in favour of Senning's procedure. While it is clear that ideally the groups would be identical in terms of current age and also their age at operation, it is perhaps relevant to point out that the jugular venous velocity flow pattern in normal children changes little with age. Therefore, for children in the current study, with no caval obstruction or impaired mitral valve function, change with time in jugular flow characteristics would not be anticipated. This is also supported by the experience of jugular venous flow velocity recordings made in children of all ages after the Mustard operation at Great Ormond Street Hospital.

Table 2 *Relative incidence of atrial filling waves per 100 cycles in jugular venous flow velocity recordings*

Mustard	56 ± 11
Senning	89 ± 2
	p < 0.01

Values are means and standard errors.

Jugular venous flow velocity traces seen in post-Mustard cases without caval obstruction at Leiden were indeed similar to those seen at Great Ormond Street Hospital in a previous study<sup>12</sup> except that atrial filling may have been slightly better in the latter group. We did not wish to include this latter

Table 3 *Dimensions of atrial filling waves compared with ventricular filling waves*

Mustard versus Senning—Atrial filling		Area ratio
	Height ratio	
Mustard	0.455	0.226
Senning	0.613	0.436
t	2.322	4.870
p	< 0.05	< 0.001

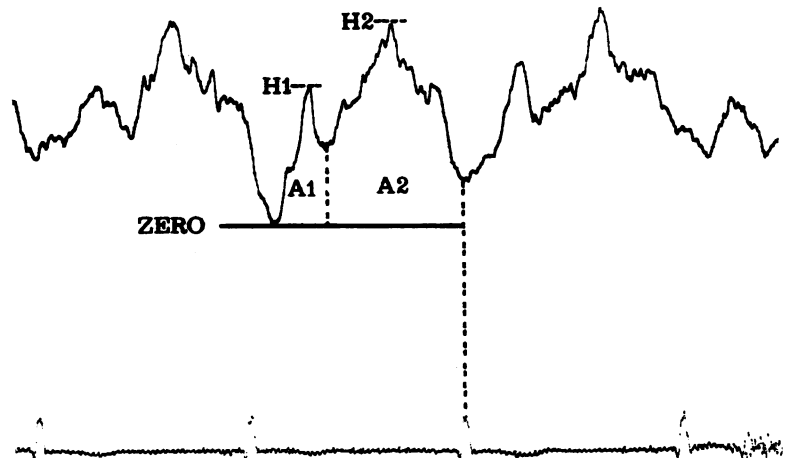
Note: Height ratio is result of dividing peak height of atrial filling wave by peak height of ventricular filling wave and is thus a measure of relative blood velocities. The area ratio is similarly a measure of relative total blood flow during two filling phases.

group in the current data, however, because it represented the addition of another variable (that is slightly different surgical techniques).

It can be difficult to make ultrasonic transcutaneous jugular venous flow velocity recordings in children because they often only keep still and silent while a few consecutive waveforms are recorded. Consequently traces may consist of noisy, useless information interspersed with the data of interest. Recordings taken in this study were no different, but subsequent recognition of those noiseless traces that are derived from jugular venous flow only is never difficult even to the inexperienced eye.

The comparison of height and area ratios in the present study contains an inherent inaccuracy because atrial filling waves were significantly less frequent in the Mustard group (Table 2). As only those cardiac cycles with atrial filling waves could be analysed in terms of height and area ratios, disproportionate values must result. Atrial filling waves occurred only 56 per cent of the time in the Mustard group. The true value of the ratios is therefore

Fig. 3 This is a jugular venous velocity recording from a patient after Senning's repair. Height ratios in all patients were determined by dividing the distance from zero to H1 by the distance from zero to H2. Mean values for each patient were derived by measuring many cardiac cycles, and these means were then pooled to give the group data. A similar process was used in determining the means of the area ratios A1/A2.



overestimated by a factor of approximately two. The value of 89 per cent, however, for the Senning patients suggests that the overestimation of the ratio in this group is only of the order of 10 per cent. The effect of this transformation is that Table 3 is substantially biased in favour of the Mustard results. Despite this, the ratios are both significantly better for the Senning group. The haemodynamic significance of the height ratio is that it reflects the absolute velocity of blood along the jugular vein during the atrial and ventricular filling phases. The height of the atrial filling wave will be influenced by a number of factors, notably, the ability of the mitral floor to descend during ventricular systole, atrial compliance, and the rate of atrial relaxation. Though this ratio was significantly different in the two groups it is not possible to say which of the above factors is predominantly responsible for this difference. Though the Mustard baffle would probably affect the former two, in Senning's repair there is physically more live atrial muscle to relax.

The relevance of the area ratio is that it reflects the total volume of blood passing along the jugular vein during the atrial and ventricular filling phases. Therefore, this ratio gives an indication of atrial capacity, which is affected not only by the variables controlling the height ratio but also by physical size. Sequential studies on these patients would be required to ascertain whether these ratios do change with time; if the atria grow with the patient in Senning's repair then this might perhaps lead to consistent ratios throughout life. The static, non-growing nature of Mustard's repair might lead one to suspect that ratios are better in the immediate postoperative period than in the ensuing years as the patient grows. Jugular venous flow velocity recordings in many such children at Great Ormond Street Hospital suggests, however, that this is not so, and that the remaining atria may grow sufficiently to prevent further reduction of the ratios.

Ratios were highly consistent for the Senning group. In the group of eight Mustard patients, however, six had poor ratios but two were as high as any in the Senning group, showing that good atrial filling can occur in some patients despite the interatrial baffle. The fact that none of these ratios for either operation correlated with the haemodynamics supports the view that they are principally affected by physical restraints placed upon the atria as well as the limitations of atrial volume and compliance rather than by the pressures and gradients beyond the mitral valve.

Since the haemodynamics of the Mustard and Senning groups were statistically inseparable and there was also no correlation between ratios and haemodynamics, we may conclude from the results

that the Senning operation compromises atrial volume and compliance less than Mustard's procedure. We cannot necessarily conclude that the Senning operation is the treatment of choice. A large alteration in atrial filling might have a relatively small effect on total cardiac performance, and systemic venous return is but one aspect of the comparison required. Pulmonary venous return, ventricular function, and arrhythmias are also important. Furthermore, with longer follow-up, the differences between the two groups might diminish. At the University Hospital, Leiden, there is currently a total commitment to the Senning operation if repair of transposition by redirection of venous inflow is sought. At The Hospital for Sick Children, Great Ormond Street, however, both the Mustard and Senning operations are still being evaluated; the present policy is for one surgeon to perform only Senning's repair and the other only Mustard's procedure. It is hoped that ultimately a consistent surgical approach to transposition of the great arteries will be reached in the light of the current study, data reflecting long-term morbidity and mortality, and the results of alternative procedures such as the arterial switch.

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