Cardiol Young 1992; 2: 277-280
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ISSN 1047-9511

Ventilation with external high frequency oscillation around a negative baseline increases pulmonary blood flow after the Fontan operation

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Abstract In this prospective study, pulmonary blood flow was measured using transesophageal Doppler echocardiography to assess whether ventilation by means of external high frequency oscillation around a negative pressure baseline can increase pulmonary blood flow, compared to intermittent positive pressure ventilation, in five patients after the Fontan operation. Pulmonary blood flow was measured when patients were ventilated by means of intermittent positive pressure ventilation and again during equivalent negative pressure ventilation using the external oscillatory technique. When compared to that with intermittent positive pressure ventilation, ventilation using external high frequency oscillation increased pulmonary blood flow by 116 ± 61.5% ($p=0.013$). These results show that ventilation using an external oscillatory device with a mean negative chamber pressure may provide hemodynamic advantages in patients requiring assisted ventilation after the Fontan operation.

The principal cause of mortality in patients after the Fontan operation[1] is low cardiac output. This usually occurs because of reduced pulmonary blood flow, itself occurring as a consequence of poor perfusion of the pulmonary vascular bed, which is at systemic venous pressure. Intermittent positive pressure ventilation is widely used in the postoperative care of patients who require respiratory support after this operation. The use of intermittent positive pressure ventilation in patients after the Fontan operation, however, may itself be associated with a significant reduction in pulmonary blood flow.[2] Conversely, we have demonstrated large increases in pulmonary blood flow in conscious patients after a total cavopulmonary shunt, when they are additionally ventilated using an external high frequency oscillation around a mean negative chamber pressure baseline, with a mean airway pressure at zero.[3] In this study, we examine the potential benefits of this technique as the only form of respiratory support in patients after the Fontan operation in whom an atrial chamber is incorporated into the pulmonary circulation.

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Accepted for publication 21 February 1992

Methods

Five patients with a median age of 108 months (range 51-107) were studied at a median interval of 38 months (19-60) after the Fontan operation. In three, the primary diagnosis was classical tricuspid atresia, with concordant ventriculoarterial connections. The other two had double inlet left ventricle with discordant ventriculoarterial connections. Direct atriopulmonary anastomoses had been performed in all. All patients were in Class 1 of the categorization of the New York Heart Association. In four patients, cardiac catheterization was performed to exclude atriopulmonary obstruction. One patient underwent cardiac catheterization in order to assess the success of a previous balloon dilatation of the pulmonary artery. Approval for the study protocol was obtained from the local Hospital Ethics Committee.

It is our policy to perform cardiac catheterization with general anesthesia. At the end of the catheterization procedure, while general anesthesia and paralysis were maintained, a transesophageal ultrasonic probe, interfaced with a Hewlett Packard Sonos 1000 ultrasound machine, was introduced into the esophagus of each patient. The position of the atriopulmonary anastomosis was identified, and a pulsed-wave Doppler sample volume was placed in the center of the signal showing pulmonary flow, at or just distal to the anastomosis. In all, the angle of incidence between the Doppler ultrasonic beam and the pulmonary flow approached 0°.

Recordings of pulmonary Doppler flow velocities were made while the patient was ventilated using a pressure-limited positive pressure ventilator (Nuffield, Penlon) with gases delivered via a Bains co-axial circuit. This was then discontinued and replaced by an oscillatory device producing negative pressure, with a mean chamber pressure of −8.5 mm Hg. This was achieved using a Hayek oscillator[4] (Flexco Medical Instruments, Zurich).

This device is composed of a clear, flexible plastic chamber, with rubber flanges, which maintain an adequate air-tight seal. The size of the cuirasse can be selected so that it extends from the clavicle to below the costal margin. The chamber is connected by a tube to the power unit (the oscillator), which creates the negative pressure baseline and produces cyclical changes of pressure within the chamber. The ventilation rate, the chamber pressure during inspiration and expiration and the ratio of inspiration to expiration were adjusted in order to keep constant, the end tidal level of carbon dioxide and the arterial saturation of oxygen. A ratio of inspiration to expiration of 1:1 was used in three and a ratio of 2:1 in two. Measurements of arterial blood gases were made prior to each Doppler study, in order to ensure comparable ventilation with the two methods. After approximately five minutes of ventilation by means of the oscillator, measurements of pulmonary blood flow were repeated with the sample volume in an identical position in the pulmonary artery.

Patterns of Doppler flow were recorded at a paper speed of 100 mm per second. Velocity-time integrals were measured by planimetry over 10 consecutive cardiac cycles, using a Summagraphics digitizing plate interfaced with a Prime mainframe computer. The mean velocity-time integral for an averaged cardiac cycle was then calculated and the minute velocity-time integral derived from the heart rate. In four patients, retrograde flow was observed during early ventricular systole. In these instances, the integral associated with the retrograde flow was subtracted from that related to forward flow, so that the net forward velocity-time integral could be calculated. No attempt was made to assess the cross-sectional area of the pulmonary artery, which was assumed to remain constant throughout the study. Thus, changes in the velocity-time integral were assumed to reflect alterations in pulmonary blood flow.

The statistical significance of differences observed between intermittent positive pressure and oscillatory negative pressure was assessed using Students t test. All results are presented as mean ±1 standard deviation.

Results

There were no significant hemodynamic abnormalities in any of the patients studied, and adequate and comparable ventilation was maintained with both techniques. Introduction of the transesophageal probe was not associated with any significant hemodynamic or ventilatory disturbance. In one patient, however, extreme anteflexion of the probe caused transient airway obstruction both during intermittent positive pressure ventilation, and during ventilation by means of the oscillator. In all patients, anterograde pulmonary flow occurred during most of ventricular systole which was augmented by atrial systole. Low-velocity retrograde flow was observed during early ventricular systole in four patients (Figure). There was no retrograde flow in one.

Heart rate was 62±8.9 beats per minute during intermittent positive pressure ventilation and 60.2±10.8 beats per minute during ventilation with the oscillator (not significant).

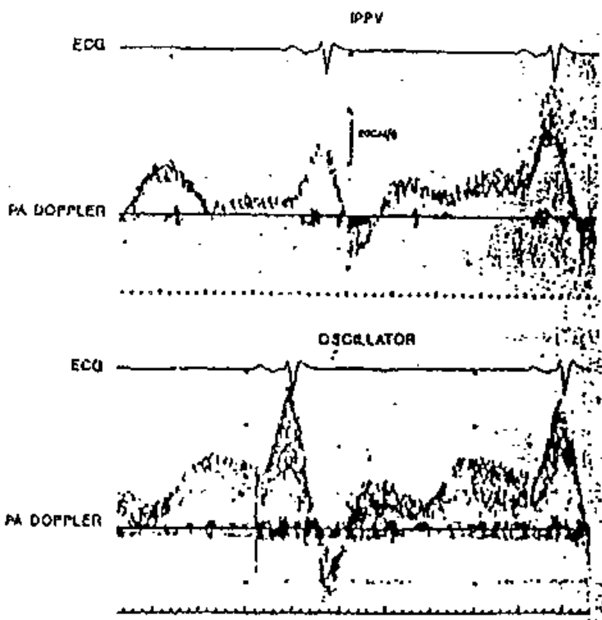

Figure. *Pulmonary artery Doppler flow in a patient after the Fontan operation, during intermittent positive pressure ventilation (upper panel) and during cuirasse ventilation, using a Hayek Oscillator, with a negative mean chamber pressure (lower panel). The use of the oscillator is associated with a large increase in forward flow.*

Total forward pulmonary flow per averaged cardiac cycle during negative pressure oscillation was 198±68% of total forward flow during intermittent positive pressure ventilation ($p=0.022$). Total retrograde pulmonary flow per cardiac cycle during negative pressure oscillation was 85±17% of that during intermittent positive pressure ventilation, but this difference was not statistically significant. Thus, net forward flow per cardiac cycle during negative pressure oscillation was 228±85% of net forward flow during intermittent positive pressure ventilation ($p=0.017$).

In all patients, an increase in forward pulmonary flow was observed during negative pressure oscillation, such that when corrected for heart rate, net forward pulmonary flow per minute during the oscillatory negative pressure was 216±61.5% of net forward flow during intermittent positive pressure ventilation ($p=0.013$).

Discussion

The major cause of mortality associated with the Fontan operation is related to an inability to perfuse the pulmonary vascular bed under systemic venous pressures. Intermittent positive pressure ventilation, while improving arterial oxygenation may reduce pulmonary blood flow by impeding systemic venous return and by increasing pulmonary vascular resistance. One study demonstrated a progressive reduction in cardiac output with increasing positive end-expiratory pressure in patients after the Fontan operation.[2] We have previously demonstrated the profound effect of alterations in intrathoracic pressure in patients after a total cavopulmonary shunt,[3] and have demonstrated that the use of external high frequency oscillation with a mean negative chamber pressure may increase pulmonary arterial flow in these patients.[3] Furthermore, our observations in 16 patients have suggested that normal inspiration is associated with an augmentation in pulmonary blood flow in patients after the Fontan operation in whom an atrial chamber is incorporated into the pulmonary circulation.[6]

This study demonstrates that respiratory support, using external oscillation with a negative mean chamber pressure, is associated with a significant increase in pulmonary blood flow when compared to ventilation at positive pressure in convalescent patients after the Fontan operation. While the effects of lung inflation using negative pressure are unclear, some experimental studies have demonstrated that expansion of the isolated lung by negative pressure may lead to a fall in pulmonary vascular resistance.[7] This effect may be invoked, but has not been addressed in the current study. The principle effect of this technique would appear to be related to a reduction in mean airway pressure, thereby removing the adverse effects of intermittent positive pressure ventilation. An additional effect of augmentation in pulmonary blood flow, by actively drawing blood from the systemic venous reservoir, needs to be invoked, nonetheless, to explain such a large increase in total pulmonary blood flow.[8] If this is the case, then this effect would not be achieved using an 'iron-lung' respirator, in which all but the head is exposed to subatmospheric pressure. Indeed, in these circumstances, a fall in cardiac output may be expected.[8] There are also practical advantages to ventilation using a cuirasse. Access to the patient is easy, and ventilation can be achieved with the patient in a sitting position.

While its effect on cardiac output in convalescent patients have been demonstrated in this study, the efficacy of ventilation using an oscillatory negative extrathoracic pressure in the immediate postoperative patients has not been demonstrated. We are currently examining the effects of changes in respiratory rate, the ratio of inspiration and expiration and electrocardiographic gating in patients in the intensive care unit. The effects of more prolonged support on the incidence of pleural effusions and edema in the extubated patient are also being explored.

In summary, these data suggest that ventilation using a cuirasse device to provide a negative oscillatory pressure will make a significant contribution to the postoperative care of patients who require respiratory support after the Fontan operation.

Acknowledgments

Daniel J. Penny is supported by the British Heart Foundation. Z. Hayek has professional associations with Flexco Medical Instruments.

References

1. Fontan F, Baudet E. Surgical repair of tricuspid atresia. Thorax 1971; 26: 240-248.
2. Williams DB, Kiernan PD, Metke MP, Marsh HM, Danielson GK. Hemodynamic response to positive end-expiratory pressure following right atrium-pulmonary artery bypass (Fontan procedure). J Thorac Cardiovasc Surg 1984; 87: 856-861.
3. Penny DJ, Hayek Z, Redington AN. The effects of positive and negative extrathoracic pressure ventilation on pulmonary blood flow patterns in patients after total cavopulmonary shunt. Int J Cardiol 1991; 30: 128-130.
4. Hayek Z, Schonfeld T. External high frequency oscillation around negative baseline–preliminary trials in humans. In: Aochi O, Amaha K, Takeshita H (eds). Intensive and Critical Care Medicine. Proceedings of the 5th World Congress on Intensive and Critical Care Medicine, Kyoto. Excerpta Medica, Amsterdam. 1990. pp 761-762.
5. Redington AN, Penny DJ, Shinebourne EA. Pulmonary blood flow patterns after total cavopulmonary shunt operation. Br Heart J 1991; 65: 213-217.

6. Penny DJ, Redington AN. Doppler echocardiographic evaluation of pulmonary blood flow after the Fontan operation: The role of the lungs. Brit Heart J 1991; 66: 372-374.
7. Adams JA, Osiovitch H, Suguihara C, Goldberg R, Martinez O, Devia C, Helhre D, Bancalari E. Comparison of mechanical ventilation using PEEP versus continuous negative extrathoracic pressure: Hemodynamic effects in piglets with group B streptococcal sepsis. Pediatr Res 1989; 25: 300A. [Abstract]
8. Lockhat D, Langleben D, Feleke G, Partyka R, Zidulka A. Hemodynamic differences between continual positive and negative pressure ventilation. Am Rev Rep Dis 1988; 137: 292-296.