Pulmonary blood supply in bidirectional cavopulmonary anastomosis with pulsatile pulmonary blood flow: quantitative analysis using radionuclide angiocardiography

Oleg Reich, Pavel Horváth, Cyril Ruth, Miroslav Krejčí, Jan Škovrňánk

Abstract
Objectives—To establish a non-invasive method for quantitative analysis of pulmonary perfusion in patients with bidirectional cavopulmonary anastomosis (BCPA) and sources of pulsatile blood flow. The method should quantify left to right lung flow ratio and relative contribution of BCPA and sources of pulsatile blood flow to perfusion of each lung.

Design—A pilot study using radionuclide angiocardiography for quantitative analysis and for visualisation of cavo-caval collaterals. No criterion standard is available.

Setting—Tertiary care centre, ambulatory and hospital inpatient care.

Patients—Consecutive sample of 18 patients with BCPA and sources of pulsatile blood flow.

Results—In eight patients (44%) cavo-caval collaterals prevented quantitative analysis. In 10 patients without cavo-caval collaterals, BCPA provided 42.3 (SEM 3.4) % of total pulmonary blood flow. From the total BCPA flow, 67.2 (4.3)% was directed to the ipsilateral lung. This lung received only 16.5 (3.3)% of all the blood from sources of pulsatile blood flow. The blood flow to the lung at the side of BCPA accounted for 35.3 (1.7)% of the total pulmonary blood flow.

Conclusions—Radionuclide angiocardiography allows the quantitative analysis of pulmonary blood supply in BCPA with sources of pulsatile blood flow except in patients with cavo-caval collaterals or bilateral BCPA. Non-pulsatile flow from BCPA is mainly directed to the ipsilateral lung, whereas pulsatile flow to the contralateral lung. Total perfusion of the ipsilateral lung is less than the perfusion of the contralateral lung.

Keywords: congenital heart defects; cavopulmonary anastomosis; radionuclide angiocardiography; pulmonary blood flow.

Surgical palliation of complex cardiac anomalies is being done increasingly by total cavopulmonary connection, on the basis that the right heart is dispensable.1 In patients who do not fulfil criteria for total cavopulmonary connection2 the results are not satisfactory.3 4 In these patients bidirectional cavopulmonary anastomosis (BCPA) may offer safer long term palliation.5 7 Late deterioration in function in a cavopulmonary anastomosis is caused by ventilation-perfusion mismatch,9 development of pulmonary arteriovenous fistulae,10 11 and formation of cavo-caval collaterals.12 13 The ventilation-perfusion mismatch and formation of pulmonary arteriovenous fistulae may be prevented by increasing the effective pulmonary blood flow with an additional source of pulsatile blood flow (SPBF).14 15 On the other hand, excessive pulsatile flow might increase superior vena caval pressure and thus facilitate cavo-caval collateral flow. The presence of a source of pulsatile blood flow following BCPA can play a beneficial role in ensuring a smooth early postoperative course and more even arterial growth.16 However, very little is known about the safe volume of the pulsatile flow and distribution of pulmonary blood flow from BCPA and from the sources of the pulsatile blood flow.

We present a new non-invasive method for quantitative assessment of relative contribution of BCPA and the sources of pulsatile blood flow to the total pulmonary blood flow, as well as to the perfusion of each lung.

Rationale
Radionuclide angiocardiography allows regional flow measurement using a peripheral vein injection and external counting. The pulmonary blood supply in BCPA with a source of pulsatile blood flow consists of venous blood from the superior vena cava and pulsatile arterial blood from aortopulmonary connections or a stenotic pulmonary valve. In this situation, after tracer injection into the drainage area of the superior vena cava, the lung dye dilution curve is composed of two peaks caused by the cavopulmonary and arterial flows respectively. The relative contribution of these two sources to the overall lung perfusion may be calculated using integrals of the two respective parts of dilution curve in a manner similar to the calculation of intracardiac shunts.17 18 Furthermore, by analogy to the measurement of cardiac output,19 20 the total flow through both lungs may be calculated separately and compared. A gamma camera system enables direct visualisation of the superior to inferior vena cava collaterals and regional pulmonary blood flow during the radionuclide angiocardiography. Subsequent
 gated blood pool scintigraphy does not require additional radionuclide and provides information on ventricular function.

Quantitative analysis is based on following assumptions:

(1) Knowing the input amount of tracer \( I_0 \) its mean concentration over the first-pass \( I_n \) and the first pass duration \( t \), flow \( Q \) through a measured region may be calculated:

\[
Q = \frac{I_n}{I_n \cdot t}
\]

The \( I_n/I_0 \) ratio equals the volume in which the tracer has been diluted and \( t \) is the time needed for that volume to pass the measured region. It is practical to calculate directly the product \( I_n \cdot t \) which equals the area under the first pass dilution curve:

\[
Q = \frac{I_n}{\int_0^t I(t) \, dt}
\]

where \( I(t) \) is the instantaneous tracer concentration over the time span \( 0, t \) of the tracer's first pass. With radionuclide studies, the input activity \( A_o \) entering a sampled region cannot be assessed by external counting. However, the ratio of the input activity \( A_o \) to the activity measured over the same region after a complete tracer dilution \( A_o \) is proportional to the total blood volume \( TBV \):

\[
TBV = \frac{A_o}{A_o} = A_o \cdot TBV \Rightarrow Q = \frac{A_o \cdot TBV}{\int_0^t A(t) \, dt}
\]

where \( A(t) \) is instantaneous activity of the sampled region. If flow through both lungs is calculated separately and pulmonary flow distribution is expressed as left to right ratio, the value of \( TBV \) is cancelled out (fig 1).

(2) In case of "competitive" pulmonary perfusion, the lung time-activity curve is composed of two peaks caused by the cavopulmonary and arterial flows. Both peaks are a reflection of the same flow, they only differ due to different input activity:

\[
\frac{A_C}{A_S} = \left( \frac{\int_0^t A_C(t) \, dt}{\int_0^t A_S(t) \, dt} \right) = \frac{\int_0^t A_C(t) \, dt}{\int_0^t A_S(t) \, dt}
\]

where \( A_C \) is input activity supplied by the cavopulmonary anastomosis, \( A_S \) is input activity supplied by arterial sources, \( A_C(t) \) and

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AVSD, anterioventricular septal defect; BCPA, bidirectional cavopulmonary anastomosis; BCPA*, left sided bidirectional cavopulmonary anastomosis; BT, Blalock-Taussig shunt; BT/OCCL, catheter occluded Blalock-Taussig shunt; BT/TH, thrombosed Blalock-Taussig shunt; contral, lung contralateral to bidirectional cavopulmonary anastomosis; DXC, dextrocardia; EBST, Ebstein's anomaly; I-MGA, I-malposition of great arteries; LPS, left pulmonary artery stenosis; LVOTO, left ventricular outflow tract obstruction; MA, mitral atresia; mitral VSD, multiple ventricular septal defect; ipsilateral lung ipsilateral to cavopulmonary anastomosis; MPA, main pulmonary artery; PDA, patent ductus arteriosus; PS, pulmonary valve stenosis; Q, blood flow; Qp, total pulmonary blood flow; RVOTO, right ventricular outflow tract obstruction; hHg, haemoglobin saturation in arterialized capillary blood; SPBF, sources of pulsatile blood flow; tr MV, straddling mitral valve; tr TV, straddling tricuspid valve; SV, single ventricle; SVA, situs viscerum ambiguus; TA, tricuspid atresia; TGA, transposition of great arteries; VI, ventricular inversion; VSD, ventricular septal defect.
Pulmonary blood supply in bidirectional cavopulmonary anastomosis

\[
\frac{Q_c}{Q_a} = \frac{A_c}{A_a} = \frac{\int_{0}^{\infty} A_c(t) dt}{\int_{0}^{\infty} A_a(t) dt}
\]

Knowing the left to right pulmonary flow ratio and the ratio of cavopulmonary to arterial blood flow supply for both the lungs, the overall (left and right) cavopulmonary to arterial supply ratio is easily calculated.

**Pilot study**

**METHODS**

First pass radionuclide angiocardiography was performed in the anterior view using \(^{99m}\)Tc in dose 435 MBq per m\(^2\) of body surface area. Stannous pyrophosphate 0·25 mg/kg was given 20 min before the radionuclide injection to provide in vivo erythrocyte labelling. The red blood cells labelling keeps \(^{99m}\)Tc within the circulation. This is essential for the proper measurement of equilibrium lung activity used for the flow calculations. A bolus of the radionuclide was injected into a superior vena caval supply, preferably the external jugular vein. In all cases a vein contralateral to the BCPA was used, so that no cavo-caval anastomoses were missed.14 The time-activity curves were constructed separately for each lung. Care was taken to construct regions of interest so that parts of lungs overlapping with the heart and great vessels were not included.

**PATIENTS**

Pulmonary blood supply was studied in 18 patients with BCPA and sources of pulsatile blood flow. Eight (44%) had to be excluded because cavo-caval collaterals were found on radionuclide angiography. In the remaining 10 patients, 12 studies were performed at the age of 2·5 to 25·3 years (median 7·25), 0·2 to 8·1 years (median 1·4) after the BCPA (table). Two of the patients were studied twice. Patient No 1 developed superior vena cava syndrome and cardiac failure two months after the BCPA. These problems were believed to be related to a high flow through a Blalock-Taussig shunt and stenotic pulmonary valve.

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**Figure 2.** Calculation of ratio of caval to arterial blood supply to each lung (see text). \(C\), area under the caval portions of the time-activity curves; \(A\), area under the arterial portions of the time-activity curves; \(\text{imp}^s\), impulses per second.

\(A_c(t)\) are instantaneous activities throughout the cavopulmonary and arterial peaks and \(tC0, tC, tA0, tA\) are the time spans of those peaks. This rather complicated equation simply states that areas under the both peaks are proportional to the respective input activities.

As the tracer is divided into branching vessels proportionally to the blood flow distribution, the input activities are proportional to the cavopulmonary and arterial flows respectively. Accordingly the ratio of cavopulmonary \(Q_c\) to arterial flow \(Q_a\) is proportional to the areas ratio (fig 2):

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**Table continued**

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The Blalock-Taussig shunt was occluded by a detachable balloon and both the results before and after the closure are shown. In patient No 8 a progressive left pulmonary artery stenosis proximal to the Blalock-Taussig shunt was detected by echocardiography. For that reason two studies were done nine months apart.

RESULTS (table)
The BCPA provided 26–61% [mean 42-3 (SEM 3-4)%] of total pulmonary blood flow, 54–98% [75-7 (3-3)%] of flow to the ipsilateral lung, and 2–60% [24-3 (5-0)%] of flow to the contralateral lung. From the total BCPA flow, 48–96% [67-2 (4-3)%] was directed to the ipsilateral lung and 4–52% [32-8 (4-3)%] to the contralateral lung. The lung at the side of BCPA received only 6–45% [16-5 (3-3)%] of blood from the source of pulsatile blood flow and the remaining 55–95% [83-5 (3-3)%] was directed into the lung contralateral to BCPA.

Total perfusion of the ipsilateral lung was less than the contralateral lung in all the patients. The blood flow to the lung at the side of BCPA accounted for 26–47% [35-3 (1-7)%] of the total pulmonary blood flow. In patient No 1, before his Blalock-Taussig shunt was occluded, BCPA supplied 32% to the total pulmonary blood flow, 61% to the ipsilateral lung perfusion and only 13% to the perfusion of the lung at the side of the Blalock-Taussig shunt. After the Blalock-Taussig shunt was occluded, the overall contribution of BCPA to the pulmonary flow increased to 53%. The BCPA contribution to ipsilateral lung perfusion increased only slightly to 68%, while the contribution to the contralateral lung perfusion increased dramatically to 44%. Left to right lung perfusion ratio remained unchanged by the Blalock-Taussig shunt closure. In patient No 8 with a progressive left pulmonary artery stenosis proximal to the Blalock-Taussig shunt, the BCPA contribution to perfusion of the left lung decreased from 14% to 5% with progression of the stenosis, while the BCPA supply to the right lung increased from 54% to 76%. As expected, the overall contribution of BCPA to the pulmonary flow did not change. Similar values were found in another patient (No 9) with left pulmonary artery stenosis at the site of Blalock-Taussig shunt.

Discussion
Purely non-pulsatile pulmonary blood flow is associated with uneven distribution of pulmonary perfusion and development of pulmonary arteriovenous fistulae. An additional source of pulsatile flow may improve the blood distribution and prevent the formation or even lead to regression of the pulmonary arteriovenous fistulae. Too much blood coming from arterial sources may on the other hand result in increased pressure in the superior vena. This may cause development of the superior vena caval syndrome and pleural effusions early after the surgery and enhance the formation of cavo-caval collaterals. The same symptoms, however, may be caused by stenotic BCPA or increased pulmonary vascular resistance. Our method may be useful in the early postoperative assessment of patients with these symptoms and in some cases may lead to a decision to decrease the pulsatile blood flow. Our limited experience shows that in all patients without effusions or stenosis of the contralateral pulmonary artery, the relative contribution of the sources of pulsatile blood flow to the total pulmonary blood flow was below 65%.

In the Doppler study, the side distribution of BCPA diastolic flow in five patients with BCPA and sources of pulsatile blood flow (ipsilateral 67%; contralateral 33%) was identical with our results. The scintigraphy in 11 patients with BCPA and sources of pulsatile blood flow proved to have a similar distribution (65%:35%). However, neither of those two methods offers quantitative analysis of flow from the pulsatile blood flow sources.

The finding that the lung on the side of the BCPA was perfused less than the contralateral lung is somewhat surprising. It is, however, in accord with experimentally proved increased vascular resistance with non-pulsatile flow. In fact, according to our findings the ratio of ipsilateral to contralateral lung perfusion ratio remained unchanged by the Blalock-Taussig shunt closure. Indeed, our results the source of pulsatile blood flow contributed only a little (mean 24%) to the flow in the lungs on the side of the BCPA. This is only slightly above the 15% of bronchial arterial flow measured in lungs supplied by a classical Glenn anastomosis. At the same time the source of pulsatile blood flow accounted for 75% of the flow to lungs contralateral to the BCPA. These findings are in agreement with the Doppler study, documenting that in patients with BCPA and a source of pulsatile blood flow, the arterial pulse is directed to the lung contralateral to the BCPA, while BCPA flow is directed in systole to the ipsilateral lung and in diastole to both lungs.

In our 18 consecutive patients with BCPA and sources of pulsatile blood flow, cavo-caval collaterals occurred in 44%, which is higher than the reported incidence in long term survivors with an end to end Glenn anastomosis. In our patients the time since the creation of the BCPA was not a risk factor for formation of the cavo-caval collaterals as compared to 3-35 (1-60) years in those with the collaterals, P = 0.20. As the collaterals occurred earlier than in patients with classical Glenn shunt, the presence of a source of pulsatile blood flow seems to contribute to their early formation, presumably by increasing...
superior vena cava pressure. Although the cavo-caval collaterals are readily detected by the radionuclide angiography, they make quantitative analysis impossible because of fragmentation of the radiotracer bolus. This also applies to patients with bilateral BCPA. However, the pulmonary blood flow supply in these situations is so complex that a quantitative analysis would hardly be possible by any other method.

In conclusion, radionuclide angiography, unlike other non-invasive methods, offers the opportunity to measure the blood flow distribution from the BCPA as well as from the sources of pulsatile blood flow. Our preliminary results show that this method can be a valuable contribution to assessment of the cause of BCPA failure in selected patients. Further research in a larger group of patients can provide more information about variations in flow distribution in the BCPA and the sources of pulsatile blood flow, related to different sources of pulsatile flow or age. Assessment of the optimum flow proportions from the BCPA and the sources of pulsatile blood flow for the best arterial saturation with minimum side effects also requires further study.

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