Cardiology in the Young

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Original Article

Cite this article: Tucker S, Cornicelli M, Loomba R, Fox J, Wald E, and Penk J (2024) Echocardiographic measured shunt velocity does not predict pulmonary blood flow in patients with Blalock–Thomas–Taussig shunt. *Cardiology in the Young* **34**: 535–539. doi: 10.1017/S104795112300269X

Received: 27 April 2023
Revised: 27 June 2023
Accepted: 3 July 2023
First published online: 2 August 2023

Keywords:
Blalock–Thomas–Taussig shunt; pulmonary blood flow; velocity time integral

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Echocardiographic measured shunt velocity does not predict pulmonary blood flow in patients with Blalock–Thomas–Taussig shunt

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Abstract

Introduction: Catheterisation is the gold standard used to evaluate pulmonary blood flow in patients with a Blalock–Thomas–Taussig shunt. It involves risk and cannot be performed frequently. This study aimed to evaluate if echocardiographic measurements obtained in a clinical setting correlate with catheterisation-derived pulmonary blood flow in patients with a Blalock–Thomas–Taussig shunt as the sole source of pulmonary blood flow. *Methods:* Chart review was performed retrospectively on consecutive patients referred to the catheterisation lab with a Blalock–Thomas–Taussig shunt. Echocardiographic parameters included peak, mean, and diastolic gradients across the Blalock–Thomas–Taussig shunt and forward and reverse velocity time integral across the distal transverse aorta. In addition to direct correlations, we tested a previously published formula for pulmonary blood flow calculated as velocity time integral across the shunt × heart rate × Blalock–Thomas–Taussig shunt area. Catheterisation parameters included pulmonary and systemic blood flow as calculated by the Fick principle. *Results:* 18 patients were included. The echocardiography parameters and oxygen saturation did not correlate with catheterisation-derived pulmonary blood flow, systemic blood flow, or the ratio of pulmonary to systemic blood flow. As the ratio of reverse to forward velocity time integral across the transverse aorta increased, the probability of shunt stenosis decreased. *Conclusion:* Echocardiographic measurements obtained outside the catheterisation lab do not correlate with catheterisation-derived pulmonary blood flow. The ratio of reverse to forward velocity time integral across the transverse aortic arch may be predictive of Blalock–Thomas–Taussig shunt narrowing; this finding should be investigated further.

Introduction

The Blalock–Thomas–Taussig shunt continues to be a widely used surgical procedure to provide pulmonary blood flow in children with CHD. Evaluating the blood flow through Blalock–Thomas–Taussig shunts is critical during the management of these patients. While catheterisation is the gold standard for measuring pulmonary artery pressure and blood flow, it involves risk and cannot be performed frequently. Echocardiography is a widely used, low-risk, and less-invasive method of evaluating cardiac physiology and thus would be an ideal tool in the serial evaluation of pulmonary blood flow in patients with a Blalock–Thomas–Taussig shunt.

Several studies have attempted to predict pulmonary blood flow using non-invasive methods. Rychik *et al.* evaluated the ability of arterial oxygen saturation to estimate the ratio of pulmonary to systemic blood flow and found that it was not an accurate predictor of the ratio of pulmonary to systemic blood flow.[1] Others evaluated the use of Doppler ultrasonography to estimate various parameters within Blalock–Thomas–Taussig shunts. Pulmonary artery pressure is one parameter that has been evaluated with varying results. DeGroff *et al.* conducted an in vitro study that showed that Doppler ultrasonography both underestimated and overestimated pressure gradients across Blalock–Thomas–Taussig shunts, depending on the location of stenosis within the shunt.[2] Tacy *et al.* showed that Doppler ultrasonography-derived pulmonary artery pressures obtained using the simplified Bernoulli equation underestimated pulmonary artery pressures obtained in the catheterisation lab if the Blalock–Thomas–Taussig shunt diameter was ≤5 mm.[3] Faherty *et al.* evaluated the use of echocardiography to predict the ratio of pulmonary to systemic blood flow in patients with atrial septal defects and found that echocardiography did not correlate well with catheterisation-derived ratios of pulmonary to systemic blood flow and tended to overestimate the degree of left to right shunting.[4]

Chaudhari *et al.* conducted a study in which Doppler ultrasonography and cardiac catheterisation were performed simultaneously. The study found that a Doppler ultrasonography-derived calculation that also included heart rate and shunt area was able to estimate pulmonary blood flow and this correlated well with catheterisation-obtained pulmonary blood flow ($r = 0.9$, $SE = 0.19$).[5] Peak velocity within the shunt, which is used by some to estimate pulmonary blood flow, did not correlate with pulmonary blood flow. This finding is particularly relevant as monitoring pulmonary blood flow with echocardiography could allow serial measures of pulmonary blood flow and more frequent clinical correlation. Unfortunately, this study was done in the catheterisation lab under exactly the same conditions as the catheterisation. A more clinically relevant comparison would be to see if, using similar techniques, we can predict catheterisation based pulmonary blood flow *outside* of the catheterisation lab.

The purpose of this study is to evaluate whether or not Doppler ultrasonography-obtained shunt measurements and pulse oximetry correlate with pulmonary blood flow in patients with a Blalock–Thomas–Taussig shunt as the sole source of pulmonary blood flow. Most importantly this study will evaluate the formula tested by Chaudhari *et al.* to see if it can predict pulmonary blood flow obtained prior to catheterisation, as opposed to echocardiography and catheterisation variables obtained simultaneously. Predicting and monitoring pulmonary blood flow during routine echocardiograms would be very clinically useful given the ease with which these measurements can be obtained and the frequency with which they can be evaluated.

Materials and methods

Study design

This was a single-centre, retrospective study. This study was approved by the institutional review board and is in concordance with the Helsinki Declaration.

Patient identification

Our study included patients with a Blalock–Thomas–Taussig shunt as the only source of pulmonary blood flow. Children with an echocardiogram performed within 3 weeks of their cardiac catheterisation procedure were included. The cut-off of 3 weeks was chosen as a convenience sample to maximise the number of patients included in the study yet also be close enough to the time of catheterisation to be unlikely to have significant changes during that time period. Patients over the age of 18 years and those who did not have measurements needed to calculate pulmonary blood flow during cardiac catheterisation were excluded.

Variables of interest

The following data were collected for each patient: primary cardiac diagnosis, gender, body surface area, height at the time of catheterisation, weight at the time of catheterisation, age at catheterisation, and oxygen saturation by pulse oximetry prior to catheterisation lab anaesthesia. The following echocardiographic data were measured by a study investigator retrospectively: peak gradient across the shunt, mean gradient across the shunt, diastolic gradient across the shunt, forward velocity time integral in the distal transverse aorta, reverse velocity time integral in the distal transverse aorta, size of the transverse aorta, and heart rate at the time of Doppler ultrasonography acquisition.

The following were calculated from the echocardiographic data: pulmonary blood flow was calculated as the velocity time integral across the shunt × heart rate × shunt area, as was done in the Chaudhari *et al.* study. Systemic blood flow was calculated as the forward velocity time integral across the aorta × heart rate × area of the transverse aorta. The ratio of the reverse to forward velocity time integral in the aorta was also calculated.

The following catheterisation data were collected: haemoglobin at the beginning of catheterisation, pulmonary blood flow as calculated by the Fick principle, systemic blood flow as calculated by the Fick principle, and presence of any visualised stenosis or thrombosis in the shunt.

The ratio of pulmonary to systemic flow was calculated from the catheterisation data.

Statistical analyses

Bayesian statistics were used for the analyses. Bayesian, rather than frequentist statistical tests were utilised as they allow for more robust modelling with probabilities for various models, modelling the same dependent variable being quantified. Not only are probabilities for the models themselves quantifiable but so is the probability of various states of the dependent variable. Additionally, the probability of each independent variable being included in the resulting models can also be quantified. This level of quantification allows for robust, reproducible models to be determined. Large scientific organisations, including the American Heart Association and American College of Cardiology, have advocated for the use of Bayesian statistics. Further explanation of Bayesian statistics is beyond the scope of this manuscript and can be found elsewhere.

Correlation analyses were run initially to determine the correlations between patient characteristics and echocardiographic parameters to catheterisation based measurements of pulmonary blood flow, systemic blood flow, and the ratio of systemic to pulmonary blood flow.

Next, a Bayesian linear regression was conducted with catheterisation-based measurement of pulmonary blood flow as the dependent variable and all echocardiographic parameters entered as independent variables. The top 10 most likely models were generated using the Jeffreys–Zellner–Siow posterior as no previously published data allowed for generation of such a posterior.

Next, a similar Bayesian linear regression was conducted with catheterisation based measurement of systemic blood flow as the dependent variable. Next, a similar Bayesian linear regression was conducted with the ratio of pulmonary to systemic blood flow as the dependent variable.

Finally, a Bayesian analysis of covariance was conducted with evidence of shunt stenosis by catheterisation as the dependent variable.

All statistical analyses were done utilising JASP Version 0.16 (Amsterdam, Netherlands).

Results

Cohort characteristics

In total, 27 patients with a Blalock–Thomas–Taussig shunt as the sole source of pulmonary blood flow were selected, though nine

Table 1. Cohort characteristics.

Primary cardiac diagnosis	
Double outlet right ventricle	5
Atrioventricular septal defect	4
Pulmonary atresia	2
Hypoplastic left heart syndrome	6
Double inlet left ventricle	1
Age (days)	130.5 ± 58.0
Weight (kg)	5.6 ± 1.9
Height (cm)	59.8 ± 8.1
Body surface area (m^2)	0.29 ± 0.07

Table 2. Catheterisation and echocardiographic data.

Catheterisation data	
Catheterisation measured pulmonary blood flow (L/min/m^2)	5.4 ± 1.8
Catheterisation measured systemic blood flow (L/min/m^2)	3.3 ± 0.8
Catheterisation based ratio of pulmonary to systemic blood flow	1.6 ± 0.7
Echocardiographic data	
Peak systolic gradient across shunt (mmHg)	53.8 ± 17.5
Mean systolic gradient across shunt (mmHg)	29.0 ± 9.5
Diastolic gradient (mmHg)	11.7 ± 4.7
Velocity time integral across shunt	1.0 ± 0.2
Forward velocity time integral across transverse aortic arch	0.25 ± 0.09
Reverse velocity time integral across transverse arch	0.10 ± 0.03
Ratio of reverse to forward velocity time integral across the transverse arch	0.43 ± 0.12
Echocardiographic estimate of systemic blood flow (L/min/m^2)	5.0 ± 2.7
Echocardiographic estimate of pulmonary blood flow (L/min/m^2)	1.9 ± 0.8

patients were excluded due to limited catheterisation or echocardiography data. Eighteen patients were included in the final analyses. The mean body surface area was 0.29 m^2. The most common principle cardiac diagnosis was hypoplastic left heart syndrome noted in six (33%) patients (Table 1). Three patients had visible shunt stenosis noted in the catheterisation lab and one of these underwent balloon dilation. Table 2 contains the means and standard deviations of the catheterisation and echocardiographic data.

Univariable correlation analyses

None of the echocardiographic parameters were found to be associated with pulmonary blood flow. Figure 1 demonstrates scatter plots for catheterisation-measured pulmonary blood flow and echocardiographic estimates of pulmonary blood flow, peak systolic gradient across the shunt, velocity time integral across the shunt, and reverse velocity time integral across the transverse aorta.

Figure 1 depicts scatter plots of a) catheterisation-derived pulmonary blood flow versus echocardiography-derived pulmonary blood flow; b) catheterisation-derived pulmonary blood flow versus Doppler-obtained peak gradient across the Blalock–Thomas–Taussig shunt; c) catheterisation-derived pulmonary blood flow versus reverse velocity time integral across the distal transverse aorta; and d) catheterisation-derived pulmonary blood flow versus velocity time integral across the Blalock–Thomas–Taussig shunt.

None of the echocardiographic parameters measured were found to be associated with systemic blood flow or the ratio of pulmonary to systemic blood flow, including the formula used by Chaudhari *et al*.

Regression analyses, pulmonary blood flow

When modelling catheterisation-based measurement of pulmonary blood flow, the most probable model was the null model at 50%. The second most probable model at 4% was 5.41–0.11 x velocity time integral across the shunt.

Across the 10 most probable models for catheterisation-based measurement of pulmonary blood flow, the velocity time integral across the shunt was the most likely to be included in these models with a 22% probability followed by the peak gradient across the shunt at 21%, mean gradient across the shunt at 21%, and diastolic gradient across the shunt at 21%.

Regression analyses, systemic blood flow

When modelling catheterisation-based measurement of systemic blood flow, the most probable model was the null model at 52%. The second most probable model had a probability of 10% and was 3.40 + 0.34 x body surface area –0.1 x peak gradient across the shunt +1.4 x area of transverse aorta.

Across the 10 most probable models for catheterisation based measurement of systemic blood flow, the peak gradient across the shunt was the most likely to be included in these models with a 28% probability followed by body surface area at 27% and area of transverse aorta at 26%.

Regression analyses, ratio of pulmonary to systemic blood flow

When modelling catheterisation-based measurement of the ratio of pulmonary to systemic blood flow, the most probable was the null model at 51%. The second most probable model had a probability of 6% and was 1.6 + 0.1 x peak gradient across the shunt –0.1 x mean gradient across the shunt –0.1 diastolic gradient across the shunt –0.2 x velocity time integral across the shunt.

Regression analyses, presence of shunt stenosis at time of catheterisation

When modelling presence of shunt stenosis by catheterisation, the most probable model at 25% was 0.12–1.1 x ratio of reverse and forward velocity time integral in the transverse aorta. The second most probable model at 14% was the null model. Blalock–Thomas–Taussig shunt stenosis was not seen on echocardiography.

To simplify the findings of the most probable model, as the ratio of the reverse and forward velocity time integral in the transverse aorta increased, the probability of visual shunt stenosis decreased.

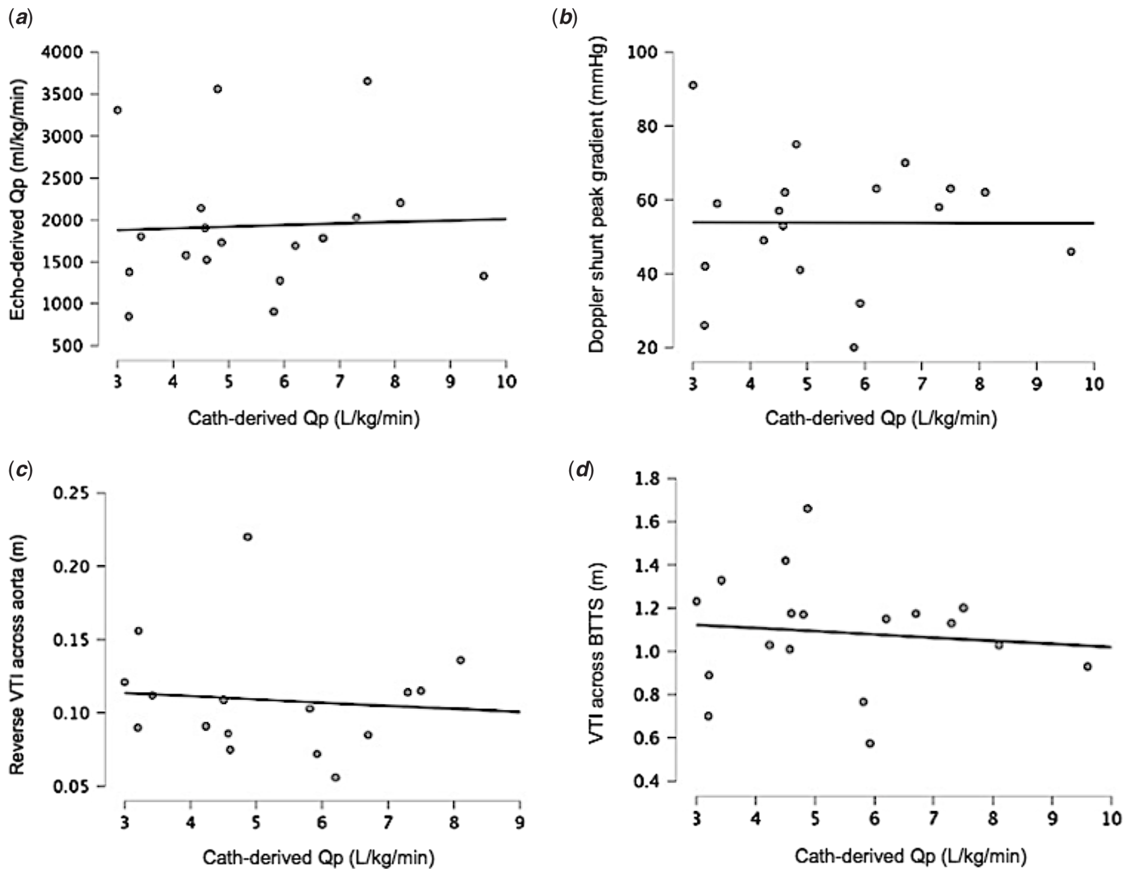

Figure 1. Scatter plots.

The receiver operator characteristic curve for reverse to forward velocity time integral and visualised shunt stenosis showed an area under the curve of 0.929 (p = 0.04). A reverse to forward velocity time integral ratio of 0.3 was 100% sensitive and 93% specific, and thus was the optimal cut-off. A ratio of 0.61 was 100% sensitive and 7% specific, and a ratio of 0.25 was 0% sensitive and 93% specific.

Across the 10 most probable models for presence of shunt stenosis by catheterisation, the ratio of the reverse to forward velocity time integral in the transverse aorta was most likely to be included in these models with a 59% probability followed by diastolic gradient across the shunt at 38% and mean gradient across the shunt at 37%.

Discussion

This study shows that echocardiography parameters including peak, mean, and diastolic gradients across the shunt, calculation of pulmonary blood flow using heart rate and shunt diameter, reverse velocity time integral across the distal transverse aorta, and velocity time integral across the shunt do not correlate well with catheterisation measurements of pulmonary blood flow, systemic blood flow, or the ratio of pulmonary to systemic blood flow in patients with a Blalock–Thomas–Taussig shunt as the sole source of pulmonary blood flow. Pulse oximetry obtained just prior to catheterisation also did not correlate with pulmonary blood flow or the ratio of pulmonary to systemic blood flow. Our results did find that as the ratio of reverse to forward velocity time integral in the distal transverse aorta decreases, the probability of Blalock–Thomas–Taussig shunt stenosis increases. This was the only echocardiographic parameter, measured in a reproducible, awake setting that yielded any information on the patency of the Blalock–Thomas–Taussig shunt and the pulmonary blood flow it provided.

Our findings are consistent with several other studies. Tacy *et al.* demonstrated that Doppler ultrasonography-predicted pressure gradients (using the modified Bernoulli equation) underestimated the actual pressure gradients, and that the Doppler ultrasonography predictions became more unreliable as the shunt diameter decreased, likely due to viscous losses that are not accounted for in the modified Bernoulli equation. For 5 mm diameter Blalock–Thomas–Taussig shunts, the mean error was −25% ± 10%.[3] Similarly, Chaudhari *et al.* showed a poor correlation between Doppler-derived mean pulmonary artery pressure calculated with peak and mean flow velocity and the mean pulmonary wedge pressure.[5] Rychik *et al.* demonstrated a strong correlation between the ratio of reverse and forward velocity time integral across the distal transverse aorta and the ratio of pulmonary to systemic blood flow ($R^2 = 0.94$, $p < 0.001$).[1] It is important to note that Rychik's measurements were performed simultaneously, similar to how Chaudhari's echocardiographic and catheterisation measurements were nearly simultaneous. We did not reproduce Rychik's finding in our cohort as our measurements were done at separate times. However, we did find a related relationship in that as the ratio of reverse to forward velocity time integral decreases, the probability of shunt stenosis increases. The presence of shunt stenosis likely reduces pulmonary blood flow, which in theory causes less reversal of flow in the aorta and thus a lower ratio of reverse to forward velocity time integral.

https://doi.org/10.1017/S104795112300269X Published online by Cambridge University Press

The study conducted by Chaudhari *et al.* compared Doppler ultrasonography estimates of pulmonary blood flow (using the formula Doppler-derived pulmonary blood flow = heart rate × velocity time integral × shunt area) to cardiac catheterisation estimates of pulmonary blood flow and concluded that there was a positive correlation ($r = 0.9$, $SE = 0.19$).[5] In contrast, our study demonstrates no correlation between Doppler ultrasonography and cardiac catheterisation estimates of pulmonary blood flow. One potential explanation for this discrepancy is that in the Chaudhari *et al.* study, Doppler ultrasonography was performed simultaneously with cardiac catheterisation, whereas in our study, Doppler ultrasonography was performed prior to catheterisation. Though their Doppler ultrasonography and catheterisation parameters were measured under the same haemodynamic conditions, this method has limited clinical utility as the patients have already undergone anaesthesia and the gold standard catheterisation parameters are about to be obtained anyway. Moreover, the Chaudhari *et al.* study excluded patients with Blalock–Thomas–Taussig shunt stenosis found during cardiac catheterisation, but in the clinical setting, the presence of shunt stenosis may not be known at the time of echocardiography. Additionally, the ability to detect possible shunt stenosis from serial echocardiography would be extremely valuable.

In clinical practice, echocardiography is often used to estimate pulmonary blood flow in patients with a Blalock–Thomas–Taussig shunt as the only source of pulmonary blood flow. Our data show that this may not be appropriate, as Doppler has not been shown to accurately predict pulmonary blood flow. Our study most importantly shows that the ratio of reverse to forward velocity time integral may predict shunt narrowing, though the strength of this association is limited by the small sample size of three patients with stenosis. This is a finding that warrants further investigation as it would be a vital non-invasive tool in the evaluation of patients with Blalock–Thomas–Taussig shunts.

There are some limitations to the study. The study was retrospective, so some echocardiography measurements may not have been obtained with the same precision as they would have if they were being intentionally evaluated. For example, velocity time integral is an important measurement that can vary significantly depending on the angle at which the image was obtained. There were up to three weeks of time elapsing between the echocardiograms and catheterizations, which means that the pulmonary or systemic blood flow could have changed within that time period, though this is a realistic clinical scenario. The small sample size is an additional limiting factor. Finally, it is worth noting that this study only included patients with Blalock–Thomas–Taussig shunts, and the results, therefore, should not be generalised to patients with other types of aorto-pulmonary shunts such as Sano conduits or patent ductus arteriosus stents.

In conclusion, echocardiography parameters do not correlate well with catheterisation-based measurements of pulmonary blood flow, systemic blood flow, or the ratio of pulmonary to systemic blood flow when not measured simultaneously in patients with a Blalock–Thomas–Taussig shunt as the sole source of pulmonary blood flow. The ratio of reverse to forward velocity time integral across the distal transverse aortic arch may be predictive of Blalock–Thomas–Taussig shunt narrowing; this is a finding that should be investigated further.

Acknowledgements. None.

Financial support. This research has received no specific grant from any funding agency, commercial, or not-for-profit sectors.

Competing interests. None.

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