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# Blood speckle imaging: A new echocardiographic approach to study fluid dynamics in congenital heart disease

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ABSTRACT

*Introduction:* Blood speckle imaging (BSI) is a new speckle-tracking-based technique for blood flow study. Flows assessment is particularly challenging in Congenital heart diseases (CHDs), where a profound distortion in cardiac anatomy gives reason of alteration in fluid mechanics. Up until now doppler methods were the only ones used for the analysis of fluid. Overcoming standard Doppler limits, BSI is becoming a promising new approach for the study of fluid dynamics.

The aim of the study was to assess fluid-dynamics of different CHDs by using BSI.

*Methods and results:* Ten children (7 with suspected CHDs and 3 controls) were enrolled for the purpose between January and June 2019. All of them underwent a complete 2D and Doppler echocardiographic assessment plus a further BSI study. We studied: one complex transposition of great arteries, one coarctation of aorta, one tetralogy of Fallot, one complete atrio-ventricular septal defect, one suspicious flow in pulmonary artery, one aortic stenosis, one hypertrophic cardiomyopathy and three normal controls.

*Conclusion:* Compared to conventional Doppler methods, BSI was able to better describe fluid dynamics and hemodynamics of these CHDs by showing laminar and turbulent flows and vortices. In our experience, it helped to define the diagnosis and, in some cases, drove the management.

## 1. Introduction

Congenital heart diseases (CHD) are often characterized by complex anatomy with wide alterations in hemodynamics and fluid-dynamics [1]. Understanding key fluid-dynamic patterns may be of value for a better definition of physiology, and may help the diagnosis and therapeutic management [2].

Traditionally, blood flow representation has been obtained through Doppler ultrasound by combining color-coded velocities together with B-mode images. Blood Speckle Imaging (BSI) is a new speckle-tracking-based technique that analyzes blood flow by tracking the movement of blood speckles [3]. This approach permits a direct angle-independent assessment, that does not require any contrast agents and is free of aliasing artifacts [4].

BSI allows the visualization of the different flow components: laminar flow, turbulent flow and vortices. Vortices are fluid structures with circular or swirling motion spinning around a virtual central axis [5]; described for the first time by Leonardo da Vinci, they are ubiquitariously present in nature wherever a fluid is flowing. Using vortices nature moves large masses of fluid preserving low cavity-walls pressure and saving kinetic energy [6].

Thus, the aim of the study was to evaluate fluid mechanics of different CHDs by using BSI and if that could improve CHDs diagnosis and management.

## 2. Methods

This study enrolled seven paediatric patients with defined or suspected CHDs, who were admitted at Royal Brompton Hospital of London

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[1] This author takes responsibility for all aspects of the reliability and freedom from bias of the data presented and their discussed interpretation.

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**Abbreviation list**

| | |
|---|---|
| CHD | Congenital heart disease |
| BSI | Blood Speckle Imaging |
| TGA | Transposition of great arteries |
| CoA | Coarctation of the aorta |
| TOF | Tetralogy of Fallot |
| AVSD | Atrio-ventricular septal defect |
| HCM | Hypertrophic Cardiomyopathy |
| VSD | Ventricular septal defect |
| PDA | Patent ductus arteriosus |
| ASO | Aterial Switch Operation |
| PV | pulmonary valve |
| CW | Continuous wave |
| LVOT | Left ventricle outflow tract |
| RVOT | Right ventricle outflow tract |
| AV | Atrio-ventricular |

between January 2019 and June 2019. A three-patients normal control population was also enrolled among children who were referred for chest pain and reveled to have normal cardiac anatomy and function.

All the studied patients underwent a complete 2D and color doppler echocardiography and a further BSI evaluation. Echocardiographic recordings were obtained using GE E95 ultrasound machine (GE Healthcare, Wauwatosa, WI) with electrocardiographic tracing and stored digitally. For BSI analysis, we used Neonatal and Paediatric presets for the 6S-D and 12S-D probes. Data were acquired while in conventional color Doppler mode at a depth <10 cm [3] and using a 60 cm/s color scale velocity. The BSI loops were acquired at very hight frame rate and then recalled to show the blood flow trajectories [2]. The images were analyzed by two blinded physicians.

Informed consent was obtained from parents of each patient. The study protocol conforms to the ethical guidelines of the 1975 Declaration of Helsinki. This study was approved from the local research committee.

## 3. Results

During the six months study period, seven paediatric patients (1 female, 6 males) were analyzed by BSI for the study purpose. We analyzed: one patient with transposition of great arteries (TGA), one patient with coarctation of aorta (CoA), one patient with tetralogy of Fallot (ToF), one patient with complete atrio-ventricular septal defect (AVSD), one patient with a suspicious flow in pulmonary artery, one patient with aortic stenosis, one patient with hypertrophic cardiomyopathy (HCM). Three normal children were also studied for comparisons.

- *Complex d-TGA* (Fig. 1, A-D; video 1): in presence of d-TGA, Ventricular septal defect (VSD) and no pulmonary stenosis, BSI demonstrated a central laminar flow across the unobstructed left outflow tract with no turbulences and no vortex appearing in the main

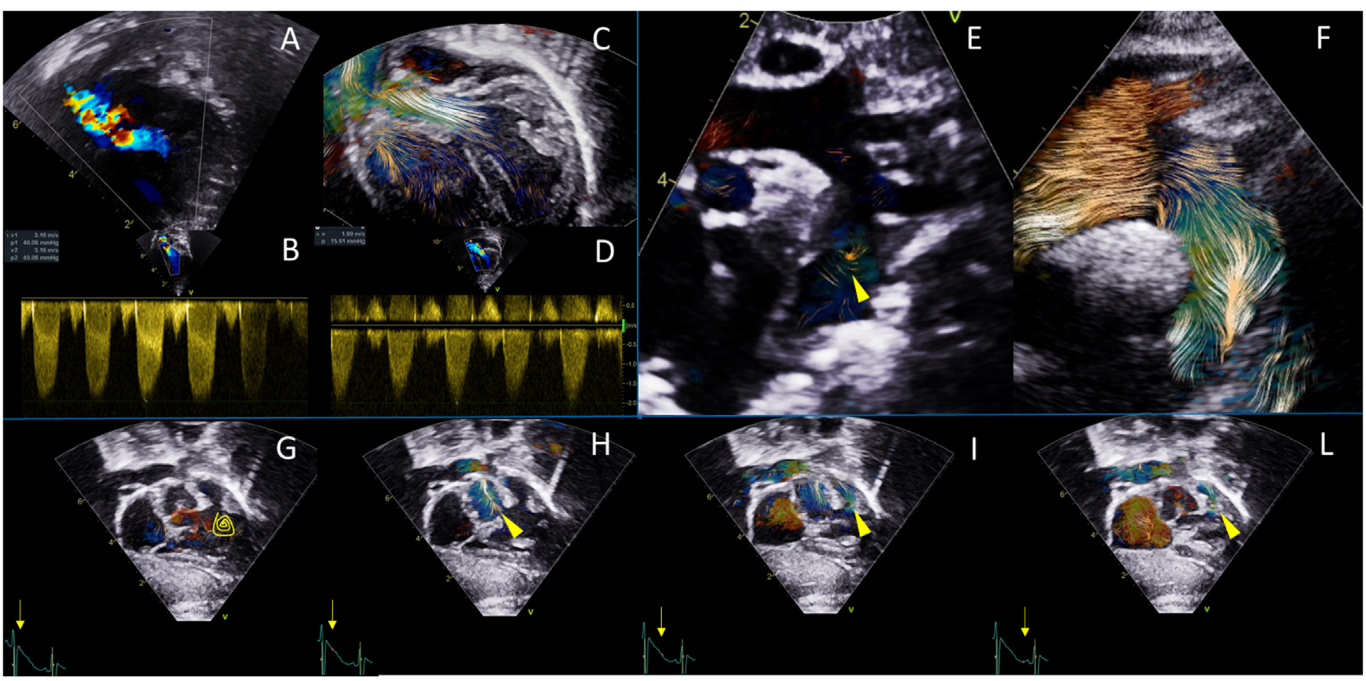


**Fig. 1. BSI analysis in TGA, CoA and ToF.**
Subcostal five-chambers view on standard color-Doppler echocardiography of TGA patient (A) showing a pre-operatively aliasing trough the PV. Picture B shows the preoperative CW Doppler on PV (peak gradient 40 mmHg). Still before surgery, BSI analysis on subcostal five-chambers (C) demonstrated laminar flow at the level of the LVOT and at the level of the PV suggesting the increased gradient on CW Doppler was only due to left to right shunt rather than a real stenosis. After ASO and VSD closure, the neo-aortic valve (original PV) did not have any gradient at the CW Doppler interrogation (D), confirming LVOT was free of stenosis.
Suprasternal view on BSI echocardiographic assessment of a patient with CoA (E) showing turbulent flow through the aortic isthmus, while a small vortex was demonstrated at the level of the post-stenotic dilatation (point of arrow). The same view in a patient with normal aorta (B) demonstrating laminar blood flow without any vortices along descending aorta.
From subcostal approach, on right anterior oblique view of a patient with ToF, BSI images were captured while in different cardiac cycle frames (a yellow arrow indicates the particular cardiac cycle time). During isovolumetric contraction, a vortex could be demonstrated just below the main arteries (yellow cycle) (F), subsequently laminar blood flow entered the aorta and turbulent flow entered the pulmonary artery (G, H), finally, persistent blood flow could be demonstrated through the stenotic RVOT during early diastole (I).
BSI, blood speckle imaging; TGA, transposition of great arteries; CoA, coarctation of aorta; ToF, tetralogy of Fallot; PV, pulmonary valve; CW, continuous wave; LVOT, left ventricle outflow tract; ASO, arterial switch operation; VSD, ventricular septal defect; RVOT, right ventricle outflow tract.

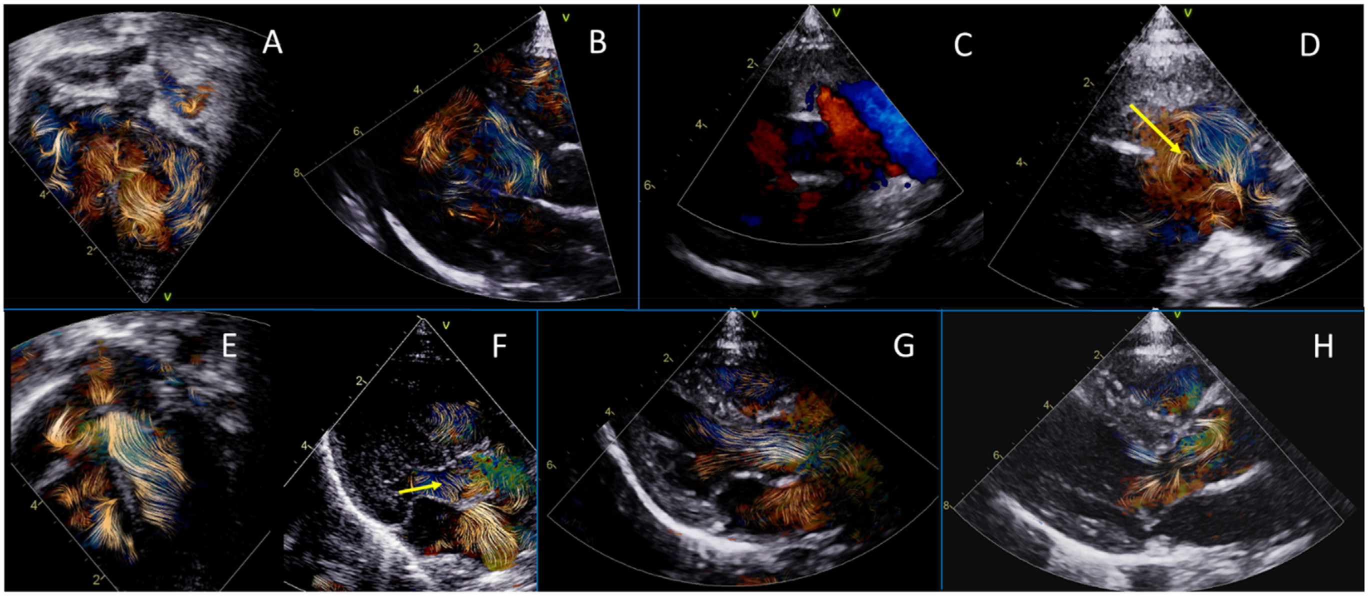


**Fig. 2. BSI analysis in AVSD, suspicious flow in pulmonary artery, aortic stenosis, HCM.**
The BSI apical five-chambers view of patient with AVSD showed vortex formation during diastole. A big apical vortex could be demonstrated, while the posterior basal vortex was smaller (A). Because of the abnormal morphology of the common AV valve, the main vortex is formed at the apical level. Of note the globular shape of the apex in the AVSD patient. Figure B shows the same process in parasternal long-axis view of a normal patient. In this case, the vortex is formed anteriorly to the anterior mitral valve leaflet and is directed to the LVOT.
Parasternal short axis view at level of pulmonary artery showing large reversal flow (red at color-Doppler) (C). On the same view BSI interrogation showed a vortex in the main pulmonary artery (arrow) (D). This is a functional phenomenon generated by recirculation of flow hitting pulmonary walls. This flow can be source of misinterpretation and can be wrongly labeled as a PDA or a moderate pulmonary regurgitation.
Parasternal long axis views of BSI analyses showing turbulent flow through a stenotic aortic valve with a vortex just above the aortic plane (E, F), laminar flow through a normal aortic valve (G), and, in mid-systole, blood flow hitting the anterior mitral valve leaflet of an HCM (H).
BSI, blood speckle imaging; AVSD, atrio-ventricular septal defect; HCM, hypertrophic cardiomyopathy; AV, atrio-ventricular; LVOT, left ventricular outflow tract; PDA, patent ductus arteriosus.

pulmonary artery arising from left ventricle, despite the presence of a significant gradient at traditional Doppler assessment.

- *CoA* (Fig. 1, E-F; video 2)*:* BSI allowed the visualization of turbulent flow across the aortic narrowed isthmus and a flow vortex just downstream the aortic coarctation. These findings were not present in a normal aorta at BSI interrogation.
- *ToF* (Fig. 1, G-L; video 3): Blood flow was traced using BSI. We could demonstrate vortices, laminar, turbulent and persistent flow during the different cardiac cycle phases.
- *Complete AVSD* (Fig. 2, A-B; video 4): Blood flow pattern and vortex formation through normal mitral valve is widely described in previous studies [5,7–9]. The profound distortion of left AV valve apparatus of AVSD patients gives reason of changes in vortexes conformation during diastole. BSI allowed the visualization of these flow patterns.
- *Suspicious flow in pulmonary artery* (Fig. 2, C-D)*:* a reversal red flow at standard color-doppler evaluation was suspicious for patent ductus arteriosus (PDA) presence. BSI demonstrated the triviality of the phenomenon.
- *Aortic stenosis* (Fig. 2, E-G): turbulent flow with a vortex was imaged by BSI. A normal patient was also studied for comparison.
- *HCM* (Fig. 2, H): In presence of asymmetrical septal hypertrophy, during mid-systole, blood flow was demonstrated heading and hitting the anterior mitral valve leaflet. This flow possibly contributed to the mitral valve regurgitation mechanism.

## 4. Discussion

In this study we used a novel technique, BSI, to analyses the fluid-dynamic of different congenital cardiopathies. BSI gave an estimation of blood velocity vectors by tracking the movement of blood speckles, resulting from constructive and destructive interference from the blood backscattered echoes [10]. In our experience, it helped the diagnosis and the management of the disease by clarifying the nature of doppler gradient, visualizing a challenging aortic isthmus coarctation and showing blood flow direction and vortices localization.

Doppler standard techniques have, indeed, many limitations, like angle dependency and Nyquist velocity limit responsible of aliasing artifacts. BSI overcame these limitations by directly following blood speckles. Moreover, doppler derived gradients are flow related and color Doppler methods, per se, are not able to properly discriminate a real stenosis from a volume mismatch.

In patients with complex d-TGA, for example, an increased flow across the pulmonary valve secondary to a large VSD may be responsible for a Doppler gradient at the level of pulmonary valve, not reflecting a real pulmonary valve stenosis. In our case, BSI assisted the diagnosis recognizing a volume overload from a real pulmonary stenosis with implication on surgical management. A simple Arterial Switch Operation (ASO) procedure with VSD closure was, indeed, chosen, avoiding a more complex Rastelli interventions.

Furthermore, direct vortices visualization and turbulent flow recognition supported the diagnosis in some cases.

In neonatal period in presence of PDA, CoA diagnosis is one of the most challenging. BSI, with its ability of showing vortices in proximity of coarctation and turbulent flow across the isthmus, gave further clues making the diagnosis clearer.

Visualizing a vortex in the main pulmonary artery generated by recirculation of flow, BSI explained a red backward flow at color-Doppler evaluation and definitely excluded a diagnosis of PDA.

In the HCM patient, a possible mechanism of mitral regurgitation was also hypothesized with the help of BSI.

## 5. Conclusion

BSI defined fluid mechanics by showing turbulent flow, laminar flow and vortices. In our experience, the availability of a technique able to overcome standard Doppler limitations, supporting direct blood flow visualization and allowing discrimination between the different components of flow, was of clinical value for the assessment, the management and the understanding of hemodynamic of CHD patients.

## Credit author statement

Nunzia Borrelli: Writing Original Draft, Methodology, Formal analysis. Martina Avesani: Visualization, Investigation. Jolanda Sabatino: Data Curation, Validation. Aladino Ibrahim: Software, Validation. Manjit Josen: Resources. Josefa Paredes: Resources. Giovanni Di Salvo: Project administration, Writing - Review & Editing, Supervision.

## Declaration of competing interest

The Authors declare no conflicts of interest.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijcchd.2021.100079.

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