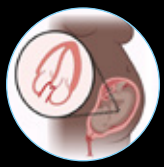
ISSUE #2

JANUARY 2025

NORTHH MEDICAL

BEATING HEARTS

THE WORLD OF FETAL CARDIAC MRI



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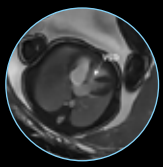
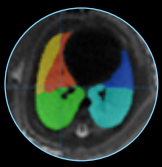
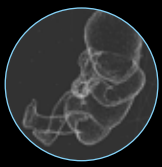


CLINICAL CASES



FETAL MRI POST PROCESSING



FUTURE FOCUS

WELCOME

Dear Friend of Fetal Cardiac MRI,

Welcome to the latest edition of *Beating Hearts*, our magazine dedicated to sharing the most recent advancements, insights, and stories from the world of fetal cardiac MRI (CMR). At Northh Medical, we are proud to lead innovation in prenatal diagnostic of congenital heart diseases (CHDs). With *smart-sync*, our mission is to empower healthcare professionals with the tools and knowledge to make informed decisions for optimal patient outcomes using MRI.

This past year has been a remarkable journey for *smart-sync*, reaching about 90 healthcare institutions worldwide. Such progress is only possible through the dedication of clinicians, researchers, and technicians who are continuously pushing the boundaries of fetal cardiac care.

In this edition, we highlight the current status of fetal CMR, share experiences from our users, present impactful clinical cases, and introduce cutting-edge advancements like our new post processing platform that is dedicated to make fetal MRI easier. We also share a glimpse into future developments shaping the field.

As we enter another exciting year, we want to emphasize that *Beating Hearts* is more than just a magazine—it's a platform for connection and collaboration.

Your insight and contribution is invaluable, and we encourage you to engage with us as we continue to drive progress together.

Thank you for your continued trust and support. Let's shape the future of fetal cardiac care—together.

Warm regards,
Your Northh Medical Team

Cover image and left top image on the back provided by the Children's Hospital Colorado fetal team (deep learning development and rendering: Takashi Fujiwara PhD, Sungho Park PhD); **Right small image on title page** by van Amerom, Joshua; Saini, Brahmdeep (2020). Fetal MRI Segmentation, Mesh Rendering. **Images on the back page** are provided by Prof. Guillaume Gorincour, Foundation LUMIERE, ELSAN Clinique Bouchard, Image and the team of Eric Schrauben, Amsterdam UMC, Netherlands

CONTENT

STATUS REPORT: THE GROWING ROLE OF FETAL CMR

Transforming prenatal cardiovascular care through innovation and collaboration

The field of fetal CMR is experiencing significant growth, driven by advancements in technology and an increasing number of healthcare institutions adopting specialized devices. As of 2024, the number of institutions equipped with *smart-sync*, the Doppler-Ultrasound fetal CMR gating technology, has risen to 90, highlighting its expanding role in prenatal diagnostics *(Figure 1)*. Recent studies have further solidified fetal CMR as an important tool in the understanding and management of CHDs[1-3].

Fetal CMR offers key advantages over traditional ultrasound, such as overcoming poor acoustic windows and reducing operator dependency. This allows for comprehensive assessments of cardiac volumes, flow dynamics, and extracardiac anomalies, significantly improving both prenatal and postnatal management of CHDs[1-3]. Advancements in technology, such as 4D-flow MRI and 3D volume reconstructions, have greatly enhanced diagnostic accuracy for these defects[4-6]. For example, Friesen et al. demonstrated the utility of these methods in diagnosing coarctation of the aorta (CoA)[4], while Englund et al. emphasized the reliability of 4D-flow MRI for analyzing third-trimester hemodynamics[5]. Additionally, Barough et al. advanced myocardial health assessment using Doppler ultrasound gating and feature tracking[7].

The clinical integration of fetal CMR continues to grow, as highlighted in reviews by Cundari et al. and Suchá et al., which underline its increasing use as a second-line imaging modality for CHDs[2,3]. These studies confirm that fetal CMR provides diagnostic insights that ultrasound alone cannot achieve. With its rising adoption and ongoing technological progress, fetal CMR is transitioning from research to clinical practice, firmly establishing its role in prenatal cardiovascular care.

Figure 1: Worldwide distribution of hospitals performing fetal CMR with *smart-sync*.

Customer Feedback: Current Trends and Applications

To gain insights into the status and clinical applications of fetal CMR, we gathered extensive feedback from active users. Key findings include:

- **Clinical Applications:** A majority of centers (60%) now integrate fetal CMR into both research and clinical workflows. Clinical-only use is reported by 20% of centers, while the remaining 20% focus solely on research.
- **Frequency of Use:** Usage varies significantly. High-frequency centers (1–4 scans per week) represent 35%, followed by medium-frequency users (18%, every 2–4 weeks), low-frequency users (26%, every few months), and very low-frequency users (21%, no or minimal scans).
- **Diagnostic Applications:** *smart-sync* technology is recommended for diverse diagnostic purposes, particularly:
  - Malformations of great vessels, such as CoA and aortic arch anomalies.
  - Hypoplastic left heart syndrome (HLHS).
  - Assessment of extracardiac structures.
  - Functional analysis, including heart function, blood flow, and dynamic imaging.

Encouragingly, 47% of users reported a direct impact of fetal CMR on diagnostics or treatment, while another 47% anticipate future impact. Only 6% reported no observed impact, emphasizing strong confidence in the technology's potential.

Addressing Imaging Challenges

Achieving consistently high image quality remains a critical barrier to broader adoption. Customer feedback *(Figure 2)* indicates that suboptimal imaging often limits the performance and utility of fetal cardiac scans. To address this, we prioritized educational efforts in the past year.

Under the leadership of MRI application specialist Domenico Gullà, these initiatives included on-site visits to optimize imaging protocols and tailor sequences to individual scanner setups. Additionally, we developed a vendor-independent guidance document

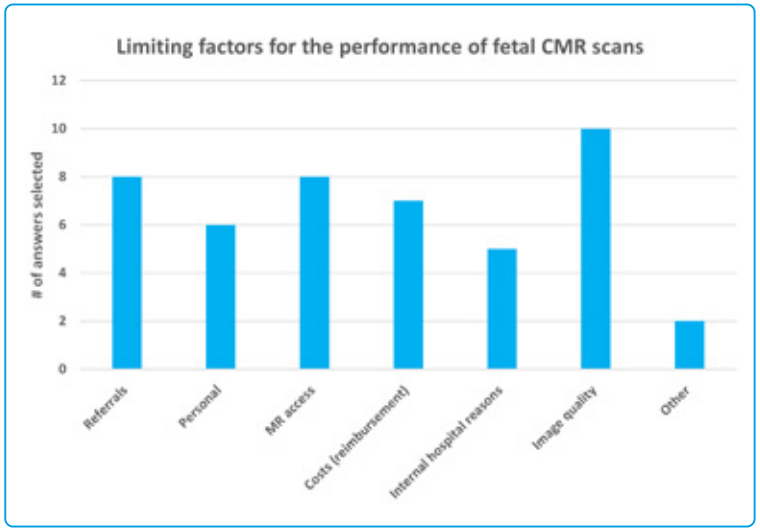


Figure 2: Customer feedback highlights key factors limiting the performance of fetal CMR scans.

(Figure 3) to help standardize protocols and improve image quality. We have made a wealth of training materials available for our customers at www.northh.de.

These efforts have boosted examination frequency and enhanced the clinical utility of fetal CMR. However, challenges remain, particularly in improving motion compensation techniques and identifying optimal imaging strategies for specific CHDs. Continued collaboration and innovation are essential to overcome these obstacles and make technology universally accessible.

Future Prospects

Despite existing challenges, the outlook for fetal CMR is overwhelmingly positive. Based on customer feedback, 80% expressed confidence that fetal CMR will play a significant role in the future, while the remaining 20% showed cautious optimism. Not a single customer doubted its potential impact.

This optimism highlights the transformative potential of fetal CMR in prenatal care. Through continued innovation, education, and collaboration, we are poised to make this technology an indispensable tool in diagnosing and managing congenital heart conditions.

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3 Suchá et al., "Fetal Cardiovascular Magnetic Resonance: History, Current Status, and Future Directions", Journal of Magnetic Resonance Imaging, 2024
4 Friesen et al., "Predictive Capability of Fetal 4D Flow and Black Blood Slice to Volume Reconstruction for Prenatal Diagnosis of Coarctation of the Aorta", Journal of Cardiovascular Magnetic Resonance, 2024
5 Englund et al., "Reliability of 4D Flow MRI for Investigation of Fetal Cardiovascular Hemodynamics in the Third Trimester", Radiology: Cardiothoracic Imaging, 2024
6 Hergert et al., "A Comparative Study of Fetal Cardiovascular Assessment", Cardiovascular Imaging, 2024
7 Barough et al., "Myocardial Strain Assessment in the Human Fetus by Cardiac MRI Using Doppler Ultrasound Gating and Feature Tracking", European Radiology, 2024

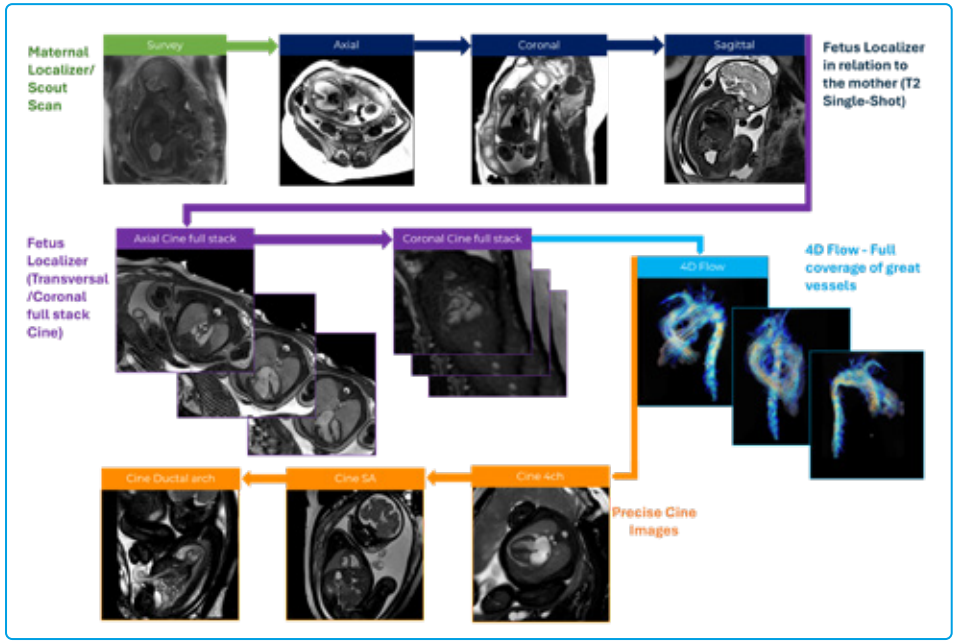
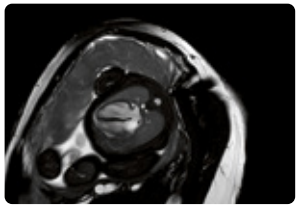


Figure 3: Step-by-step guidance for fetal CMR–How to plan sequences?

Integrates easily in your clinical workflow

smart-sync detects cardiac motion and synchronizes the fetal cardiac cycle with the MR image acquisition. In that way, fetal CMR becomes possible and can be used for anatomical and functional imaging. The quick setup in less than three minutes requires no special training. *smart-sync* utilizes standard cardiac MR sequences, being a plug and play solution that can be easily incorporated in your daily workflow. Its clinical utility is proven: *smart-sync* helps with delivery planning, organization of early postnatal care and provides valuable information for parental counseling.

Assisting on all levels



Physicians gain greater diagnostic confidence through crisp images, enabling effective counseling and thorough delivery planning.

Parents are reassured with a better grasp of the diagnosis thanks to more understandable imaging.

Working with one of a kind MR technology allowing you to stand out as a pioneer in prenatal diagnostic.

FROM RESEARCH TO CLINICAL APPLICATION

Experts in the field of fetal CMR share their experiences. Through their insights, we explore how fetal CMR has evolved from research-driven innovation to a vital tool in clinical practice.

Erik Hedström,
Associate Professor at Pediatric Radiology at Lund University

Your general workflow at Lund University Hospital:

The patients are referred to the hospital after an ultrasound performed by a midwife has shown suspicion of a cardiovascular malformation. A fetal echocardiogram is then performed by the obstetrician and fetal cardiologist, whereafter fetal CMR is considered in cases where ultrasound seems insufficient. Clinical fetal CMR scans are planned during office hours, and all patients are invited to participate in research scans. Pure research scans including healthy volunteers are commonly executed during evenings and weekends. Two dedicated techs and one researcher are available to perform fetal CMR scans, with a senior available if needed. The formal reports are written by a paediatric radiologist and usually images are shown for the fetal cardiologist and discussed together with echocardiography findings.

Common patients you scan?

Tetralogy of Fallot (TOF), hypoplastic left and right heart syndrome (HLHS/HRHS), CoA, Ebstein anomaly, multiple malformations.

Common MRI protocol you use?

A standard clinical protocol is commonly used, with addition of research sequences as feasible. The basic protocol consists of overlapping anatomical tra/sag/cor SSFP stacks for anatomy, cine transversal and short-axis stacks together with the standard cine 4/3/2 chamber views for function. A 3D sequence is used for fetal weight determination, and T2-weighted images for nutmeg pattern assessment. 2D flows are performed at least in the umbilical vein and descending aorta, which may be repeated during maternal hyperoxygenation.

Any research? Or only clinic?

All clinically referred patients are also offered participation in research scans added to their clinical scans. Healthy volunteers are imaged for development and reference values.

Do you write reports? Who writes them and what to include?

A paediatric radiologist writes the report, which includes a dedicated cardiovascular report. As part of the report, there is also an overview assessment of the fetal, placental, and maternal anatomy. Other incidental findings have so far ranged between herniated discs, cysts including more severe multicystic disease, placental anomaly, to tumours.

VOICES FROM THE FIELD

"Fetal CMR is an amazing tool that has transformed the way we diagnose congenital heart diseases prenatally, and more importantly has helped us provide more clarity and understanding for expecting parents. It has helped us prepare for high-risk infants and allowed for lower risk infants to remain with their mothers with less intensive monitoring after birth, allowing for that important bonding."

Richard Friesen, M.D.
Pediatric Cardiologist, Children`s Hospital Colorado, USA

"Fetal CMR as a complement to fetal echocardiography can provide valuable diagnosis and prognosis-relevant information in cases of cardiac malformations or anomalies."

Prof. Laurent Salomon,
Maternal Fetal Medicine, Hospital University Paris Necker, France

"Fetal CMR is a great addition for us when things get tough, and ultrasound reaches its limits! It helps us prepare for the time after delivery of babies with the most complex cardiac and situs anomalies and we are learning more about the structure and function of the fetal myocardium."

Prof. Brigitte Strizek,
Director of obstetrics and prenatal medicine, University Hospital Bonn, Germany

"As a member of the team who first published on this topic, I see two groundbreaking futures in fetal CMR: From a clinical standpoint, a major improvement in our diagnostic and prognostic capabilities regarding congenital heart diseases when ultrasound examinations are limited, e.g. by maternal obesity. From a research standpoint, a paradigm shift on the way we understand the physiology and pathophysiology of both fetal and placental circulations."

Prof. Guillaume Gorincour,
Pediatric Cardiologist, Foundation LUMIERE, ELSAN Clinique Bouchard, France

"Fetal CMR has the potential to become an adjunct to echocardiography for comprehensive assessment of cardiovascular disease and recent technical developments support its integration into clinical practice."

Prof. Julian Luetkens,
Interim Chair Radiology, University Hospital Bonn, Germany

Your general workflow in the Hospital:

Fetal CMR is mentioned at time of fetal diagnosis at the 20-week scan. Patients are then referred for fetal CMR, either at the 20-week scan or at the 28-week scan when they return for repeated monitoring. The fetal CMR then coincides with the last clinic visit around 32 to 34 weeks. We try to book the fetal CMR at the same time as the fetal cardiac echo and the clinician review.

Who is referring patients to the fetal CMR?

Our patients are referred by our fetal cardiologists after diagnosis.

Common patients you scan?

Our referrals include patients with single ventricular pathology, including hypoplastic left heart syndrome, but also other duct-dependent circulations that require ductal stenting in the postnatal period, suspicion of coarctation, transposition of the great arteries, severe tricuspid regurgitation, and other unusual cases.

Common MRI protocol you use?

We have a standard protocol that we slightly adapt according to clinical referral questions. We start with real-time CINE imaging for initial localisation of the heart. We then perform a quick 3D volume for fetal volumetrics

Malenka Bissell, M.D.,

Pediatric Cardiologist at Department of Biomedical Imaging Science at University of Leeds

followed by our cine imaging and flow imaging. At the end, we acquire the black blood HASTE for the slice-to-volume (SVR) reconstruction.

Any research? Or only clinic?

All our patients receive a clinical report and are also consented for research.

Do you write reports after your scan? Who writes them and what to include?

The fetal CMR reports are written by me, a pediatric cardiologist with level 3 EACVI accreditation in congenital CMR. We have reporting templates for the different common diagnoses. For example, see our CoA template on the next page:

REFERENCES FOR REPORTING TEMPLATE

8 Kacem et al., "Fetal Weight Estimation: Comparison of Two-dimensional US and MR Imaging Assessments", Radiology, 2013
9 Maskatia et al., "A Fetal Risk Stratification Pathway for Neonatal Aortic Coarctation Reduces Medical Exposure, J Pediatr., 2021
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REPORTING TEMPLATE: COARCTATION OF THE AORTA

HISTORY: Fetal suspicion of coarctation of the aorta

FETAL WEIGHT: Estimated fetal weight based on volumetrics today was *xx* kg[8].

EXAM: A fetal CMR scan was performed. The scan was well tolerated. Static imaging, cine imaging, 4D Flow MRI, 2D Flow MRI, and static black blood with fetal USS ECG gating completed. Fetal HR was *xx* bpm. Standard images are available to view on *xx* platform, 3D reconstruction on *xx* platform. Key images are attached to the report below. Mother is aware that this is a cardiac scan only and not designed to assess any structures outside the heart.

CONCLUSION: Haemodynamic risk stratification tool suggests *xx* risk of coarctation, and anatomical risk stratification suggests a *xx* risk.

LEFT HEART: 4 pulmonary veins drain into the left atrium. The left ventricle *is/is not* apex forming (RV/LV length = *xx*). *Mildly slender/normal sized* mitral valve annulus. Visually good LV function. The ascending aorta arises from the LV. Normal sized ascending aorta. Left-sided arch with conventional branching pattern. The transverse arch is narrowed measuring *xx* mm (z-score *xx*) with a *xx* risk of coarctation[9]. On 4D Flow MRI imaging there is very *little/reduced/acceptable* mitral inflow seen (tricuspid/mitral inflow *xx:xx* %).

RIGHT HEART: Single right SVC and IVC drain into the RA. The tricuspid valve annulus is non-dilated. Normal RV function. The main pulmonary artery arises from the anterior RV. MPA is normal in size. Good sized branch pulmonary arteries.

VOLUMETRICS[10]:

LV:
LVEDV *xx* ml, *xx* ml/kg (N: 1.9-2.9 ml/kg)
LVESV *xx* ml, *xx* ml/kg (N: 0.8-1.6 ml/kg)
LVSV *xx* ml, *xx* ml/kg (N: 0.9-1.5 ml/kg)
LVEF *xx*% (N: 56-70%)

RV:
RVEDV *xx* ml, *xx* ml/kg (N: 2.5-3.7 ml/kg)
RVESV *xx* ml, *xx* ml/kg (N: 1.3-2.1 ml/kg)
RVSV *xx* ml, *xx* ml/kg (N: 1.1-1.7 ml/kg)
RVEF *xx*% (N: 46-59%)

MEASUREMENTS IN MM*:

- Mitral valve: *xx* (z-score *xx*)
- LV length: *xx* (z-score *xx*)
- Ascending aorta: *xx* (z-score *xx*)
- Distal transverse arch : *xx* (z-score *xx*)
- Isthmus (sag): *xx* (z-score *xx*)
- Isthmal displacement: *xx*
- Descending aorta : *xx* (z-score *xx*)
- Ductal arch : *xx* (z-score *xx*)
- Tricuspid valve: *xx* (z-score *xx*)
- RV length : *xx* (z-score *xx*)
- MPA: *xx* (z-score *xx*)

*Gestation specific z-score [xxx insert local reference for z-score]

FLOW VOLUMES PER CARDIAC CYCLE IN MLS (2D/4D FLOW MRI):

- Mitral valve: *xx*
- Tricuspid valve: *xx*

RISK STRATIFICATION SCORES:

ANATOMICAL:

- TV/MV = *xx* suggests *reduced/increased* risk of CoA (>1.48 increased risk for CoA[11,12]).
- Aortic arch/Descending aorta ratio = *xx* suggests *reduced/increased* risk of CoA (<0.50 increased risk for CoA[11]).
- Transverse aortic/Ductal arch ratio = *xx* suggests *reduced/increased* risk of CoA (<0.7 increased risk for CoA[9])

HAEMODYNAMIC:

- 2D/4D Flow MRI imaging tricuspid/mitral inflow = *xx:xx* mls and *xx:xx*%. (normal 50:50%; false positive 70:30%; true CoA 75:25%[13]).
- Cardiac MRI risk score is *xx* [*xx*%] (using Isthmal displacement/descending aorta ratio and left heart flow mls/kg/min[13]).

HIGH-IMPACT CLINICAL CASES IN FETAL CMR

This section highlights clinical cases that demonstrate the transformative impact of fetal CMR in prenatal care. Captured using different scanner vendors, each case demonstrates the versatility of this technology in addressing complex diagnostic challenges and optimizing prenatal management.

PHILIPS scanner, 3T

ABSENT PULMONARY VALVE SYNDROME WITH TETRALOGY OF FALLOT (APVS/TOF)

Authors: *Thomas M. Vollbrecht, Christopher Hart, Julian A. Luetkens*
Institution: *Department of Diagnostic and Interventional Radiology, University Hospital Bonn*

CASE PRESENTATION

- A 31-year-old woman from Bangladesh (gravida III, para II) with a BMI of 26 at MRI presented with suspected APVS/TOF during second trimester anatomy scan and was referred for detailed diagnostic evaluation.
- Pregnancy history indicated early postnatal death of the first child due to suspected CHD.
- Prior to referral, fetal DiGeorge syndrome was diagnosed via amniocentesis.

INVESTIGATION

- Fetal echocardiography confirmed APVS/TOF with associated agenesis of the ductus arteriosus, aneurysmal branch pulmonary arteries, and right ventricular hypertrophy; also, a left persistent SVC was suspected.
- A fetal CMR was performed at gestational week (GW) 37+6 to validate the diagnosis and evaluate the size and extent of pulmonary artery aneurysms.

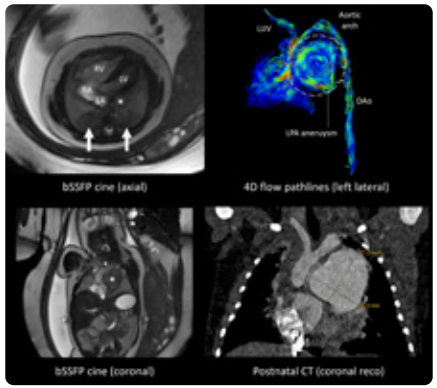


Figure 4: SbSSFP cine images reveal mesocardia/rightward shift of the heart, along with RV enlargement and hypertrophy. Characteristic of APVS, aneurysmal branch pulmonary arteries were observed, including a giant LPA aneurysm (asterisks), measuring 27 x 26 mm on postnatal CT, showing vortical flow at 4D flow pathline visualization. Prenatal axial cine MRI also revealed hypointense changes in both lower lung lobes, indicative of early pulmonary involvement (arrows).

- MRI scan protocol included T2w TSE images, axial and coronal bSSFP cine images, and 4D PC flow imaging.
- MRI findings were: APVS/TOF with agenesis of the ductus arteriosus; mesocardia with right ventricular enlargement and hypertrophy; aneurysmal branch pulmonary arteries with a giant LPA; absence of LSVC; structural lung changes in both lower lobes, likely due to compression of the hilar structures.

DIFFERENTIAL DIAGNOSIS

- Fetal CMR confirmed the previously suspected diagnosis of APVS/TOF, including agenesis of the ductus arteriosus.
- In addition to previous echocardiography, fetal CMR revealed mesocardiac/rightward shift of the heart, which affected the right hilar structures in addition to the RV enlargement; also, the extent of the giant LPA aneurysm could be assessed. The presence of a LSVC could be excluded *(Figure 4)*.

OUTCOME AND FOLLOW-UP

- The child survived the initial corrective surgery and subsequent follow-up operations but suffers from severe failure to thrive, attributed to recurrent pneumonia with respiratory insufficiency and right heart failure caused by concomitant tracheobronchomalacia.

TAKE HOME MESSAGES

- In addition to evaluating intra-cardiac and cardiovascular anatomy, fetal CMR offers the distinct advantage of visualizing the anatomical relationships between the heart and lungs, as well as between the thoracic vessels and bronchi. Therefore, the clinical report should emphasize a detailed description of these anatomical relationships and assess potential adverse postnatal effects.

GE scanner, 1.5T

DORV OR TOF IN A FETUS WITH VSD, ABNORMAL ORIGIN OF THE AORTA AND HYPOPLASTIC MAIN PULMONARY ARTERY?

Authors: *Julia Geiger*, Emanuela Valsangiacomo Buechel***
Institution: *University Children's Hospital Zurich, *Imaging Department, **Department of Ped Cardiology*

CASE PRESENTATION

- A 32-year-old G1P0 pregnant woman was referred for fetal CMR at GW 34 after fetal echocardiography suggested TOF with ventricular septal defect (VSD) and right ventricular outflow tract (RVOT) stenosis. The exact morphology of the pulmonary bifurcation and side branches could not be defined.
- Fetal CMR was requested because of limited echocardiographic image quality due to maternal obesity.

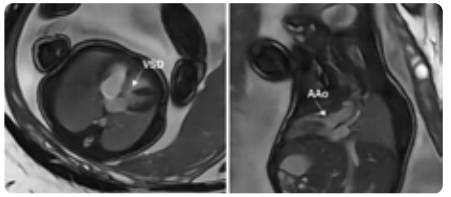


Figure 5: The axial and sagittal oblique DUS-gated cine bSSFP images depict the large VSD with overriding AAo.

INVESTIGATION

- Echocardiography at GW 28 showed balanced ventricles connected by a large VSD with overriding of the aorta. The RVOT, main and branch pulmonary arteries appeared hypoplastic and the pulmonary artery bifurcation was not visible. In addition,

double outlet right ventricle (DORV) was expressed as a possible differential diagnosis for TOF.
- Genetic assessment revealed no abnormalities, in particular no suspicion of DiGeorge syndrome.
- Fetal CMR at GW 34 showed symmetric ventricular size and a large VSD with overriding aorta arising from both ventricles *(Figure 5)*. The RVOT and main pulmonary artery (MPA) could be visualized showing a smaller size compared to the ascending aorta. The PA bifurcation and both PAs could be identified, whereas the arterial duct was hardly visible *(Figure 6)*.

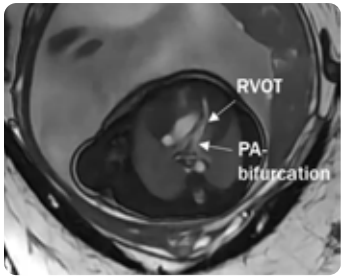


Figure 6: The axial DUS-gated cine bSSFP image shows the hypoplastic RVOT and MPA, but a non-stenotic pulmonary bifurcation and pulmonary arteries.

DIFFERENTIAL DIAGNOSIS

- Fetal CMR demonstrated the origin of the ascending aorta overriding the VSD. The differential diagnosis of DORV could be excluded and the diagnosis of TOF was favoured.
- In contrast to echocardiography, the anatomy of the RVOT, pulmonary bifurcation and pulmonary arteries was clearly visualized.

OUTCOME AND FOLLOW-UP

- Postnatal echocardiography confirmed the diagnosis of TOF with malalignment VSD, overriding aorta, and mild hypoplasia of the MPA and pulmonary arteries. Transcutaneous oxygen values were within the desired range and the newborn did not require any cardiac neonatal interventions.

TAKE HOME MESSAGES

- Fetal CMR overcame echocardiography limitations from maternal obesity, accurately diagnosing TOF with VSD, overriding aorta, RVOT/MPA stenosis, and hypoplasia but patent pulmonary artery bifurcation and side branches. Combined with echocardiography, it enabled optimized perinatal management, avoiding prostaglandin use.

SIEMENS scanner, 1.5T

FETAL CMR FOR POSTNATAL INTERVENTION PLANNING IN OBSTRUCTED INFRADIAPHRAGMATIC TOTAL ANOMALOUS PULMONARY VENOUS RETURN

Authors: *Eleanor Schuchardt and Team*
Institution: *Rady Children's Hospital Heart Institute, University of California San Diego*

CASE PRESENTATION

- 28-year-old gravida-3 obese (BMI 47) female with a fetus, prenatally diagnosed with complex CHD including DORV, subaortic ventricular septal defect, pulmonary stenosis and infradiaphragmatic total anomalous pulmonary venous return (TAPVR).
- Fetal echocardiography suggested pulmonary venous obstruction with loss of pulsatility. The vertical vein insertion site was presumed to be near the ductus venosus but could not be definitively identified.
- The postnatal care plan considered a staged interventional approach, with percutaneous stenting of pulmonary venous obstruction, followed by surgical repair.

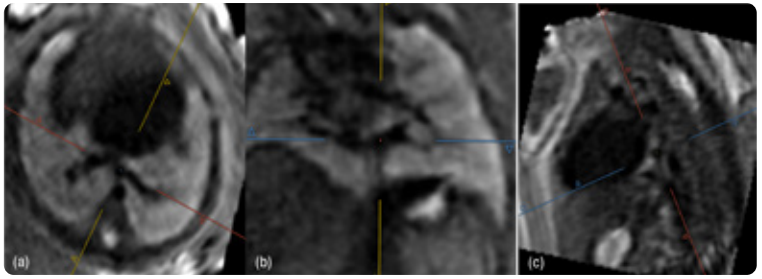


Figure 7: After motion correction using the slice to volume reconstruction tool kit, the multiplanar reconstruction was utilized to systematically assess the anatomy. Transverse (a), coronal (b) and sagittal (c) views demonstrate the inferior pulmonary veins meeting the confluence.

INVESTIGATION

- Three echocardiography scans at GW 25, 29 and 34. Imaging limited due to maternal body habitus and fetal movement.
- Fetal CMR with *smart-sync* gating was performed and showed the pulmonary venous drainage. T2 black blood imaging was found to be most useful for the intrathoracic anatomy.
- Slice-to-volume (SVR) reconstruction with Northh Medical's post processing platform was performed to define intrathoracic anatomy *(Figure 7)*. Below the diaphragm, SVR was less effective due to reduced vessel-liver contrast. Cine imaging clarified pulmonary venous drainage, showing the vertical vein joining a left-sided vein before reaching the ductus venosus.

DIFFERENTIAL DIAGNOSIS

- Fetal echocardiography identified the key elements (complex intracardiac anatomy and infradiaphragmatic TAPVR), however, the vertical vein's connection to the systemic vein was unclear. Fetal CMR clarified this, offering a 3D reconstruction as a backup in the event of no postnatal CT, boosting provider confidence in postnatal planning *(Figure 8)*.

OUTCOME AND FOLLOW-UP

- After stenting of the ductus venous, the infant was allowed to recover, transition and grow.
- Complete intracardiac repair and TAPVR repair was successfully performed at 3 months of age.
- Now at 4 months, the infant is doing well with no pulmonary venous obstruction and has mild pulmonary hypertension, improving on sildenafil.

TAKE HOME MESSAGES

- Fetal CMR provided a clear characterization of pulmonary venous drainage, enhancing confidence in postnatal care planning.

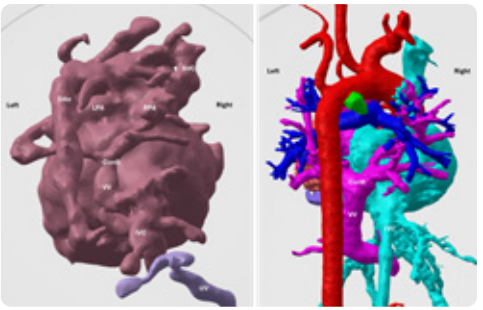


Figure 8: A 3D reconstruction was generated using Mimics. Here the posterior view shows the pulmonary venous confluence (Confl) to the vertical vein (VV), which ultimately crosses rightwards and drains to the superior aspect of the IVC.

FETAL MRI POST-PROCESSING

Using slice-to-volume reconstruction for fetal MRI post-processing of the fetal brain, thorax and body

Fetal MRI plays a crucial role in clinical settings, offering valuable insights for diagnosing and supporting fetal health. While postprocessing of MR images is well-established across all patient groups, there remains a significant gap when it comes to fetal imaging – no dedicated software solution exists. To address this unmet need, we have developed a fetal MRI post-processing platform. Our vision is to make post-processing of fetal MR images as seamless and accessible as it is for pediatric and adult imaging. The platform already integrates a slice-to-volume reconstruction algorithm, developed by King's College London (auto-proc-SVRTK package)[14], to provide a single volumetric motion corrected dataset.

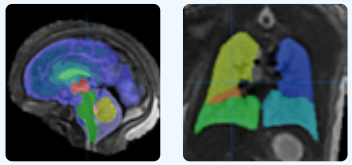
It is readily available for the brain[15,16], thorax[17] and body[14] for download and can be easily integrated into your preferred software for further analysis or annotation. Furthermore, we have incorporated the automated brain and lung volume segmentation algorithm developed by Uus et al.[18,19]. Development of the automated fetal weight estimation is underway in cooperation with Takashi Fujiwara and Alex Barker of the University of Colorado and we look forward to releasing it soon.

Fetal Motion Correction

BRAIN THORAX BODY

Turning 2D motion-corrupted images in a comprehensive motion-corrected 3D volume through slice-to-volume reconstruction.

Volume Segmentation



BRAIN THORAX

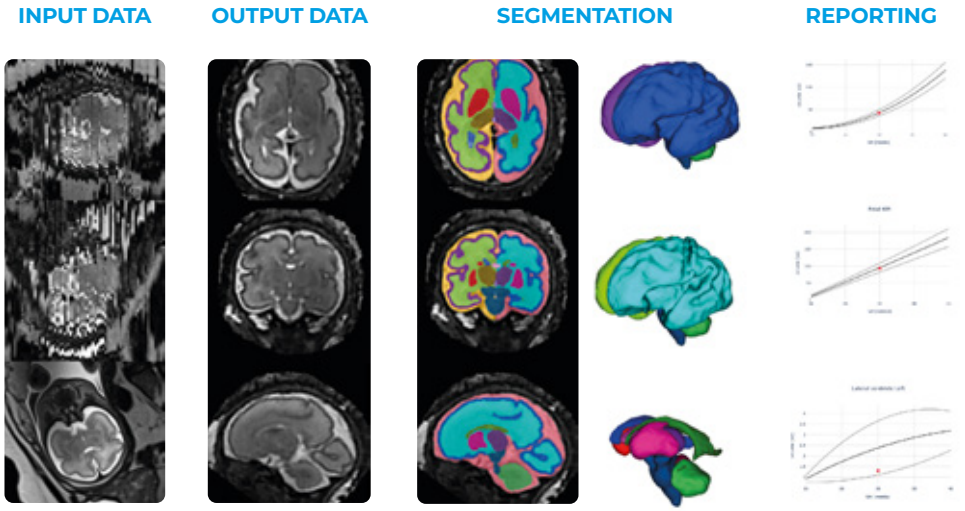
Automated segmentation and multi-regional parcellation with no manual work necessary.

Disclaimer:
The fetal MRI Post-Processing Software is only for research purposes and is not yet CE or FDA approved.

REGION OF INTEREST: BRAIN

CHALLENGE: Image acquisition in specific planes can be complex and may require repeated scans for accurate results. Extensive training of MR personnel is necessary.

SOLUTION: A comprehensive brain volume offers re-orientation and accessibility in any imaging plane, significantly improving diagnostic capabilities. Additionally, automated brain segmentation and parcellation provide enhanced insights and efficiency.



One motion-corrupted example image stack

Motion-corrected 3D volume

Automated multi-regional segmentation

Automated volumetry reporting for brain

AUTOMATIC BRAIN SEGMENTATION

For any reconstruction of the brain, a brain volumetry and brain segmentation with parcellation in different regions of interests is performed and can be viewed on the platform as well as downloaded.

The used algorithm was developed by Uus et al.[18] and incorporated a deep learning pipeline for the automated fetal brain segmentation.

The labeled region of interests include:

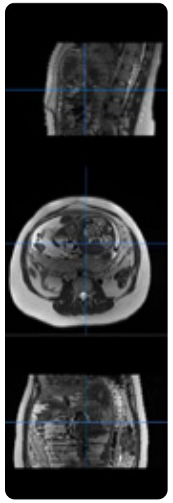
- Cortical grey matter
- White matter
- Cerebrospinal fluid
- Deep grey matter
- Ventricles
- Cavum
- Brainstem
- Cerebellum

REGION OF INTEREST: THORAX

CHALLENGE: Manual segmentation of the lungs in motion-corrupted 2D slices is both time-intensive and prone to errors due to motion artifacts, often resulting in incorrect volume assessments.

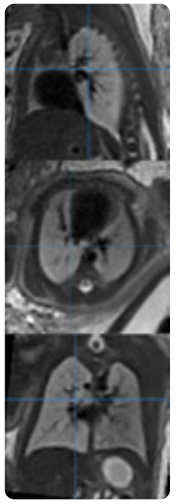
SOLUTION: A comprehensive 3D volume reconstruction facilitates tracking of anatomical structures. This is further enhanced by automated multi-regional lung segmentation and accurate volume calculation, streamlining the diagnostic process.

INPUT DATA



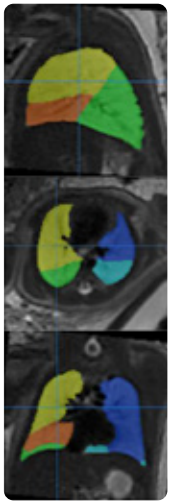
One motion-corrupted example image stack

OUTPUT DATA



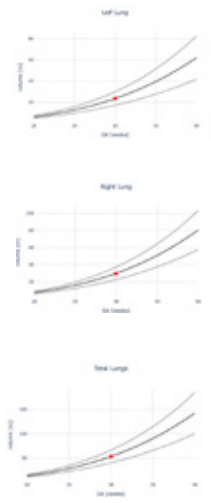
Motion-corrected 3D volume

SEGMENTATION



Automated multi-regional segmentation

REPORTING



Automated volumetry reporting for lungs

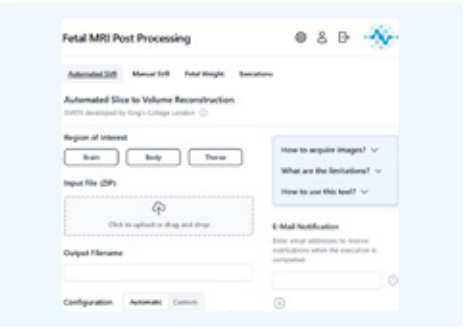
AUTOMATIC LUNG SEGMENTATION

Uus et al.[19] developed the automated lung segmentation pipeline and enabled the multiregional deep learning segmentation for both normal and abnormal congenital diaphragmatic hernia lung anatomy.

No more manual segmentation in corrupted individual slices is necessary. The parcellation is guided by location of bronchi and pulmonary vessel branches and regions with no pronounced vasculature, fetal lung histology studies and annotated adult CT lung lobe segmentation datasets.

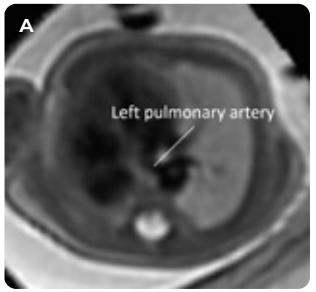
THE POST-PROCESSING PLATFORM

Register for FREE by simply scanning this code or visiting pp.northh.de and start the reconstruction of your fetal MR images!



EXAMPLE FOR PRACTICAL USE: ABSENT RIGHT LUNG AND SUSPICION OF COARCTATION OF THE AORTA

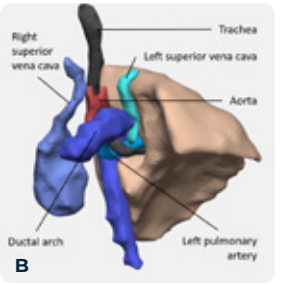
Clinical Case Report – Malenka Bissel & Lisa Ferrie (University of Leeds, Leeds teaching hospitals trust):



Fetal CMR was performed at gestational week 27 alongside body MRI to assess right lung tissue presence and investigate possible coarctation. Fetal echocardiography revealed no right pulmonary artery and raised suspicion of coarctation.

Serial ultrasounds, echocardiograms, and fetal body and heart MRIs were conducted in the same session. Due to early gestation, DUS *smart-sync* gating was not attempted, but the SVR platform with black blood imaging proved effective *(Figure 9)*.

In this case, the fetal CMR added very important additional information that was incredibly useful to understand the postnatally encountered difficulties with ventilation and oxygenation, as the baby was too unwell to undergo postnatal cross-sectional imaging.



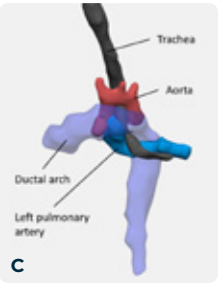


Figure 9: **(A)** SVR reconstruction from black blood HASTE stacks **(B)** 3D reconstruction from SVR data showing LPA sling **(C)** 3D reconstruction from SVR data showing all cardiac structures and lung volumes (right lung aplasia)

OUTLOOK: FETAL WEIGHT

CHALLENGE: Normalization of fetal anatomy and function using fetal weight. For example, blood flow measurements and the dimensions of the heart chambers are often described and analysed in relation to fetal weight[20].

SOLUTION: Fetal weight estimation using a deep learning network using a quick (< 10s) 3D acquisition (algorithm developed by Takashi Fujiwara and Alex Barker from the Children's Hospital Colorado in Denver).

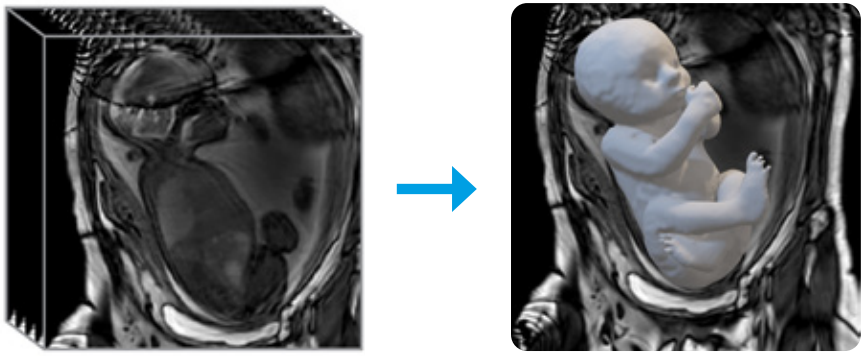
"We have extremely promising results but we're still in a multi-vendor validation phase and the release will be dependent on peer-reviewed publication of the results."

Alex Barker, University of Colorado

FETAL WEIGHT CALCULATION

On the segmented fetal body, the fetal weight is calculated using a conversion factor of 1.04 g/cm³ according to Kacem et al.[8].

Weight = Volume • 1.04 g/cm³



9-second breath-hold 3D FFE

Fetal weight estimate obtained in < 2 minutes

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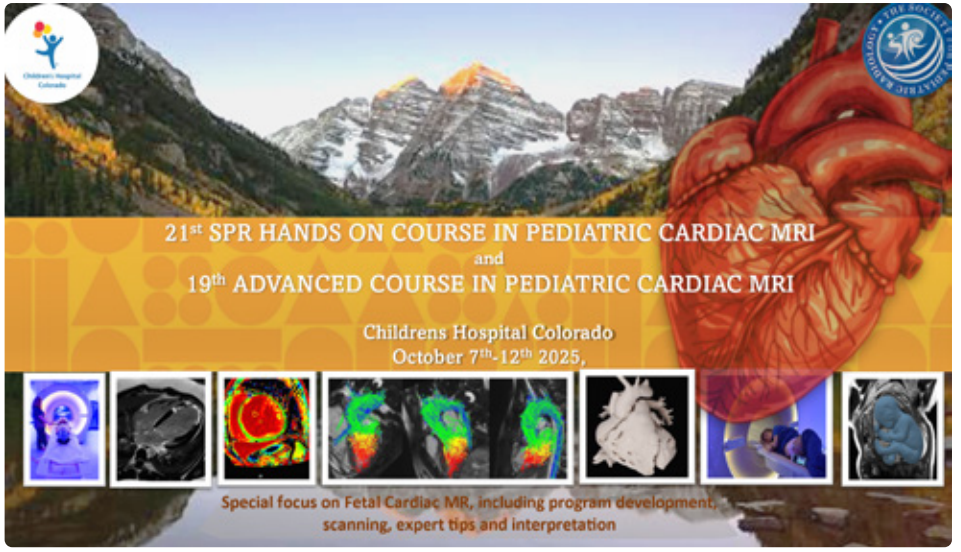


WE'D LOVE TO HEAR YOUR OPINION ON FETAL MRI POST-PROCESSING!

Scan the code to participate in a short survey.

UNITED STATES UNIQUE CPT CODE FOR FETAL CARDIAC MRI

As fetal CMR becomes more widely used and accessible, the billing structure will need to keep pace. In the US, this would involve creation of a unique CPT code for fetal CMR. This code would recognize fetal CMR as a distinct procedure which utilizes unique acquisition methods (DUS gating) and unique expertise (fetal cardiology). US Groups wishing to assist with this effort can contact Dr. Schuchardt at ***ESchuchardt@health.ucsd.edu***

FUTURE FOCUS: WHAT'S NEXT?

Key developments and expert insights on functional fetal CMR

Building on the content from our last webinar, we'll explore how fetal CMR is set to advance prenatal care and where this technology may take us in the future. Moderated by Dr. Malenka Bissell, the session featured leading experts who discussed key advancements and challenges in the field.

In this section, we share highlights from the session in an interview-style format, showcasing the most promising developments and future directions in fetal cardiac imaging.

RESEARCH TOPIC PRESENTED BY FOUR FETAL CMR EXPERTS

Julian Luetkens' presented research focuses on "Myocardial Strain Analysis in CHD." This technique tracks tissue motion and deformation of the fetal myocardium, specifically measuring longitudinal, radial, and circumferential strain. In a recent study involving 60 fetuses, Prof. Luetkens and his team found that strain patterns differ between healthy fetuses and those with CHD. They observed reduced left ventricular longitudinal strain, particularly in HLHS, and increased left ventricular longitudinal strain in fetuses with CoA. By using fetal CMR and optimized software for strain analysis, this method has shown high feasibility and reproducibility, possibly improving the understanding and differentiation of CHD.

Prof. Julian Luetkens,
Interim Chair Radiology, University Hospital Bonn

Can you explain what impact temporal resolution has on strain measurements, and whether it significantly affects the potential clinical use of this technique?

"For accurate strain estimation, high temporal resolution is essential. In our study, we had an average-temporal resolution of 17 milliseconds for reconstructed 25 images, which is much lower than what's used in adults when doing feature tracking strain with CMR. In echocardiography, however, the temporal resolution is even higher. Also, fetuses have much higher heart rates, the average in our cohort was 137 beats per minute. Although the temporal resolution of MRI cine acquisition is high, you still might miss the peak strain values. To use this as a clinical tool, it's crucial to accurately capture the peak strain. To determine if this is possible, we would need to conduct comparative studies, possibly with echo strain. However, we don't yet have clarity on this. Temporal resolution might be a limitation for fetal MRI strain assessment right now."

The second presentation by Alex Barker focused on efforts to establish normal values for fetal CMR in the third trimester, specifically regarding ventricular volumes, function, and strain. He and his team compared CMR to echocardiography and found that CMR-derived ventricular volumes were 50–100% higher due to geometric assumptions in echocardiography. However, when indexed by fetal weight, CMR values closely aligned with newborn studies. Alex also highlighted the importance of combining 4D flow MRI measurements with anatomical data to enhance the accuracy of diagnosing conditions like suspected CoA. The results showed promising predictive capabilities for adverse outcomes and high reliability in distinguishing true cardiac anomalies, paving the way for future multi-center studies and further advancements in fetal CMR.

Alex Barker, PhD,
Associate Professor Radiology at University of Colorado

We often encounter a lot of fetal motion throughout the stack. How do you handle this? Do you take multiple stacks? Do you have any tips for making the process more reliable?

"Sometimes we need to reacquire the stack or a specific slice of the stack due to motion. The more views you acquire, the higher the chance the baby will move, and for things to go wrong. In about 75% to 80% of our cases, we manage to get the short-axis stacks. We're also very careful with the timing of our acquisitions to avoid waking up the baby. However, once we start acquiring cine images with breath holds, we risk waking the baby up, which can be challenging and we need to reacquire. Since we're doing these as research studies for a reference value paper, we're fortunate to have the time to reacquire. But we need to consider what a realistic clinical workflow would look like. In a clinical setting, you can't keep trying to get that perfect stack – sometimes, you have to move on."

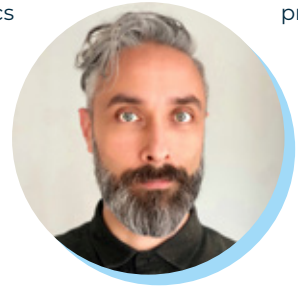
Eric Schrauben demonstrated the potential of 4D flow MRI for fetal cardiac imaging, emphasizing the importance of motion correction to improve its reliability. He presented cases where 4D flow provided valuable complementary information to echocardiography, such as in the diagnosis of transposition of the great arteries (TGA) and CoA. By introducing a motion correction pipeline consisting of a free-running (PROUD) acquisition and retrospective adjustments, he and his team significantly improved image quality, recovering smaller vessels and reducing mass conservation error from 14% to 5%. This advancement enhances the accuracy of both flow measurements and anatomical scans, supporting the clinical use of 4D flow MRI.

Eric Schrauben, PhD,
Scientist, MRI-Researcher, Amsterdam UMC, Netherlands

You're using a 3T scanner, but would prefer to use a 1.5T scanner. Why is that?

„I think the preference for a 1.5T scanner is because many other anatomical scans benefit from it. For 4D flow segmentations, it's often useful to have an imaging method that provides a more accurate representation of the anatomy, rather than just relying on a spoiled gradient echo image. That said, I understand your point—at 3T, we do get a stronger signal, especially in 4D flow acquisitions. So, it's definitely a trade-off."

Final insights into future topics were given by Joshua van Amerom on the 'Assessment of Cardiovascular Physiology'. He presented advancements in fetal CMR using 2D phase-contrast imaging to measure blood flow, offering key insights into fetal cardiovascular physiology. Furthermore, he highlighted the combination of T1 and T2 mapping for reliable blood oxygenation measurements and demonstrated how golden-angle radial acquisition improves motion correction compared to traditional Cartesian methods, enhancing image quality. Through clinical examples, including HLHS, Ebstein's anomaly, and TGA, he showcased the utility of fetal CMR for diagnosing CHD, guiding interventions, and informing delivery planning. The improved image quality and precise measurements provide critical insights for the diagnosis and management of CHD.



Joshua van Amerom, PhD,
Research Associate, Imaging Science & Biomedical Engineering, Sick Kids Toronto, Canada

Sometimes we don't try to identify each vessel right away; instead, we focus on capturing all the vessels and sort them out later. How do you approach this to ensure you've captured everything accurately?

"We have an excellent team here who are skilled and experienced at creating these prescriptions. It seems to be somewhat of an art, and that may limit wider adoption. But one way to learn would be to visit and see how it's done. There are also reference guides that include cross-sectional planes that show how to plan these scans."

CONCLUDING COMMENTS ON FUTURE DIRECTIONS

Are we really moving towards 2D flow as the future, or will we ultimately transition to 4D flow, eliminating the need to pinpoint individual vessels?

Joshua: I think low prescription complexity and redundant motion robust acquisition is the way to go. That's, I mean, just from based on my own background, being non-clinical, but also just what I've seen work quite well in the fetal brain, for example.

This involves densely covering the region of interest with numerous images and then assembling the data afterward. Similarly, with radial phase contrast acquisitions, we can extract the motion that occurred, perform data rejection, and process the results accordingly. For flow measurements, [...] a direct 4D flow acquisition is really appealing, especially if it is motion robust. We have done some work on this data, and I believe Eric was involved as well. At one point, we explored using 2D phase contrast measurements and reconstructing them using a slice-to-volume framework.

This approach remains appealing because it potentially combines the best of both worlds. However, it comes with extremely high computational complexity, making it a significant trade-off.

Eric: I don't think we'll be moving away from 2D flow anytime soon. However, as Josh suggests, it might be feasible to acquire multiple images or slice locations within a single stack. For example, the group in Denver is already doing this—they set up a prescription and then capture the next slice up from there. The idea is that, between the two slices, at least one will be usable, given the likelihood of motion.

That said, I agree it's a challenging task. Ultimately, the best approach moving forward will likely involve placing a box around the heart, developing an effective way to detect motion, and correcting for it. Measurements could then be performed retrospectively. However, while retrospective analysis is effective, it isn't always fast enough to meet clinical needs.

Alex: Building on what Eric and Josh have discussed, we often can't reliably capture some of the pulmonary flows, but we can almost always measure the descending aorta and the umbilical vein. In short, we try to get the 2D flows, but we don't spend too much time if the results aren't coming through. In those cases, we move on to 4D flow instead.

CONCLUSION

Fetal CMR is rapidly developing into a valuable diagnostic tool that connects research with clinical practice. Advances in functional imaging, motion correction, and data standardization are paving the way for more comprehensive fetal cardiac assessments, with the potential to significantly improve postnatal outcomes. However, there remains a strong need for further research in this area. Multi-center studies are essential to validate current findings and establish standardized protocols.

WANT TO WATCH THE RECORDING?
https://www.northh.de/recording

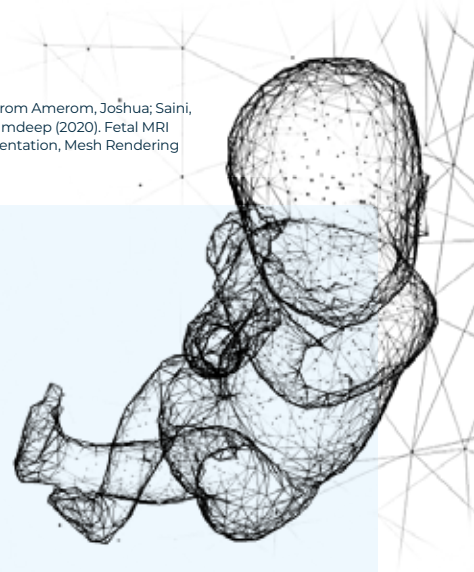


Figure from Amerom, Joshua; Saini, Brahmdeep (2020). Fetal MRI Segmentation, Mesh Rendering

KEY TAKEAWAYS

Promising research projects by using fetal CMR are ongoing:

- **Myocardial strain analysis:** Provides insights into fetal cardiac function, offering a complement to traditional echocardiography for enhancing the understanding and differentiation of CHD.
- **Normative Data:** Establishing MRI-specific benchmarks in healthy fetuses are vital for accurate diagnoses, especially in combination with 4D flow measurements.
- **Motion Correction in 4D flow:** Techniques to mitigate motion artifacts and therefore increase robustness are critical for advancing the clinical utility of fetal CMR due to better accuracy.
- **2D phase-contrast imaging:** Combining flow and oxygen saturation measurements by using 2D phase-contrast imaging helps plan delivery and improve neonatal outcomes.

Main Challenges remain:

- **High fetal heart rates** and **motion** are challenging. Temporal spatial resolutions must improve to ensure accurate diagnostic markers.
- Workflows and expertise for integrating these technologies with fetal CMR into **routine clinical** care need further refinement to improve efficiency and reduce manual adjustments.

WRAP UP
2ND WEBINAR SERIES

Our second webinar series on fetal CMR in 2024 was a valuable opportunity to further advance knowledge in the field. Focusing on clinical cases, the series aimed to provide practical insights while building and connecting the growing fetal CMR community.

Each of the five sessions highlighted different aspects of fetal CMR, featuring renowned experts who shared their knowledge and hands-on experience. This year's series emphasized practical applications and clinical implications with the aim to educate both seasoned professionals and newcomers for the application of fetal CMR.

WEBINAR REGISTRATION GROWTH
mean value over all sessions
63 in 2023 → 181 in 2024

A LOOK BACK AT 2024

- **Kick-Off Session (January):** We began the year with a focus on the fundamentals and technical advancements in fetal CMR. Topics included motion correction strategies for 3D and 4D imaging and developments in 3D black blood imaging.
- **Spring Session (March):** Experts guided attendees through clinical cases, addressing challenges in fetal cardiac imaging and optimal sequence selection for various scenarios.
- **Summer Session (June):** We explored the broader clinical impact of fetal CMR, discussing optimal image quality, conditions like hypoplastic left heart syndrome, and motion-compensated 3D reconstruction of black blood imaging.
- **Autumn Session (September):** Case studies on critical CHD cases such as right superior vena cava to left atrium, rhabdomyoma, and TGA with VSD illustrated the importance of fetal CMR in clinical decision-making.
- **Winter Session (December):** Looking ahead, we discussed the future of fetal CMR, including myocardial strain analysis and advances in motion correction.

We extend our gratitude to the speakers whose expertise made this series a success!

LOOKING AHEAD TO 2025

Reflecting on last year's success, we're excited to announce the upcoming **3rd Webinar Series** in 2025. The growing interest in fetal CMR and the expansion of the community continue to drive our commitment to providing valuable educational opportunities. We look forward to seeing you in the upcoming webinar session this year!

3RD WEBINAR SERIES 2025

FETAL CARDIAC IMAGING USING MRI
A FREE one hour educational webinar

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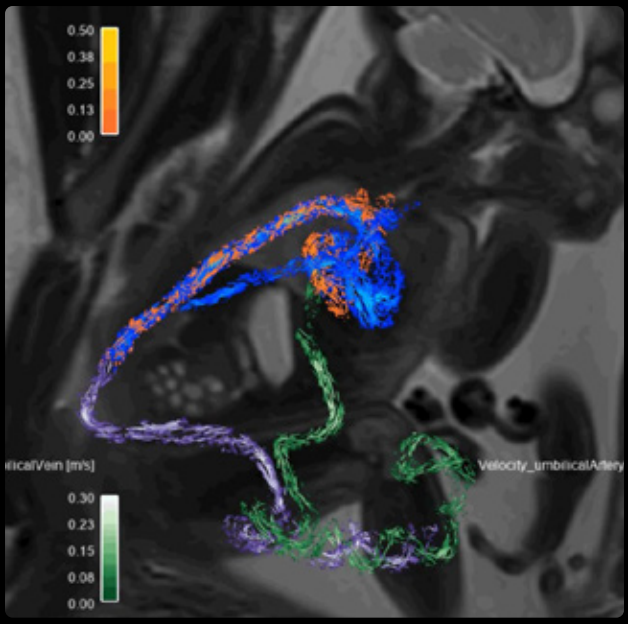

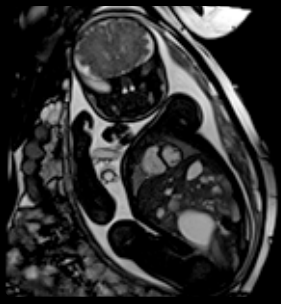

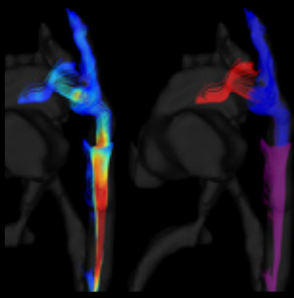

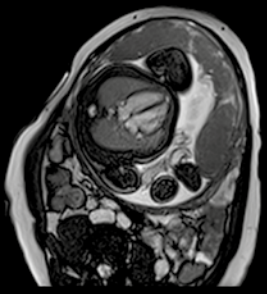

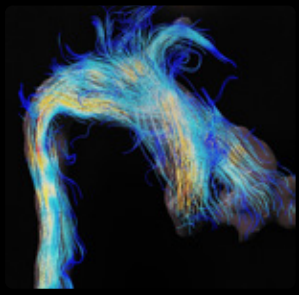

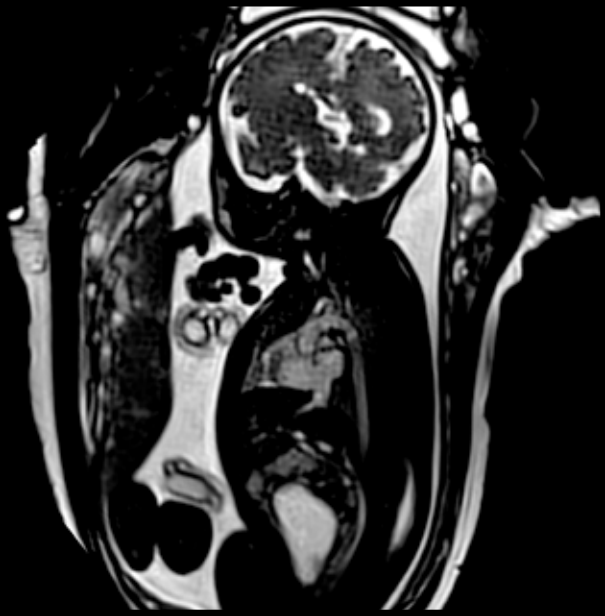

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