How To Do Fetal Cardiac MRI at 3T

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Background

Diagnostic uncertainty adds additional burden to an already stressful pregnancy. While fetal echocardiography is the mainstay of antenatal diagnosis, some prognostic uncertainty remains in a number of cases. This can be due to the difficult nature of prenatal diagnosis, such as coarctation of the aorta or due to poor echo windows in oligohydramnios or maternal obesity. In neuro imaging, fetal MRI[1] is already routinely used in a number of centers to enhance diagnosis in the prenatal setting. Fetal cardiac MRI has previously been restricted to a few research centers with access to advanced motion correction and self-gating methods [1]. Over the last 24 months, with the advent of an MRI-compatible ultrasound gating device [2], fetal cardiac MRI has become available to clinical centers, as now standard sequences can be adapted and used for fetal cardiac imaging.

Fetal cardiac MRI can be performed at 1.5 Tesla or 3 Tesla. While 3T creates additional challenges during anatomical data acquisition, it provides better signal-to-noise ratio (SNR) and makes phase contrast imaging for 2D and 4D Flow[2] MRI more achievable.

Despite this, fetal cardiac MRI scans remain challenging due to very small fetal organs in a large maternal field of view, which limits the maximal resolution that can be achieved. Standard sequences are only successful when fetal movement is small. Therefore, fetal cardiac MRI is currently performed in late stages of pregnancy (33–37 weeks of gestational age). SNR will be achieved from the larger fetal body. Moreover, the fetal movement will be restricted due to reduced amniotic fluid and less space for the fetus to move. Additionally, it is important to reduce maternal anxiety as much as possible as calmer mothers often have calmer fetuses. Therefore, for a successful fetal cardiac MRI scan, careful patient preparation and adaptation of standard sequences are important and outlined in detail in this manuscript.

Patient preparation

Pre-appointment preparation

Fetal cardiac MRI can be stressful for expectant mothers, especially for those whose fetuses are suspected to have congenital heart condition or have confirmed congenital anomaly on echocardiography. Parents are frequently concerned about the safety of the MRI scan for the fetus. Therefore, it is important to prepare the patient with all necessary information before the scan. It can be beneficial to send the patient an information leaflet prior to the scan, answering frequently asked questions and providing information about MRI safety for pregnant patients, as well as information about how the scan will be performed. Including pictures makes the information easier to understand.

[1]Siemens Healthineers disclaimer: MR scanning has not been established as safe for imaging fetuses and infants less than two years of age. The responsible physician must evaluate the benefits of the MR examination compared to those of other imaging procedures. Note: This disclaimer does not represent the opinion of the authors.
[2]Work in progress: The application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.

The day of the scan

It is important to provide a calm environment where the safety screening can be discussed with the patient before the scan. Sufficient time should be allowed prior to each slot so the patient can discuss any concerns, to allow the patient to feel comfortable with the team and less stressed about the outcome of the scan. If possible, offer pregnant mothers to change into hospital scrubs to keep her as comfortable as possible. Hospital gowns rarely fit, and often make women feel more self-conscious and stressed during the MRI scan. Additionally, it is important to ask patients to empty their bladder just before the beginning of the scan.

Scanner room preparation, patient positioning, and gating

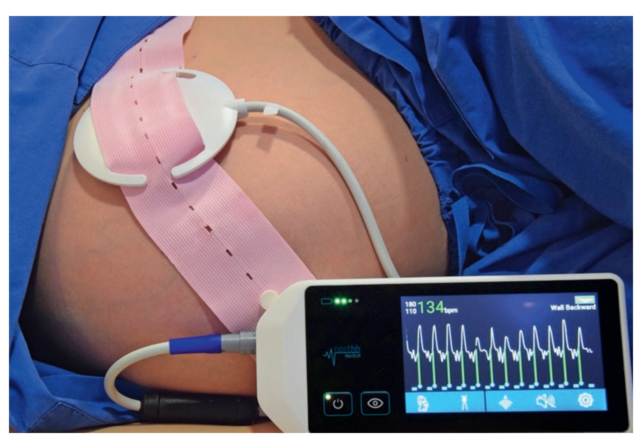
The MRI scanner room should be well prepared before the patient arrives (Fig. 1). The setup should be for entering the bore feet first. The spine coil should be in place. At least three pillows should be available as it is more comfortable for some patients to have more than one pillow under their head and an additional pillow between their legs. Also, MRI-compatible wedges should be in place on the right-hand side of the bed to provide support for the patient's back so the pregnant woman is placed in the left-lateral position when lying supine. Moreover, the leg support wedge placed under the patient legs reduces the lower leg pain often experienced in late pregnancy.

If the Doppler ultrasound (DUS) gating device is being used, it is important to charge the device before the day of the scan. Also, the ultrasound gel should be to hand and the wireless device should be connected to the MRI scanner. The straps to keep the ultrasound probe in place should be placed in a cross position onto the MRI table at the level of the lumbar spine.

Once the patient arrives in the scanner room, it is vital to make sure the patient is as comfortable as can be. Often, maternal movement degrades imaging more than fetal movement. The patient will be usually positioned left-lateral feet-first into the bore of the magnet. Feet-first reduces anxiety as the patient can look upwards and out when moving into a restricted space. As the scanner bore is a confined place, most patients will have to be placed into the left-lateral position, ideally at least 35 degrees. However, if the patient's hip circumference allows, placing the patient completely onto the left-hand side can improve patient comfort and reduce maternal breathing motion. After making sure the patient is comfortable in her position, the ultrasound gating device will be placed on the maternal abdomen to search for the fetus's heartbeat (Fig. 2). It is useful to palpate the abdomen for the fetal spine and then position the ultrasound head near the left shoulder facing towards the fetus. If the fetus's back is to the mother's back, it can be very difficult to obtain a reliable Doppler gating signal and sometimes only non-gated imaging can be possible.

If struggling with positioning, the device can be placed randomly on the lower abdomen before the localizers are acquired to localize the position of the transducer in regard to the fetal heart. With this information, it is very easy to find the fetal heartbeat. It is very important that the transducer is localized centered above the fetal heart in order to prevent signal loss due to fetal movement. It is

1 MRI setup with pillows, wedges, and the crossed straps to keep the ultrasound probe in place.



2 Positioning of the ultrasound gating transducer.

also important to have a clear procedure in place to check for fetal well-being if the MRI team is unable to locate a fetal heartbeat. Once the heartbeat is heard clearly through the device headphones and a good signal is observed on the monitor, the ultrasound transducer will be held in place by securing it with the straps. Additional small wedges can be useful to keep a tilted position, if needed. After that, the 18- or 30-channel coil will be placed onto the abdomen. It is helpful to provide music via the headphones to keep the mother calm and distract her during the scan. It is important to stay in contact with the patient during the scan to provide her with updates about the scan's progress and to make sure she is doing well.

In the MRI control room, patient information such as height, weight, feet-first and the fetal heart protocol will be selected to start the scan. The time at the beginning of the scan will be documented to make sure the 30 minutes are not exceeded.

MRI safety considerations

When scanning during pregnancy particularly consideration must be given to both maternal and fetal safety. Radiofrequency (RF) exposure must be limited to avoid undue heating, and excessive acoustic noise must be avoided to mitigate risk of damage to developing hearing organs. When performing fetal CMR it is therefore paramount to remain in normal mode – both specific absorption rate (SAR) and gradients – and use the lowest gradient modes available on each sequence (with Whisper gradients used wherever possible). Low SAR RF pulse types are used where possible. Furthermore, scan duration is limited to approximately 30 minutes to restrict accumulated RF energy deposition (specific energy dose, SED) and to minimize maternal discomfort. To further support maternal comfort, we favor the use of fixed table positions once initial localization has been performed and the fetal heart positioned at isocenter. Scanning should be performed without the use of exogenous contrast agents to avoid the hazards associated with these, as many are known to cross the placenta and enter the fetal bloodstream.

Consequently, there is a need to image rapidly, albeit with restrictions on gradient switching and RF exposure, while exploiting only endogenous contrast mechanisms. Additional challenges arise due to unpredictable fetal movement within the uterus, potential maternal movement due to discomfort, and (when acquiring cardiac synchronized images) significantly higher heart rates than in older children or adults.

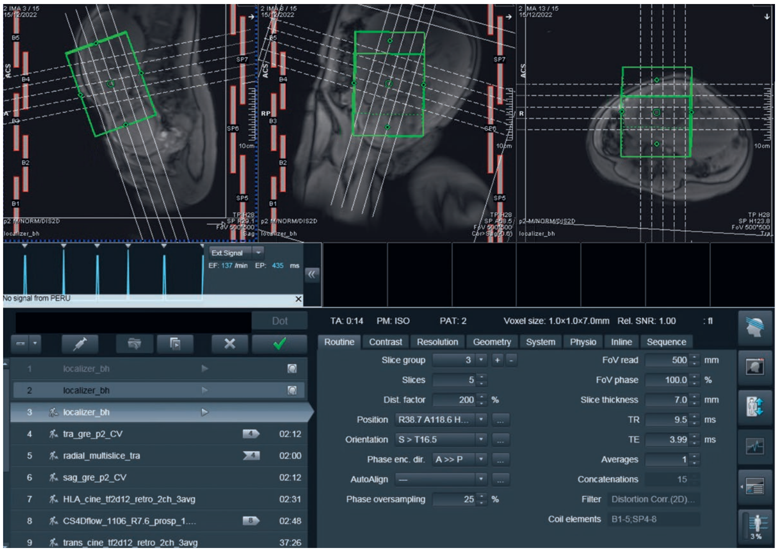
Due to the small fetal heart size in the larger maternal field of view, it is challenging to acquire images with sufficient spatial resolution while avoiding wrap from the surrounding maternal body.

In addition to field-of-view and resolution concerns, the extra tissue and fluid around the fetus can cause challenges with signal intensities. SNR can be adversely affected if the fetal heart is deep inside the mother, due to distance to the coil elements. To further maintain acceptable SNR, the use of parallel imaging is avoided for the majority of sequences (except for initial localizers where GRAPPA with acceleration factor 2 is used). However, partial phase Fourier acquisition is used where there is sufficient SNR without averaging and asymmetric echoes and where there is a need to minimize TE. Furthermore, Compressed Sensing allows 4D Flow[2] MR imaging (research sequence) in an acceptable timeframe for fetal imaging.

Signal scaling around the fetal heart can also be adversely affected by dominating signals from material closer to the coil, particularly fat and amniotic fluid, which (depending on the sequence weighting) can have particularly high intensity. Consequently, the Image Scaling Correction is routinely increased (in the System – Tx/Rx window) and high receiver gain selected. This may lead to the signals from maternal fat and fluid appearing saturated, but results in much better contrast resolution over the fetal anatomy of interest. Trial and improvement may be needed to find optimal values, but values between 5 and 15 for different sequences is a good initial guide. Note that the Image Scaling Correcting setting can also be edited in retrospective reconstructions, which can allow fine tuning without the need to repeat image acquisition.

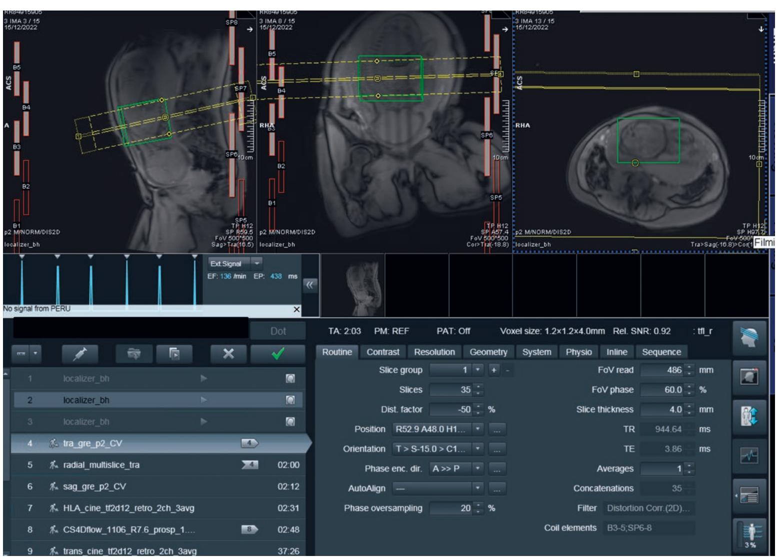
Given the above considerations, image quality comparable with adult CMR should not be expected when performing fetal CMR. Compromises are to be expected and a protocol that carefully prioritizes sequences must be developed, with the flexibility to allow for repeat imaging as and when required due to fetal movement.

Anatomical scanning



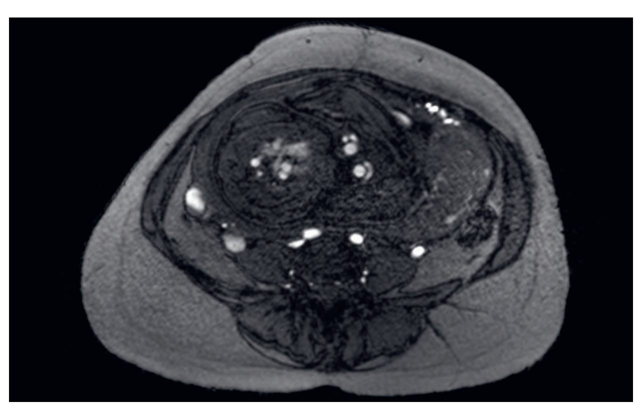
3 It is important to place the final localizer directly over the fetal heart and align it to the fetal thorax orientation. A tight shim box is important to reduce artifacts and improve image quality, especially at 3T.

Vasculature-triggered TurboFLASH (approx. 2 minutes for 30 slices)



4 Cover the entire thorax with 50% overlap transverse to the fetal thorax.

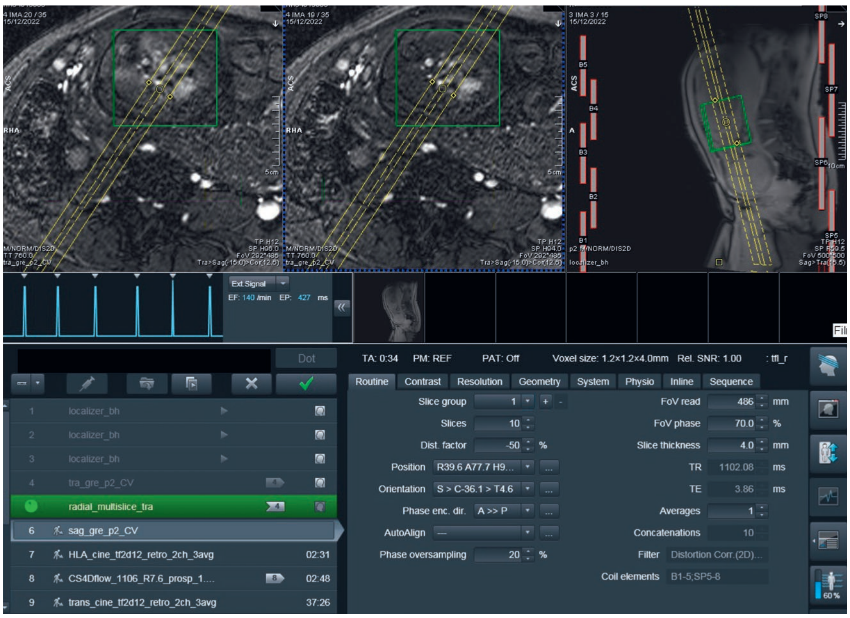
After standard three-plane localizers aligned to the maternal anatomy, we acquire a stack using 2D TurboFLASH imaging, which generates high signal from the vasculature due to inflow enhancement effects. Single shot (per slice) triggered imaging is performed, providing resilience to motion and allowing stacks of 30 slices to be acquired in approximately 2 minutes. A high flip angle (for a FLASH sequence) of 30° is used to maximize saturation of stationary tissue, yielding high contrast of the flowing blood. We find that a single acquisition (no averaging) and 5/8 phase partial Fourier yields sufficient SNR with this sequence. A base resolution of 400 yields an in-plane resolution of approximately 1.2 × 1.2 mm^2.



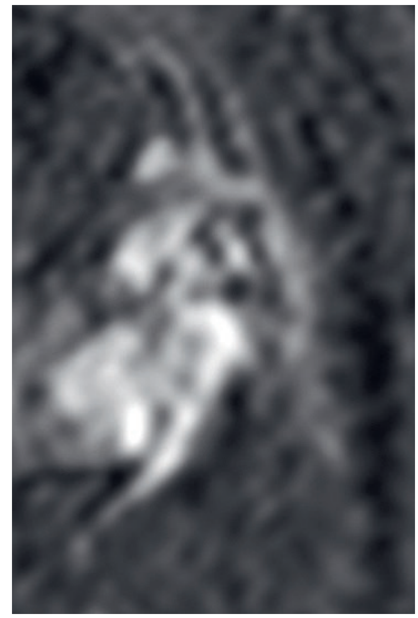
5 Transverse TurboFLASH "white blood" stack depicting the main pulmonary artery and branch pulmonary arteries.

A stack of 4 mm slices overlapping by 2 mm (-50% distance factor) are acquired. Acquisition is triggered (single-phase) using the Doppler US device, to acquire data every other heartbeat with a minimal trigger delay of 1 ms.

This sequence is often repeated with fewer slices to provide targeted views of specific vascular anatomy, for example, aligned to show the aortic arch.

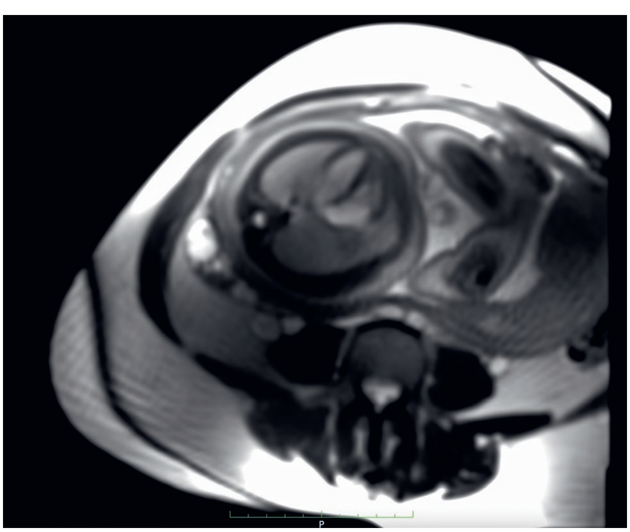


6 Planning of a smaller sagittal stack through the aortic arch perpendicular to the fetus. Watch out for wrap.



7 TurboFLASH of the aortic arch.

Radial multi-slice TrueFISP (approx. 2 minutes for 30 slices)



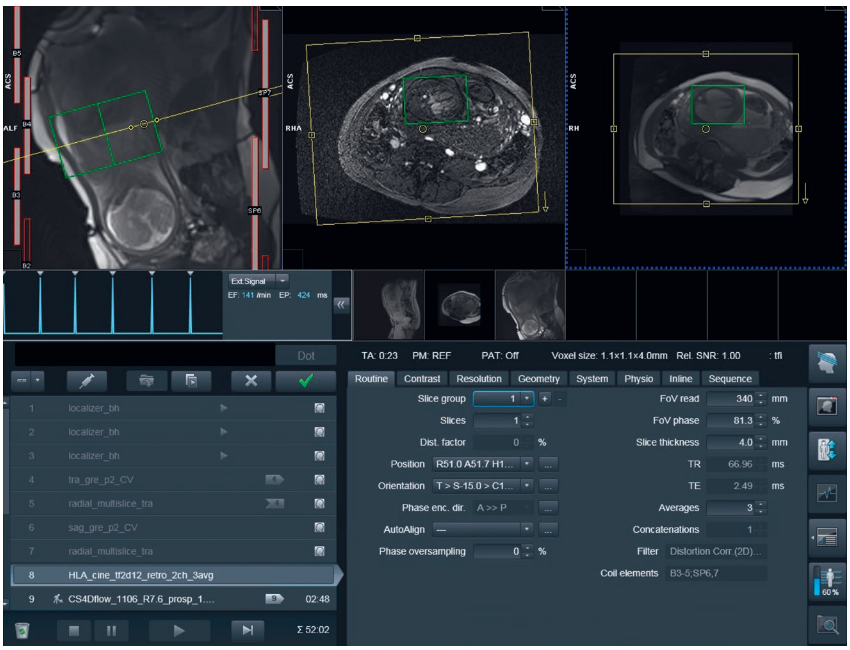
8 Radial transverse stack depicting 4 chambers.

We also acquire a stack of 2D TrueFISP images transverse to the fetus for an overview of fetal anatomy and to aid further planning. These are acquired as 4 mm thick contiguous slices but with 2 mm separation between slice centers (i.e., distance factor of -50%) to provide overlapping slices with the higher SNR associated with the thicker slices than would be achieved with 2 mm slice thickness. As alternate slices are acquired first, followed by the intermediate slices, cross-talk is kept to acceptable levels (despite the negative distance factor). However, fetal movement between the odd and even slices can lead to a jumpy appearance when scrolling through the stack.

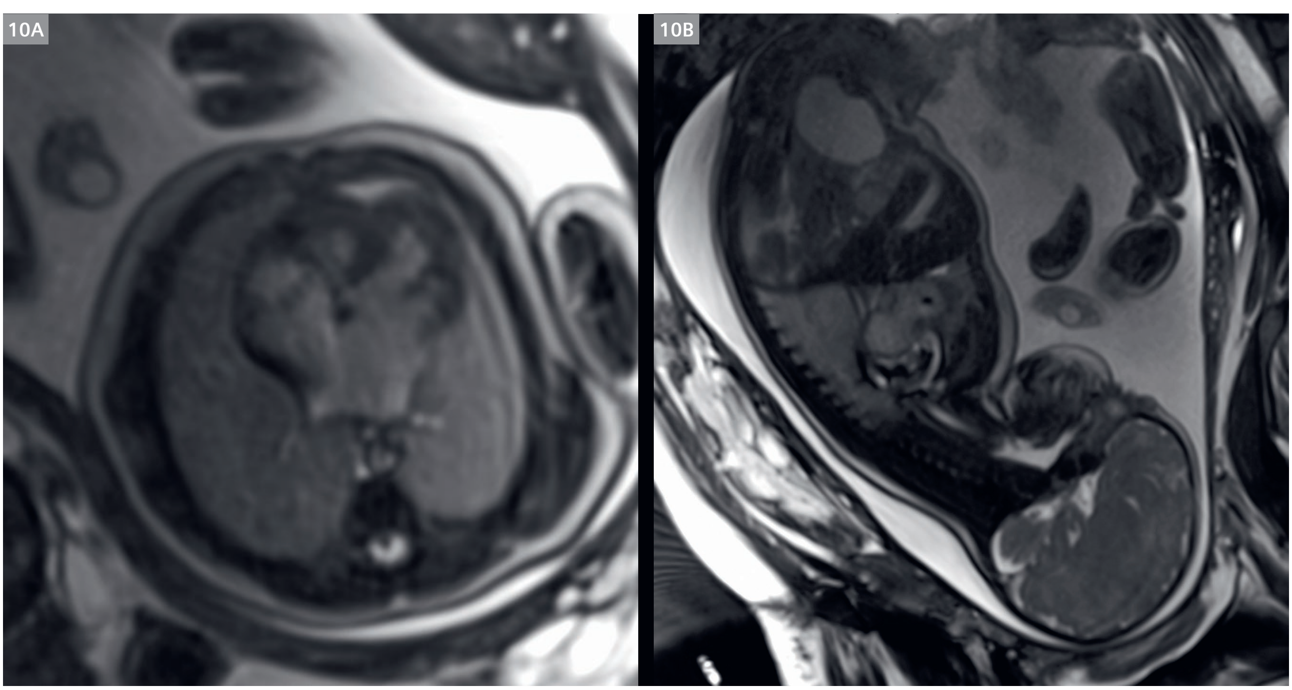
Radial *k*-space sampling is used to minimize motion artifacts with a base resolution of 144 (143 radial views), leading to an in-plane resolution of approximately 2.2 × 2.2 mm^2 for a typical field of view. Signal averaging is used (number of acquisitions, NSA = 4) with short-term averaging mode.

Cine imaging (approx. 1 minute per slice)
For Cine imaging, we use a TrueFISP acquisition with 4 mm slice thickness and approximately 1.1 × 1.1 mm^2 in-plane resolution. To obtain sufficient SNR, we use averaging (NSA = 3) and do not use parallel imaging or partial Fourier acquisition, although weak asymmetric echoes are allowed to minimize TE. Short-term averaging mode is used to minimize motion artifacts.

A Cine transverse stack is useful for initial Cine imaging. Our sequence is retrospectively gated into 25 cardiac phases using the Doppler US device. Where multiple slices are required, they are acquired contiguously in sequential mode. If the DUS ECG is unstable, we choose to change to prospectively gated to allow for improved image quality.

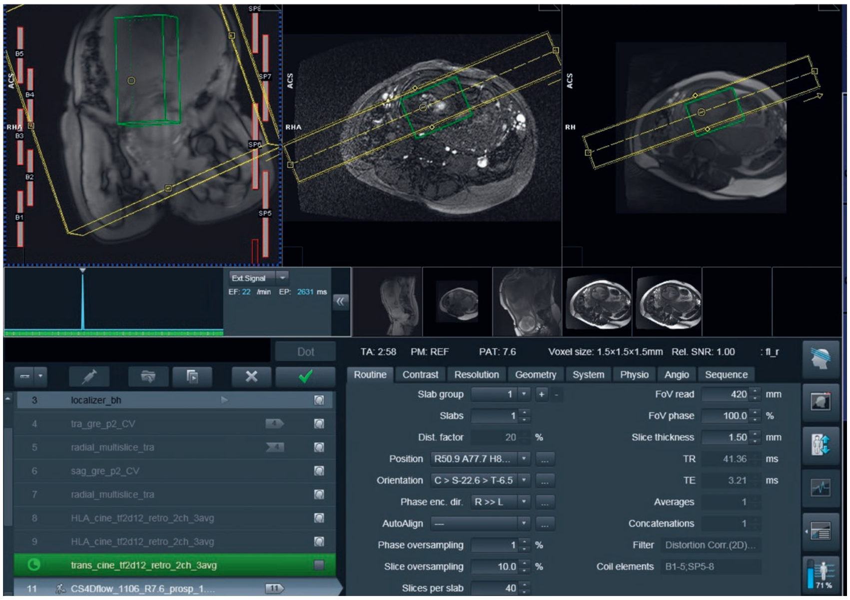


9 Planning of 4-chamber Cine using acquired transverse stacks as planning guide.



10 **(10A)** 4-chamber-view Cine in a patient with hypoplastic right ventricle and tricuspid regurgitation.
(10B) Image of the aorta.

CS 4D Flow² MRI (approx. 3 minutes for 40 slices)

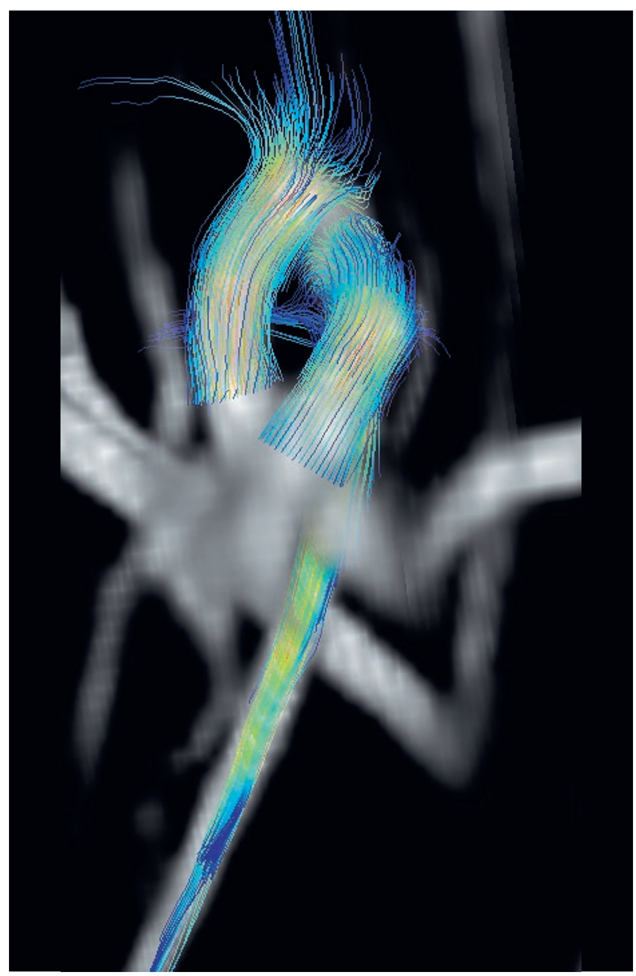


11 Planning of CS 4D Flow MRI using the 4-chamber view as orientation and the transverse stack to check that pulmonary artery and aorta are included. Watch out for wrap and check on localizers.

To assess blood hemodynamics we use Compressed Sensing 4D Flow² MRI, which allows volume coverage of the heart and proximal vasculature in an acceptable time frame for fetal imaging. This approach allows a 3D volume to be acquired with velocity encoding in all three dimensions. It can therefore be significantly simpler and more robust than planning multiple 2D flow acquisitions, particularly in this application, as in a 2D approach, where it is critical for each view to be accurately prescribed, it is common for repeat scanning to be required when the fetus moves during the time required to accurately plan each acquisition.

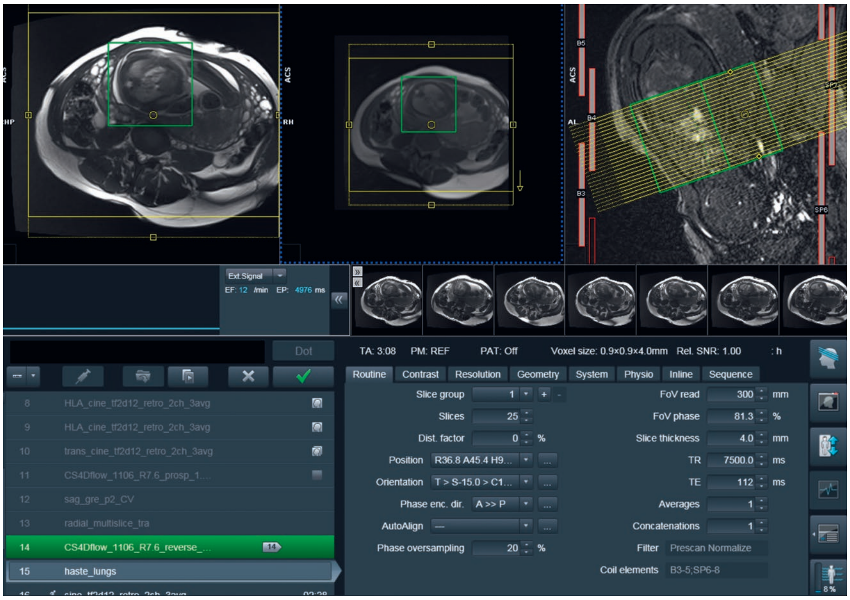
We acquire data with approximately 1.5 mm³ isotropic resolution, prospectively triggered using the Doppler US device with a minimal (1 ms) trigger delay and 9 cardiac phases. A venc of 70 cm/s is used. Strong asymmetric echoes are allowed to allow TE and TR to be minimized, and a constant 7° is used.

It should be noted that image reconstruction can take significantly longer than acquisition for this sequence (up to around 15 minutes), and other sequences acquired subsequently will not be reconstructed until the 4D Flow MRI reconstruction completes. We therefore generally perform this sequence towards the end and accept that it is not feasible to review the data while the patient is still on the scanner. Instead, we allow the reconstruction to occur while the patient is being removed from the scanner and while the scanner is being prepared for the next patient.



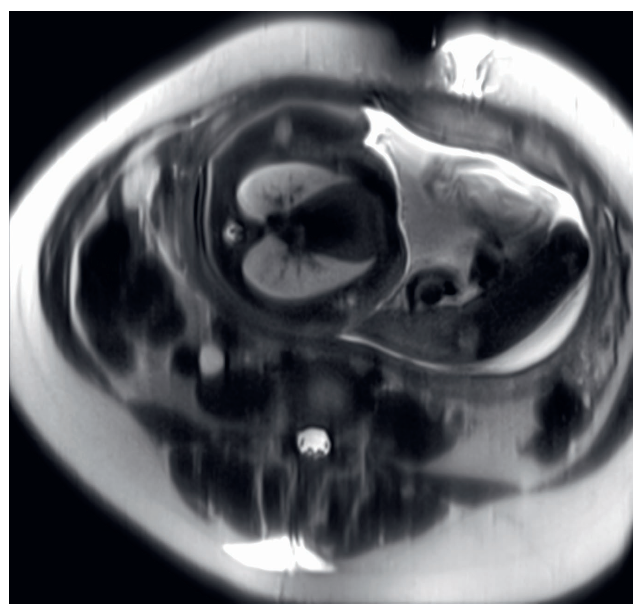
12 Compressed Sensing 4D Flow MRI of the aorta and main pulmonary artery.

Lung HASTE (approx. 3 minutes for 25 slices)



13 Transverse HASTE stack for lung volume using more slices than for the previous stacks to ensure lung volume is acquired completely.

If lung volumetry is required, we acquire a stack of contiguous 4 mm T2-weighted HASTE slices covering the fetal thorax in a transverse orientation (i.e., similar geometry to the above sequences but without overlapping and with larger coverage in the slice direction to encompass the entire fetal thorax). A base resolution of 320 yields approximately 1.1 × 1.1 mm^2 in-plane resolution. This sequence provides sufficient SNR to not require averaging and to allow 4/8 phase partial Fourier sampling. As HASTE is a single-shot sequence, the TR can be minimized without influencing signal contrast, although care must be taken not to increase SAR too much.



14 HASTE for lung volume quantification.

Frequent challenges in fetal cardiac MRI

Ultrasound gating

The Doppler ultrasound gating device increased the utility of dynamic fetal cardiac MRI scanning, but searching for the fetal heartrate can be challenging due to fetal movement and can require time. Therefore, communication with the patient is important to explain that searching for the heartbeat may take some time and does not mean there is a problem with the fetus.

Positioning the body coil above the ultrasound gating device can cause compression on the device, which results in losing the gating signal and requires repositioning of the device. It is therefore important to ensure that there is no contact between the body coil and the transducer. Applying pads on the side of the ultrasound transducer can avoid the compression caused by the coil.

The trigger signal will be displayed on the scanner computer for signal monitoring under external trigger. Sometimes the fetal heartbeat will be lost during the scan, due to maternal and/or fetal movement, which will increase the scanning time. But it is often useful to wait rather than reposition, as the heartbeat can often be detected again after a pause. Often the signal is lost due to deep inspiration taken by the mother. Therefore, the mother is asked to take shallower breaths, which will reduce the movement and avoid missing the heartbeats. Additionally, the DUS will simulate up to 15 heartbeats if the heartbeat is lost. This often bridges short gaps due to breathing motion. However, retrospective 4D Flow MRI is often not easily achievable at present, as the sequence fails if heart beats are missed.

Maternal breathing artifact is in our experience the largest movement artifact. Breath-holding can be sufficient to eliminate the maternal movement. But the DUS transducer often moves position during breath-holding and the Ultrasound gating is lost all together. It is also very challenging for pregnant patients. Therefore, applying free-breathing techniques is often the more successful option.

Outlook

Fetal cardiac MRI faces a number of challenges, and one has to accept that there will be a percentage of fetuses where image quality might not be of diagnostic quality. We find that running a number of different transverse stacks with some targeted sagittal images will often provide sufficient information to understand the fetal cardiac anatomy. This can be useful to assess, for example, the degree of ventricular disproportion during the third trimester [3, 4]. Lung volume assessment [5] can be useful in significant tricuspid regurgitation and right atrial enlargement to assess the degree of right lung hypoplasia. In hypoplastic left heart syndrome, lung parenchyma can be assessed for damage (nutmeg lung) from a restrictive inter-atrial septum. Flow assessment allows further assessment of whether the inter-atrial septum is restrictive in both hypoplastic left heart syndrome and transposition of the great arteries. Quantification of tricuspid or mitral valve regurgitation can also be useful. Furthermore, comprehensive cine and flow assessment can also add information in borderline left ventricles. As more and more centers start using fetal cardiac MRI, further clinical uses will likely become apparent [6–8].

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