Basic Principles, Technique and Planning for Cardiac Magnetic Resonance Imaging

Shimaa Elsayed Abdo Abdellatif [1], Ghada Kamal Gouhar [1], Elsayed Hamed Zidan[1], Samar Mohammad Shehata[1], Hisham Samir Roshdy[2]

1 Department of Radiodiagnosis, Faculty of Medicine – Zagazig University, Egypt

2 Department of Cardiology, Faculty of Medicine – Zagazig University, Egypt

Corresponding author: Shimaa Elsayed Abdo Abdellatif

E-mail: seaabadr@medicine.zu.edu.eg, drshimaa30@gmail.com

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Abstract

Cardiovascular magnetic resonance (CMR) is an established advanced cross-sectional imaging modality for the functional and anatomical assessment of a wide range of cardiovascular diseases. CMR is safe, does not use ionizing radiation, provides diagnostic and prognostic information, and guides patient management. There are certain technical challenges unique to cardiac MRI. Most notably is the rapid and complex motion of the heart and pulsatility of the great vessels due to normal contractility. In addition, the effects of respiratory motion and systolic ventricular blood velocities up to 200 cm/s further complicate cardiac imaging. To select the optimal protocol to interpret cardiac MRI studies, the radiologist should understand the basic pulse sequences. In addition, the radiologist interpreting cardiac MRI studies should be familiar with basic cardiac anatomy and standard imaging planes.

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Introduction:

Cardiovascular magnetic resonance (CMR) is an established advanced cross-sectional imaging modality for the functional and anatomical assessment of a wide range of cardiovascular diseases. CMR is safe, does not use ionising radiation, provides diagnostic and prognostic information, and guides patient management. [1].

Indications for cardiac MRI.

Primary indications for cardiac MRI include, but are not limited to, assessment of the following: [2]

- **Acquired Heart Disease**

- Dynamic cardiac anatomy and ventricular function: Echocardiography is a reasonable first test for left ventricular (LV) function, although MRI is considered to be more accurate and reproducible because of its 3-D data acquisition.
- Assessment of cardiomyopathies, myocardial fibrosis, and infarction.
- Myocardial ischemia and viability: Magnetic resonance perfusion imaging during gadolinium infusion can be used to detect areas of perfusion abnormality at rest or during pharmacologically-induced stress.
- Characterization of cardiac masses: Magnetic resonance imaging is indicated to evaluate tumors with regard to specific tissue characterization (fat containing, cystic, fibrotic, etc.), origin, relationship to chambers and valves, and myocardial-extra cardiac extension.
- Pericardial disease: Cardiac MRI can be used to evaluate the size and location of pericardial effusions, help differentiate simple from complex or loculated fluid collections, and assess for pericardial thickening.
- Valvular Disease: Using phase contrast techniques and functional assessment, cardiac MRI has the capability to evaluate congenital or acquired cardiac valve stenosis or insufficiency.

Contraindications for cardiac MRI:

A) Absolute contraindications: [3]

- The cardiac implantable electronic device (CIED) such as pacemakers, implantable cardioverter defibrillators and cardiac resynchronization therapy devices.
- Metallic fragments such as intraocular foreign bodies, bullets, shotgun pellets, and metal shrapnel.
- Cochlear implants/ear implant.
- Drug infusion pumps (insulin delivery, analgesic drugs, or chemotherapy pumps).
- Catheters with metallic components (Swan-Ganz catheter)
- Magnetic Cerebral artery aneurysm clips
- Magnetic dental implants [3].

B) Relative contraindications:

There are several relative contraindications. A patient presenting with any of the following objects require an evaluation with caution before MRI:

- Coronary and peripheral artery stents
- Programmable shunts.
- Airway stents or tracheostomy.
- Ocular prosthesis
- Joint replacement or prosthesis
- Pregnancy is considered a relative contraindication for cardiac MRI, although there are no known risks to the fetus [4].

Technical challenges unique to cardiac MRI:

There are certain technical challenges unique to cardiac MRI. Most notably is the rapid and complex motion of the heart and pulsatility of the great vessels due to normal contractility. In addition, the effects of respiratory motion and systolic ventricular blood velocities up to 200 cm/s further complicate cardiac imaging [4].

Respiratory motion correction:

One of the simplest techniques for compensating for respiratory motion is breath holding. Using this approach, the acquisition of an image is performed while the subject is asked to hold breath for 10–30 s. Breath holding approaches offer the advantage of rapid imaging, and are technically easy to implement in compliant subjects. The breath-hold is usually done at end-expiration [5].

Navigator technique is used for patients who are not able to hold their breath. During free breathing the motion of the diaphragm changes the position of the heart, greater vessels and liver causing inconsistent image quality. This is because the same anatomical position is not found for each sampled k-space point. The navigation box detects the position of the diaphragm during each slice acquisition and imaging only occurs when the diaphragm falls within the acceptance window [6]. In addition, single shot and real-time acquisition can be used to assess cardiac function and flow in patients in whom breath holding is difficult [6].

Cardiac motion correction:

These issues are generally mitigated by implementation of ECG (cardiac) gating; and advanced pulse sequences. ECG gating can be either prospective or retrospective. Prospective gating consists of initiating image acquisition with R wave triggering. The advantage to this approach is that only the necessary data are collected. However, excessive heart rate variability limits the application of

this technique [4]. Retrospective gating involves continuous image acquisition throughout the cardiac cycle and selecting the desired data subsequently during post-processing. Although retrospective gating is less sensitive to heart rate fluctuations, retrospective gating is more time-consuming than prospective gating [4].

Technique of cardiac MRI:

- **Patient Preparation:**

Adequate patient preparation before a CMR examination is a mandatory part of good CMR practice. Checklists include MR indication, contraindications, informed consent, fasting, food, medications, renal function test and CBC analysis. Request the patient to use the rest room before procedure. Ask the patient to remove all metal object. Peripheral IV line is inserted. A detailed explanation of the exam and instructions on how to breathe should be provided to the patient. Patients should be comfortable during their MR examination [7].

- **Placement of the ECG electrodes**

Cardiac gating is usually performed using electrocardiogram (ECG) triggering. In general, vectorcardiography (VCG)-based QRS detection algorithms are used, which aim to detect the R-wave in their peak by recognizing the R-wave's rising edge [8].

Prior to the placement of ECG leads, skin preparation is essential to achieve optimal electrode contact. Chest hair must be shaved and the skin surface scrubbed with a mildly abrasive soap. The skin should be bare and clean prior to electrode application. [9]. In Philips MRI scanner, the wireless VCG sensor has a dual lead VCG monitoring capabilities based on 4 electrodes (MRI compatible). Place the first electrode (green) approximately 1 cm left to the xiphoid. Place the second (white) and third (red) electrodes to form a triangle around the nipple. The distance between the electrodes should be approximately 15 cm. Place the fourth (black) electrode to the left of the white electrode, near the axilla. Connect the green, white, red and black leads to the VCG electrodes as shown in **figure 1** [10,11].

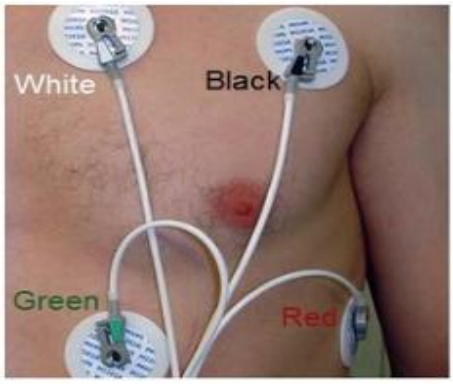

Figure 1: green, white, red and black leads denote the standard position of the conventional electrodes. Quoted from MRImaster.com [10].

Positioning:

Position the patient in a supine position (head first supine). Connect the ECG electrodes as specified above. Check the quality of the ECG in the integrated ECG display on the scanner terminal. If the signal is not satisfactory and consistent, change the location of the electrodes.

Place the body coil or the dedicated cardiac coil over the chest. Securely tighten the coil using straps to prevent respiratory artifacts. Give cushions under the head and legs for extra comfort. Center the laser beam localizer over mid chest (i. e. over the nipples) [10].

CMR general techniques:

To select the optimal protocol to interpret cardiac MRI studies, the radiologist should understand the basic pulse sequences. In addition, the radiologist interpreting cardiac MRI studies should be familiar with basic cardiac anatomy and standard imaging planes [4].

A. Dark-Blood Imaging sequences:

Dark blood imaging refers to the low-signal-intensity appearance of fast-flowing blood and is mainly used to delineate anatomic structures [4]. Morphologic black blood imaging is now performed with single-shot double inversion fast spin-echo techniques (Double-IR FSE). A fat saturation pre-pulse can be applied. These result in images that usually acquired in the standard orthogonal imaging planes (axial, sagittal, or coronal) [12]. **(fig. 2)**

The rapidity of acquisition is such that breath holding is not required. These sequences produce excellent depiction of the overall myocardial structure, as well as the relationships of the great vessels. They also provide excellent depiction of the walls of the great vessels and myocardium [12].

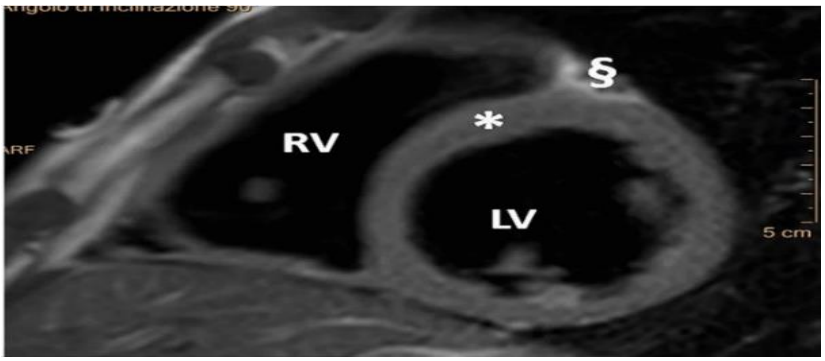

Figure 2: Short axis double inversion recovery black blood FSE image. In both ventricles left (LV) and right (RV) the blood signal is completely dark, allowing good evaluation of myocardium (*). Also, epicardial fat is clearly visible (§). Quoted from Russo et al. 2020 [13].

B. Bright-Blood Imaging Sequences:

Bright blood imaging describes the high signal intensity of fast-flowing blood [4], in which, low flip angle and gradient pulses are used. It is a popular form of CMR due to short acquisition time

(better temporal resolution). It yields faster image acquisition than spin-echo sequences [7]. It can be achieved through two strategies, either spoiled Gradient-echo (GRE) or Balanced steady-state free precession (SSFP). Spoiled GRE can yield fast acquisition of T1 images after injection of contrast agent, however, there is signals saturation when the TR is very short or the flow is very slow. Balanced steady-state free precession (SSFP) sequence provides rapid image acquisition with a high contrast to noise ratio (CNR), in addition, signal strength mostly unaffected by blood flow, however, it is sensitive to the off-resonance effect, causing dark band artifacts [7].

C. Cardiac Function (Cine Imaging):

The same steady state free precession (SSFP) technique used to produce bright blood static images may be adapted for cine acquisition. In this instance, multiple images are obtained at a single slice location in rapid succession during different phases of the cardiac cycle and can be displayed as a continuous movie loop. Cine imaging allows evaluation of ventricular wall motion abnormalities, dynamic changes in wall thickness, and measurement of chamber sizes. It also allows assessment of valvular morphology and function [12]. **(Fig. 3)**

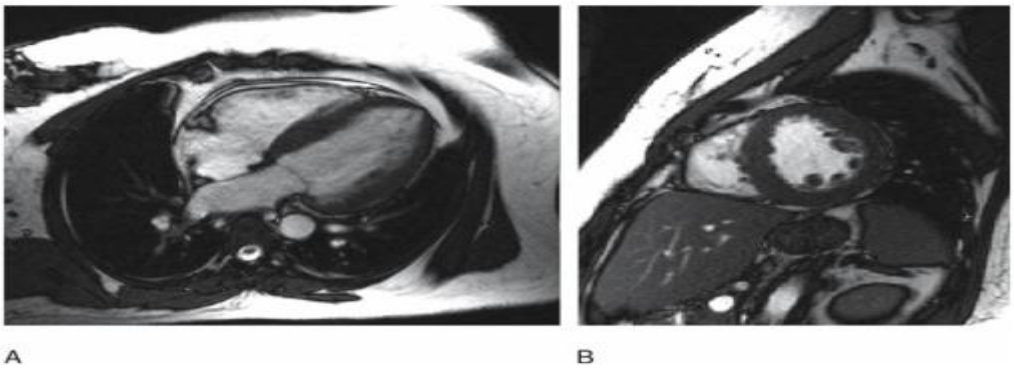

Figure 3: Four chamber (A), and short axis (B) cine images using SSFP. Quoted from Grizzard et al, 2008 [12].

D. Phase-Contrast (PC) and Flow/Velocity Studies:

PC-MRI is acquired similarly to conventional cardiac gated cine MR but, in addition to magnitude images, phase images are also acquired to indicate flow velocity. Phase images are obtained adding a bipolar velocity-encoding gradient and, since the phase shift is proportional to the flow velocity along the direction of the gradient, it is possible to quantify the phase shift caused by the flowing blood [13]. In phase-contrast cine, the stationary tissue appears intermediate signal intensity on the phase contrast image, while the flowing blood would appear white or black signal intensity, depending on the direction of the flow relative to the velocity-encoding gradients [14]. It is important to set the magnitude of the velocity-encoding gradient according to the estimated maximal velocity of the target vessel, otherwise aliasing artifact can appear [15].

PC-MRI is used for flow quantification through cardiac valves and within great vessels **(Fig. 4).** The technique allows for quantification of cardiac output, valve regurgitation, severity of vascular

and valvular stenosis, pulmonary to systemic flow ratio (i.e., QP/QS ratio, which reflects shunting of blood) and shunting flow in congenital heart disease [13].

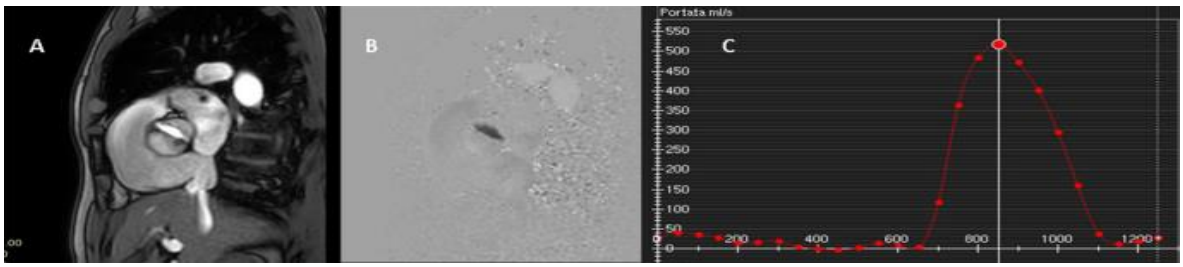

Figure 4: Example of evaluation of aortic flow in a patient with bicuspid aortic valve. Magnitude image (a) clearly depicts valve anatomy whereas signal intensity in phase image (b) indicates flow direction and velocity. Flow through the aortic valve plane is than calculated as the product of measured velocities by time within the valve (panel C). Quoted from Russo et al. 2020 [13].

E. Tissue characterization

Advanced myocardial tissue characterization may be achieved by MRI using both contrast-enhanced sequences (late gadolinium enhancement imaging) and parametric myocardial mapping techniques (T1, T2 mapping) [13].

1- Late gadolinium enhancement:

LGE has represented a milestone in cardiac MRI examination. The mechanism of the delayed enhancement in CMR is based on the kinetics of gadolinium. This paramagnetic contrast agent, once injected intravenously, diffuses from the plasma to the interstitial spaces of tissues, with extracellular distribution, then is completely washed away in 10–20 min. [13]. When myocardial tissue is damaged, the wash-out is reduced because of the augmented distribution volume of gadolinium due to cell membranes ruptures as in infarcted lesions or to the expanded interstitial space like in tissue fibrosis or inflammation. This delayed wash-out is emphasized by MRI acquiring a T1-weighted sequence generally 10–15 min after gadolinium injection to differentiate bright areas of contrast medium accumulation (LGE) from normal myocardial areas, where gadolinium has already been washed away [16]. The conventional LGE sequence is an ECG-gated segmented inversion recovery fast low angle shot (FLASH) gradient-echo acquisition [17].

It starts with a trigger delay after the r-wave (to acquire in diastole) applying a non-selective 180-degrees inversion pulse to prepare longitudinal magnetization (TI dependent) and the acquisition starts after an inversion time (TI) that approximates the zero crossing of magnetization recovery to null the signal of normal myocardium that appears black. The choice of the proper TI can be facilitated by a preventive look-locker sequence that acquires multiple images at different TI [13]. The currently preferred LGE sequence is a phase-sensitive inversion recovery (PSIR) acquisition, that differently from traditional magnitude inversion recovery preserves the polarity of tissues while

recovering from the inversion pulse, so that it is less sensitive to TI variations, improving the contrast-to-noise ratio [17].

The mostly used protocol is the one with a bidimensional (2D) PSIR that requires multiple breath-holds (each for a single slice) to cover the ventricles. This approach achieves high-quality images with high spatial resolution allowing for the evaluation of thin walls, the analysis of subtle lesions or the identification of the lesion borders for the quantification of the area at risk of myocardial infarcts [13]. Breath-hold acquisitions may suffer from respiratory artifacts. In addition, in case of arrhythmias the R–R interval variation could affect the signal intensity over a breath-hold and generate artifacts. For this reason, faster sequences have been developed. Single-shot imaging with SSFP allows for multislice acquisitions within a breath-hold using a different read-out technique of K-space [18].

For breath-hold duration limitations another alternative sequence is the single-shot navigated free-breathing sequence that uses multiple repeated measurements averaging to correct respiratory motion and may enhance its SNR [18]. Another approach to reduce the limitation of multiple breath-hold uses a 3D LGE within a single breath-hold or the image navigated free breathing 3D protocol that could obtain high-quality imaging (isotropic resolution) reducing the time acquisitions compared to the standard 2D sequences [17,19].

2- Myocardial mapping

LGE imaging is based on the contrast resolution between different areas of the myocardium so that it may identify a focal fibrosis (scar) or a segmented lesion while diffuse fibrosis of the myocardium may be difficult to be depicted [13]. Parametric maps of T1 and T2 values and extracellular volume (ECV) quantification represent an emergent opportunity for the quantification of the myocardial diseases process and their spatial visualization following the changes of myocardial T1 and T2 relaxation rates pixel by pixel, differently from traditional T1 and T2 weighted sequences [20]. **(Fig. 5)**

The myocardial T1 is influenced by disease processes altering the water concentration (edema), the interstitial collagen concentration or other proteins like amyloid [13].

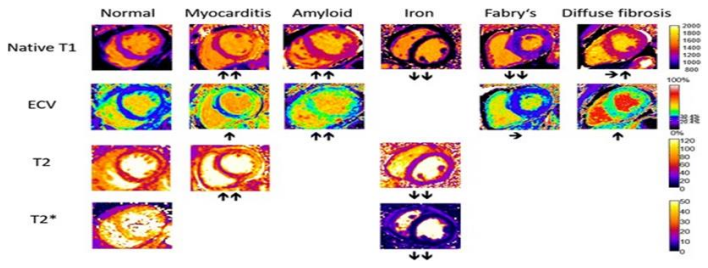

Figure 5: Typical appearance of T1, T2, T2*, and ECV maps in healthy subjects and in patients with myocardial disease. Arrows denote relative change in respective parametric maps. Quoted from Messroghli et al. 2017 [21].

- **T1 mapping and ECV**

The T1 mapping sequences similarly to the LGE acquisitions start with a 180 degrees inversion pulse to excite magnetization, a series of single-shot T1 weighted images are acquired at different TI with a temporal pre-defined scheme related to the heart-beats. The process is repeated following a pause for complete T1 recovery with a slight variation of TI to sample more points on the relaxation curve until all the pixel of cardiac image are covered. The set of images are ordered with increasing TI. A T1 map of the slice is created with an estimate of T1 of each pixel that is encoded as signal intensity in the map [21]. There are different T1 mapping sequences whose duration depends on heart rate. The estimates of T1 for each pixel are affected by several potential source of error like breath-hold alterations, cardiac motion, rhythm irregularities and blood signal artifacts. The most used and solid sequences are the Modified Look-Locker Imaging (MOLLI) and Shortened MOLLI (ShMOLLI) acquisitions that derive from the original Look-Locker sequence. The ShMOLLI has a reduced breath-hold time that anyway best fits with long pre-contrast T1 [22,23]. Another application is the Saturation Recovery Single-Shot Acquisition (SASHA) that uses a saturation recovery pulse instead of the inversion pulse. The mapping technique may be acquired as a pre-contrast application (native T1) that can investigate diffuse pathological changes of myocardium. Diffuse fibrosis elevates myocardial T1 mapping values, but is not specific because it occurs also in myocarditis and infarction. The most robust parameter to quantify diffuse fibrosis is the extra cellular volume fraction (ECV) that represents the distribution volume of the gadolinium in the myocardium and it is less sensitive to the various confounding factors that affect native and post-contrast T1 like gadolinium clearance rate and injection parameters, body composition and others [24]. **(Fig. 6)**

It is calculated by the application of a specific formula with the adjoin of hematocrit value and requires both native and post-gadolinium T1 measurement [21].

ECV = (1 – hematocrit) × (1/T1 myocardium post-contrast – 1/T1 myocardium pre-contrast)/(1/T1 blood post-contrast – 1/T1 blood pre-contrast)

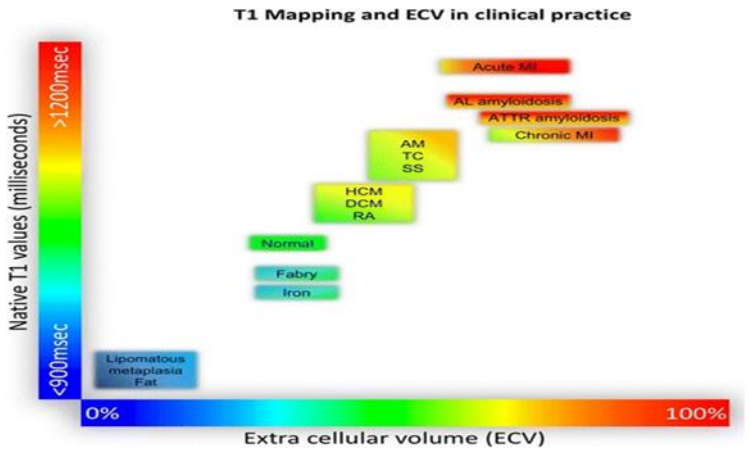

Figure 6: Alterations of T1 and ECV in different myocardial diseases T1 values refer to MOLLI-based techniques at 1.5 T. Quoted from Messroghli et al. 2017 [21].

Cardiac imaging planes:

A. Body Axes:

Generally, a CMR study starts with "localizers" which usually are non-gated steady-state free precession (SSFP) sequences oriented orthogonal to the long axis of the body and consist of axial, sagittal, and coronal planes, which can serve as a starting point for generating all the imaging planes needed for the examination. The standard three orthogonal planes normally used for MR imaging do not match with the cardiac axes [13]. **(fig. 7).**

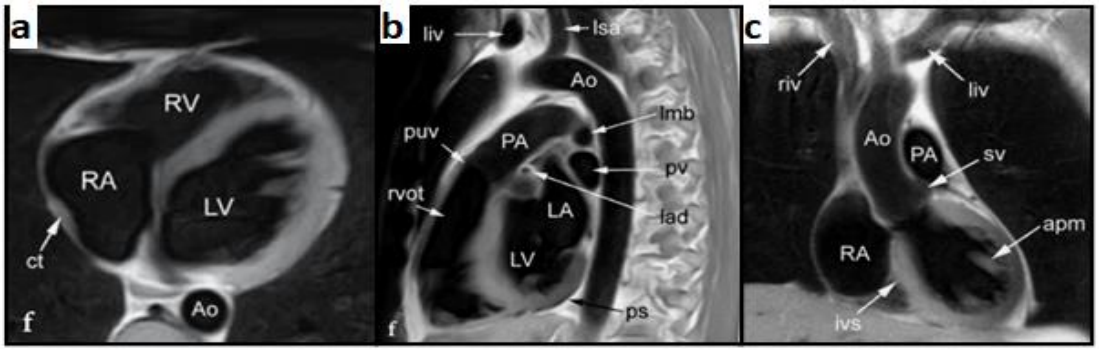

Figure 7: Axial (a), Sagittal (b) and coronal (c) images for the heart (Quoted from, Bogaert et al. 2011) [6].

B. Cardiac Axes:

The standard cardiac planes are established using the scout images and include horizontal long axis (four-chamber view), vertical long axis (two-chamber view) and short axis view. These planes are prescribed along a line extending from the cardiac apex to the center of the mitral valve (long axis of the heart) using the axial body plane images [4] and then perform the cardiac planes as follows:

- <u>Localizers Modules:</u>

- Planning the vertical long axis (2-chamber scout view):

Using the axial scout image, a new plane is chosen running through the apex of the LV and the center of the mitral valve. This yields the vertical long-axis (VLA) plane [25]. **(Fig. 8)**

- Planning the horizontal long axis (4-Chamber scout view):

A plane aligned orthogonal to the vertical long axis (2 chamber), passing through the center of the mitral valve and left atrium and continuing through the long axis of the LV [26]. **(Fig. 8 , 9)**

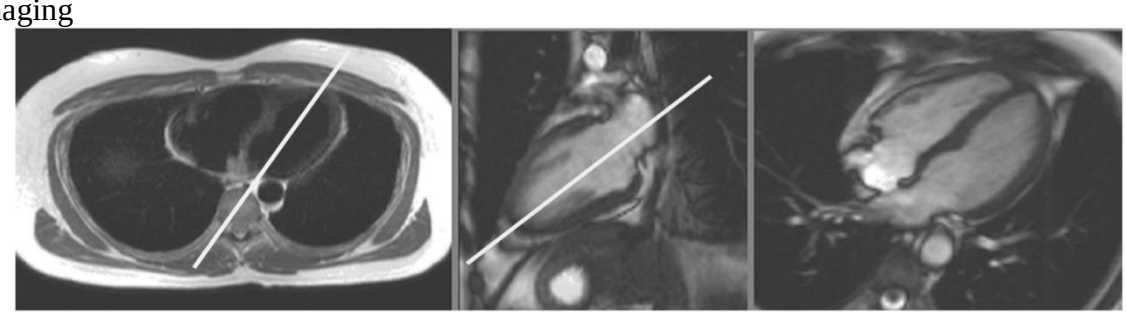

Figure 8: Left – Black blood axial scout image through the base of the left ventricle (LV) and right ventricle (RV). Planning of the 2 chamber long-axis is shown by the white line. Center – White blood 2 chamber long axis scout image. Planning of the 4 chamber long-axis is shown by the white line. Right – White blood 4-chamber long axis scout image. Quoted from Kramer et al,2020. [26].

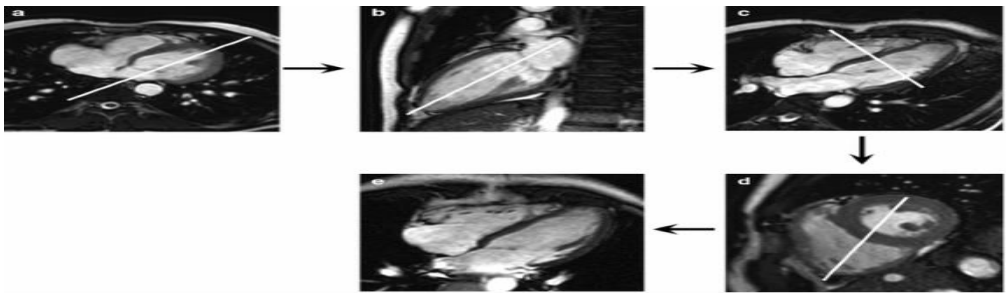

Figure 9: Cardiac axis imaging planes for the left ventricle, images acquired using a SSFP sequence. The vertical long-axis plane (VLA) (b) is aligned from the axial plane (a) through the mitral valve and the LV apex, which may be on a separate more inferior slice. The horizontal long-axis plane (HLA) (c) is aligned from the VLA through the mitral valve and LV apex. The short-axis plane (SA) (d) is aligned from the VLA and HLA planes—perpendicular to both. The 4-chamber plane (e) is aligned from the SA through the anterior mitral valve papillary muscle and the apex of the RV. Quoted from Taylor et al. 2011 [25].

- **Left ventricular (LV) structure and function:**

- **Planning the short axis (SAX) bSSFP cine images:**

Acquired from the base of the LV through the apex. The first short-axis cine plane should be planned using the 4- and 2-chamber long-axis views, and it should be perpendicular to the long-axis of the body of the LV. Slice thickness 6–8 mm, with or without 2–4 mm interslice gaps (to make a total of 10 mm) [26]. **(Fig. 10)**

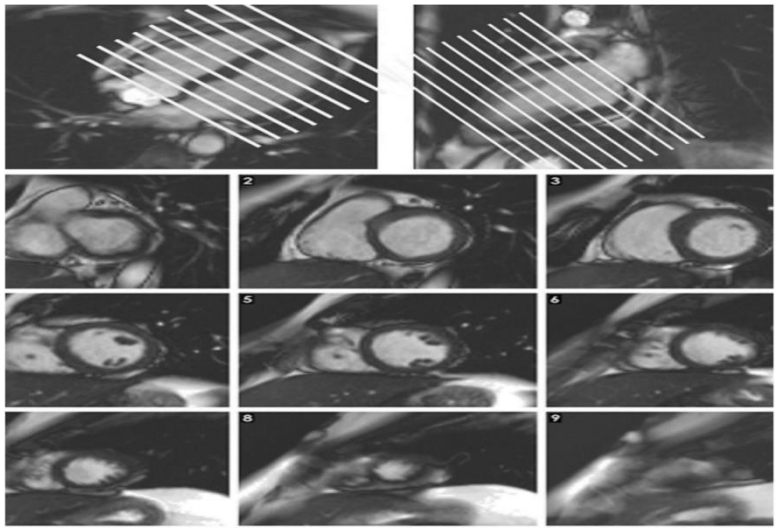

Figure 10: Top – Planning of the short axis image plane parallel to the mitral valve in the 4 chamber long axis plane (left) and 2 chamber long-axis plane (right). Bottom panel – 9 short axis cine slices shown from base (top left) to apex (bottom right). Quoted from Kramer et al,2020 [26].

- **Long axis bSSFP cine images:**

- **The 4-chamber long-axis view** is prescribed from the 2-chamber long-axis view through the apex and center of the mitral and tricuspid valves. This can be modified and/or cross-checked on basal short-axis views, to have the plane cross the acute margin of the right ventricular (RV) free wall and perpendicular to the interventricular septum.

- **The 2-chamber LV view** is prescribed from the vertical long-axis scout already acquired with modification to pass through the anterior and inferior myocardial walls.

- **The 3-chamber LV** view is prescribed passing through the apex, the center of the mitral valve (on 2 chamber view) and aligned with the center of LV outflow tract (LVOT) to aortic valve, as seen on a basal short axis cine [26]. **(Fig. 9, 11)**

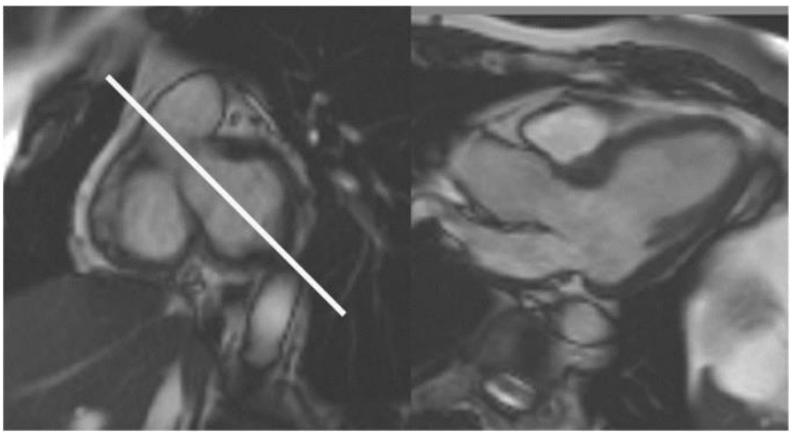

Figure 11: Left – Basal short axis cine image. Planning of the 3-chamber long axis is shown by the white line. Right – 3-chamber long axis cine image. Quoted from Kramer et al,2020. [26].

- **bSSFP LVOT cine images**

LVOT view can be acquired by passing an imaging plane through and perpendicular to the aortic valve; oblique coronal orientation **(Fig. 12)** This can be easily achieved by indicating on an LV 3-chamber image a perpendicular imaging plane through the middle of the LVOT and aortic valve. A plane through the aortic root ("aortic valve plane"), just above the aortic valve, perpendicular to both the LV inflow/outflow and LVOT views, can be used to assess through-plane aortic flow [25].

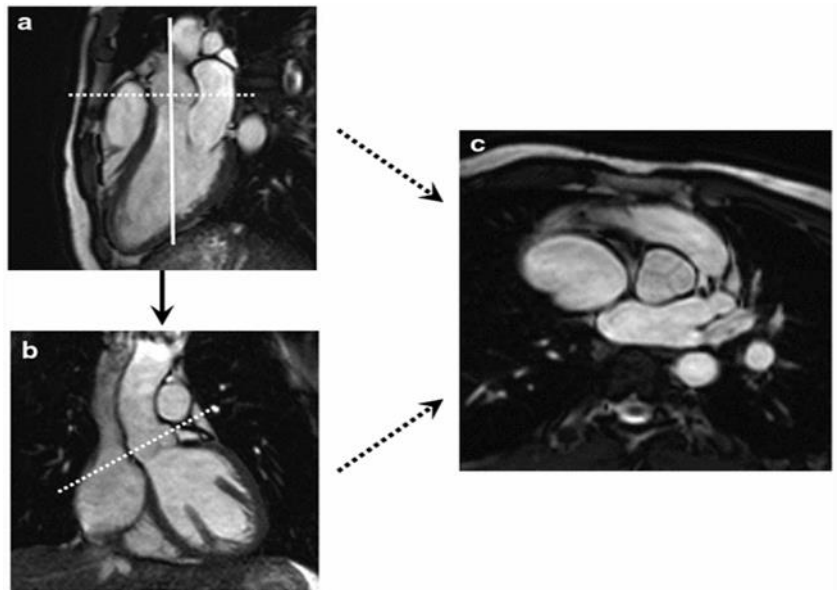

Figure 12: Alignment of the aortic valve plane (c) for aortic flow assessment from the LV 3 chamber view (a) and the left ventricular outflow tract (LVOT) (b) views (dotted lines). The imaging plane should be placed just above the aortic valve, yet just below the origin of the coronary artery. The LVOT view is prescribed perpendicular to the LV inflow/outflow view (complete line on (a)). Quoted from Taylor et al, 2011 [25].

- **Right ventricular (RV) structure and function**

- Transaxial stack of cines covering the RV can be considered as an alternative for RV volumetry. **(Fig. 13)**

- Long-axis images should include an RV vertical long-axis view aligned with tricuspid valve inflow and an RV outflow tract view (sagittal or oblique sagittal plane through the pulmonary valve) [26]. **(Fig. 13)**

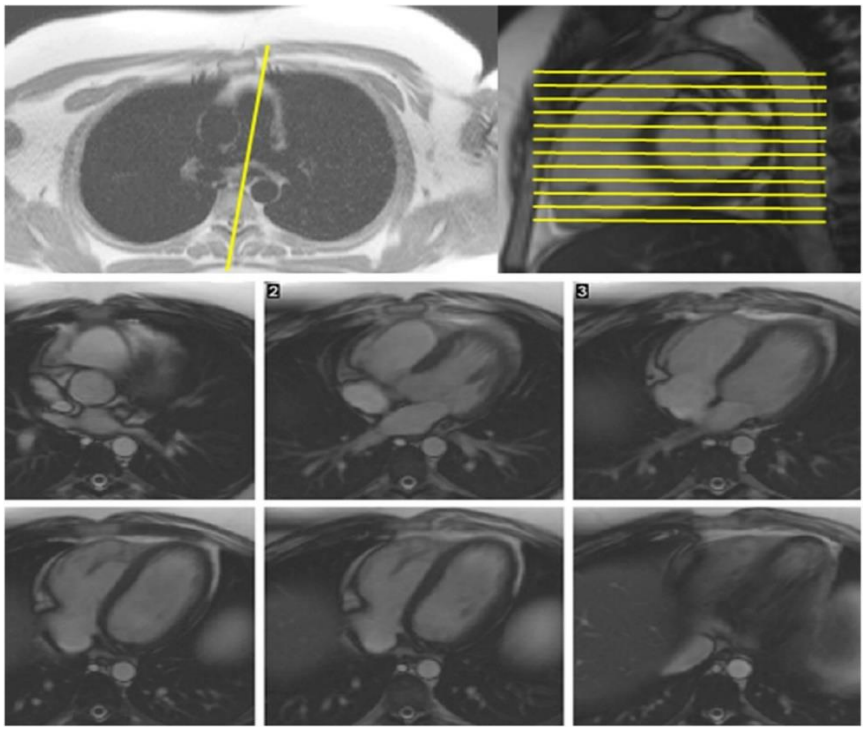

Figure 13: Top left – Axial black blood scout image through the pulmonary artery. Planning of the RV outflow tract (RVOT) view is shown by the yellow line. Top right – RVOT cine image. Planning of axial stack of images is shown by the yellow lines. Bottom panel – 6 sequential axial images are shown from the RVOT (top left) to the inferior pole of the RV (bottom right). Quoted from Kramer et al. 2020. [26].

- **Late gadolinium enhancement (LGE)**

2D segmented inversion recovery GRE or bSSFP, Phase-Sensitive Inversion-Recovery (PSIR) is performed in approximately 10 minutes after contrast injection in short axis stack, 2, 3 and 4 chamber view.

Slice thickness, same as for cine imaging. In-plane resolution, ~ 1.4–1.8 mm [26].

- **T1 mapping**

Native T1 mapping is performed in the absence of contrast agents. Look Locker imaging (modified Look Locker Inversion recovery (MOLLI) or shortened MOLLI (ShMOLLI) or equivalent) should be used. The number and orientation of slices obtained will depend upon the indication. At least one short-axis map should always be obtained. Slice thickness: 6–8 mm, in-plane resolution ~ 1.6–2.0 mm [26].

For extracellular volume measurements, T1 mapping should be performed prior to contrast and at least 1 time point between 10- and 30-min post contrast bolus. The hematocrit should be measured, ideally within 24 h of imaging, for the most accurate extracellular volume fraction (ECV) measurement [26].

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