EUROPEAN SOCIETY OF RADIOLOGY

eBook for Undergraduate Education in Radiology

CHAPTER: Cardiac Imaging

Preface

Undergraduate teaching of radiology in Europe is provided according to national schemes and may vary considerably from one academic institution to another. Sometimes, the field of radiology is considered as a "cross-cutting discipline" or taught within the context of other clinical disciplines, e.g., internal medicine or surgery.

This e-book has been created in order to serve medical students and academic teachers throughout Europe to understand and teach radiology as a whole coherent discipline, respectively. Its contents are based on the *Undergraduate Level of the ESR European Training Curriculum for Radiology* and summarize the so-called ***core elements*** that may be considered as the basics that every medical student should be familiar with. Although specific radiologic diagnostic skills for image interpretation cannot be acquired by all students and rather belong to the learning objectives of the *Postgraduate Levels of the ESR Training Curricula*, the present e-book also contains some ***further insights*** related to modern imaging in the form of examples of key pathologies, as seen by the different imaging modalities. These are intended to give the interested undergraduate student an understanding of modern radiology, reflecting its multidisciplinary character as an organ-based specialty.

We would like to extend our special thanks to the authors and members of the ESR Education Committee who have contributed to this eBook, to Carlo Catalano, Andrea Laghi and András Palkó who initiated this project, and to the ESR Office, in particular Bettina Leimberger and Danijel Lepir, for all their support in realising this project.

We hope that this e-book may fulfil its purpose as a useful tool for undergraduate academic radiology teaching.

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Chapter Outline

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eBook for Undergraduate Education in Radiology

Based on the ESR Curriculum for Undergraduate Radiological Education

Chapter: **Cardiac Imaging**

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Anatomy

Strengths, Weaknesses and Role of Imaging Modalities

Ischemic Heart Disease

Cardiomyopathies and Myocarditis

Pericardial Disease

Congenital Heart Disease

Cardiac and Paracardiac Masses

Test Your Knowledge

Anatomy

The heart is located in the centre of the thoracic cavity, in the middle mediastinum
- Behind the sternum and the costal cartilages, which protect it like a shield
- In front of the vertebral column, from which it is separated by the oesophagus and aorta
- On top of the diaphragm, which separates it from the underlying viscera
- Between the two lungs

Its shape can be approximated to that of a truncated cone, that is orientated in the thorax with its apex projecting forward, to the left and downward, and the base faces in a posterior direction.

The weight is about 250-300 g in the adult, measuring 12 cm in length, 9-10 cm in width and about 6 cm in thickness.

Fig. 1. Different coronal views of the heart on a conventional X-ray (A: PA projection), CT (B) and MRI (C) images.

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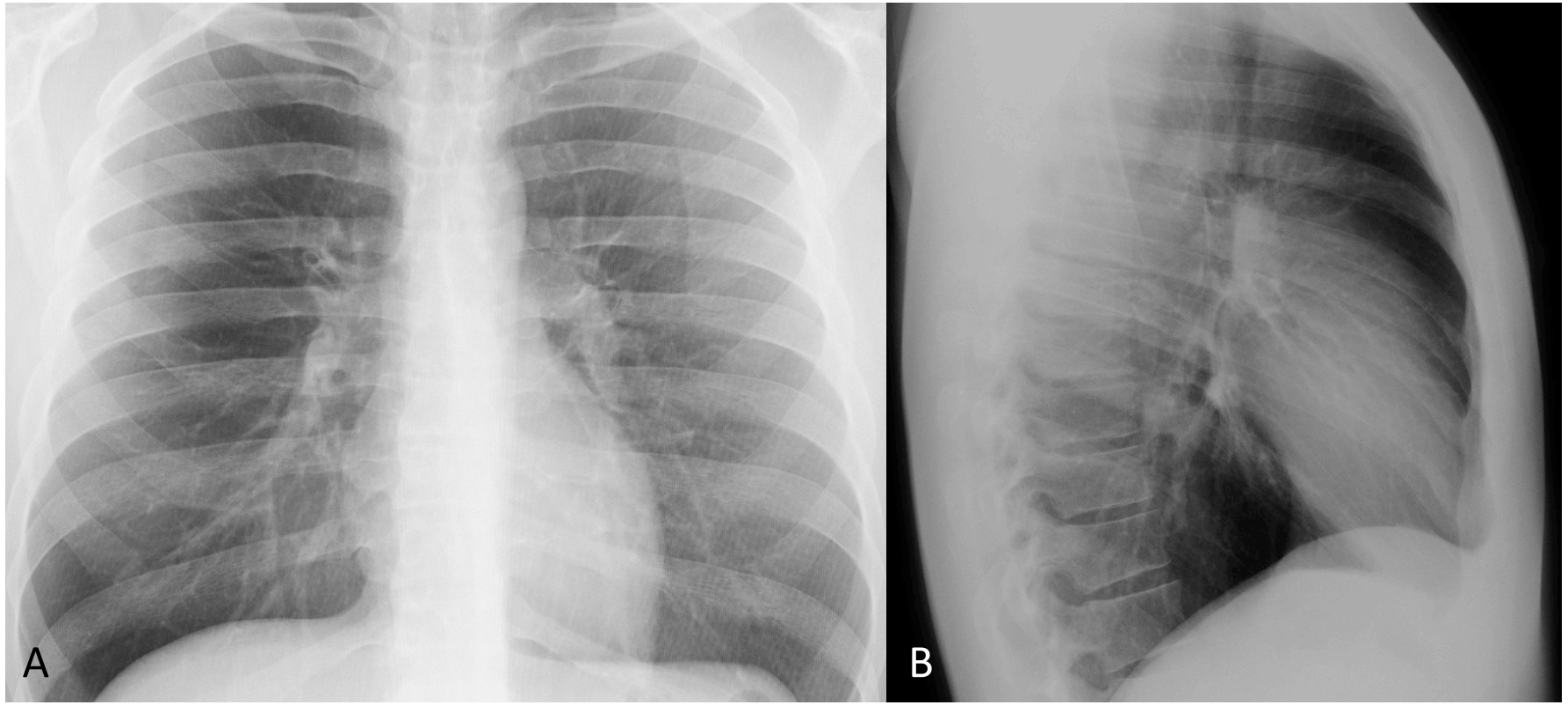

Fig. 2. Chest X-ray; the cardiac silhouette can be appreciated in PA (A) and left lateral (LL, B) projections.

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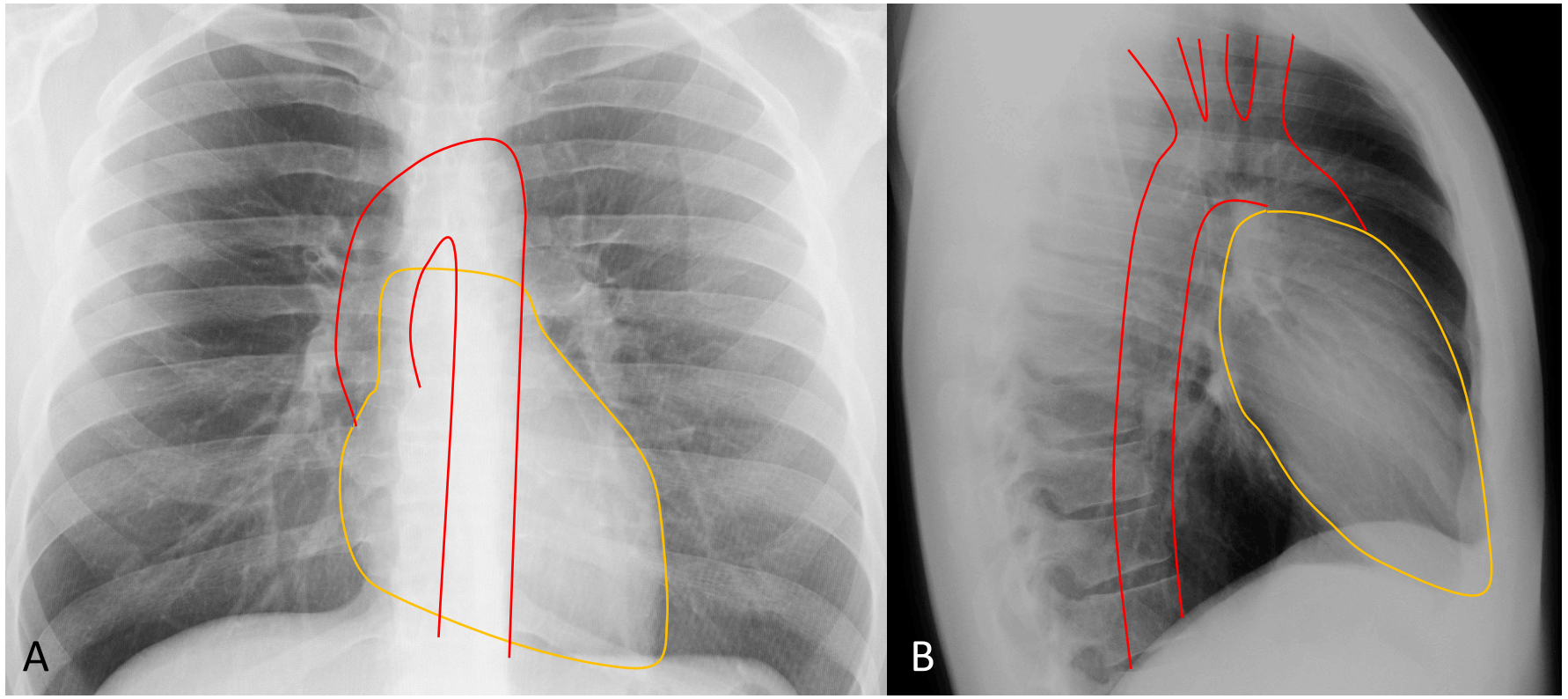

Fig. 3. Chest X-ray (CXR): A: postero-anterior (PA) view; B: left lateral (LL) view; the yellow line encircles the cardiac silhouette, that projects for 1/3rd on the right side and 2/3ds on the left side of the midline. The red line encircles the thoracic aorta: ascending aorta arises from the left ventricle and continues in the aortic arch and then in the descending aorta, whose outline is easier to appreciate in the LL projection rather than in the PA projection.

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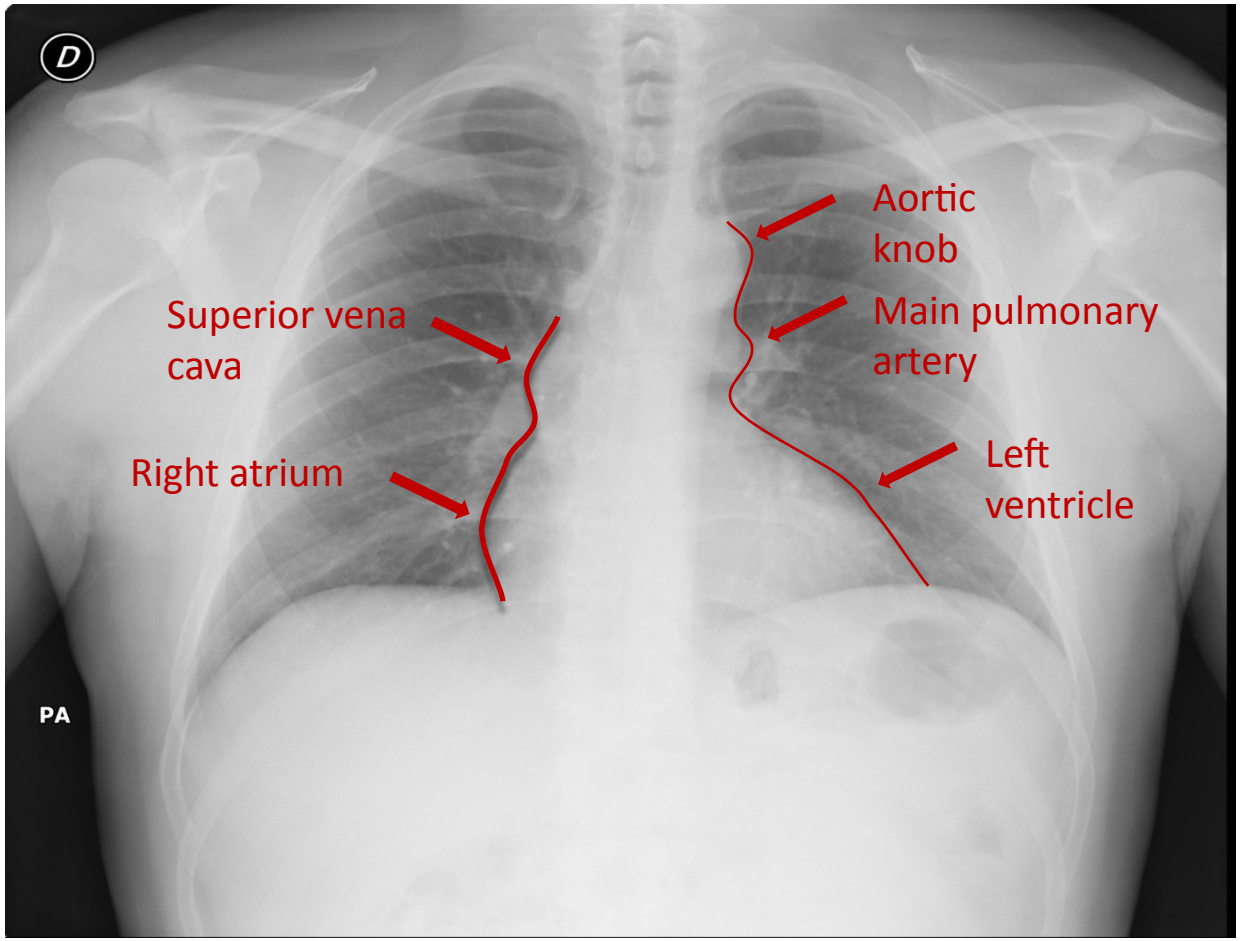

Cardiac contours on Chest X-ray

Fig. 4. Chest X-ray, PA projection. On the right side two contours can be identified, the superior one is a low-density line close to the vertebral column, it is caused by the superior vena cava. This contour meets inferiorly with the second one, formed by the right atrium. On the left we can identify three contours: the most cranial one is known as the aortic knob, it is formed by the overlapping of the aortic arch and the the first portion of the descending aorta. Just below this first contour is the second one, the main pulmonary artery. The third and most caudal of the left contours is formed by the left ventricle.

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Computed Tomography

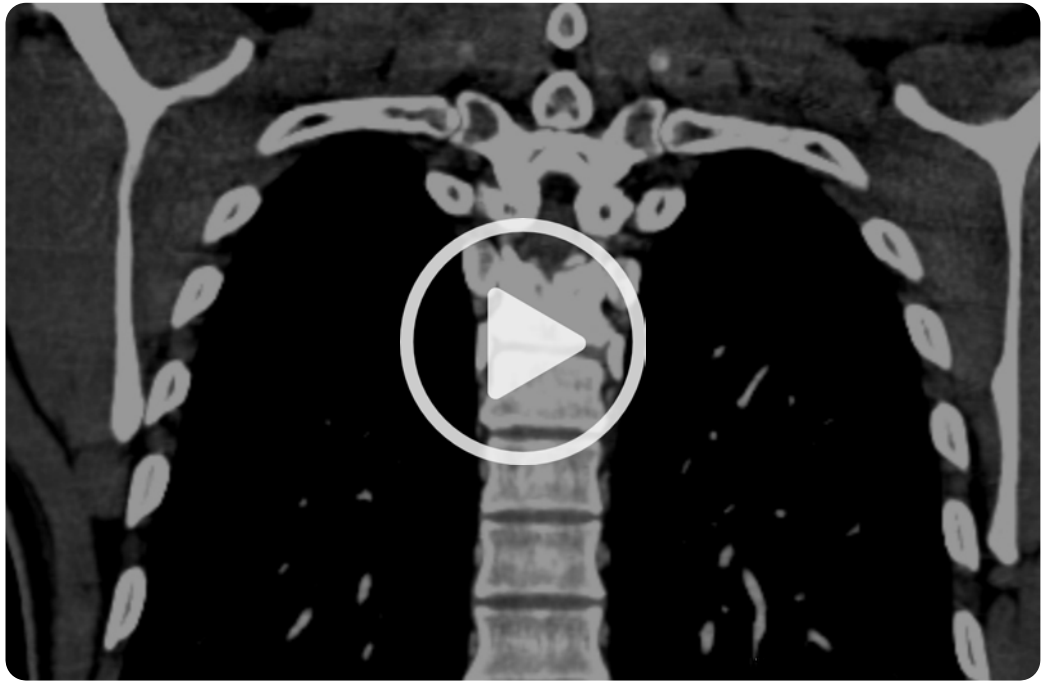

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Fig. 5. CT series of coronal slices showing the heart (yellow line) located in the mediastinum between the two lungs, and the thoracic aorta (red line). The aorta can be clearly seen originating from the left ventricle at the aortic valve.

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Cardiac Chambers

The heart has four chambers: two right chambers and two left chambers separated by interatrial and interventricular septa.

Right atrium and right ventricle receive blood from the superior and inferior vena cava and eject it into the pulmonary trunk.

Left atrium and left ventricle receive blood from the pulmonary veins and eject it into the aorta.

The atria have thin walls and a reservoir function, they receive blood from the veins and convey it into the corresponding ventricles through the atrioventricular valves (mitral and tricuspid).The ventricles have a pump function, they push the blood into the large arteries through the semilunar valves (aortic and pulmonary).

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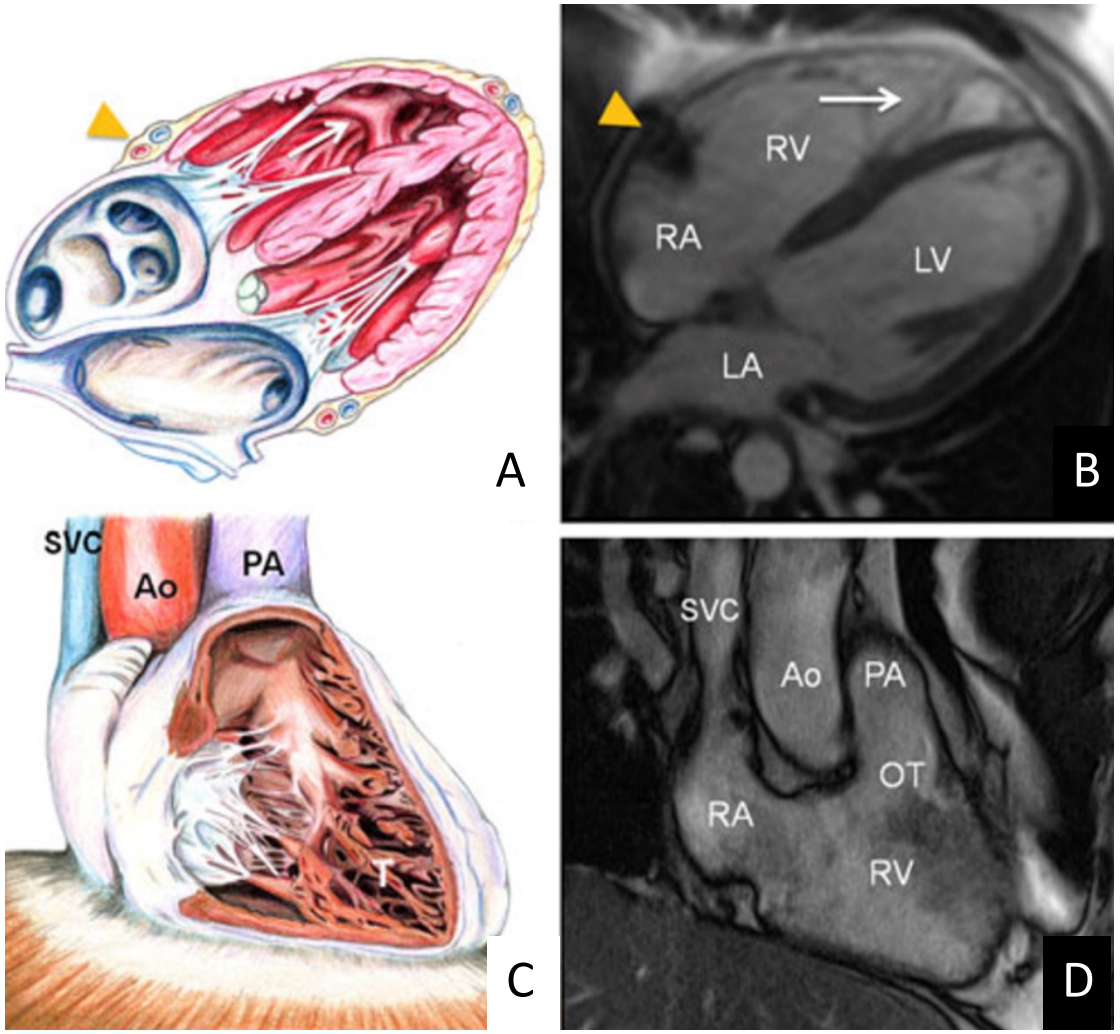

Fig. 6. Freehand drawings (A, C) and corresponding MRI images on four-chambers (B) and three-chambers view (D) demonstrating right ventricular anatomy. We can appreciate the moderator band (white arrow), and the right atrio- ventricular groove (orange arrowheads), containing the right coronary artery and small cardiac vein.
In (D) the RA and RC are depicted along with the OT, the PA and the inflow tract (SVC).

RA=right atrium, RV= right ventricle, LA= left atrium, LV= left ventricle, SCV=superior vena cava, Ao=aorta, PA=pulmonary artery, OT=right ventricular outflow tract. T = trabeculations.

Figure reproduced from: Galea, N., Carbone, I., Cannata, D. *et al.* Right ventricular cardiovascular magnetic resonance imaging: normal anatomy and spectrum of pathological findings. *Insights Imaging* **4**, 213–223 (2013). https://doi.org/10.1007/s13244-013-0222-3

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Cardiac Valves

- Atrioventricular valves: open during diastole and close during systole
  - Tricuspid valve, on the right side, made of three leaflets;
  - Mitral valve, on the left side, made of two leaflets

- Semilunar valves: so named for the crescent shape of their cusps, open during systole and close during diastole
  - Aortic valve, on the left side, typically tricuspid
  - Pulmonary valve, on the right side

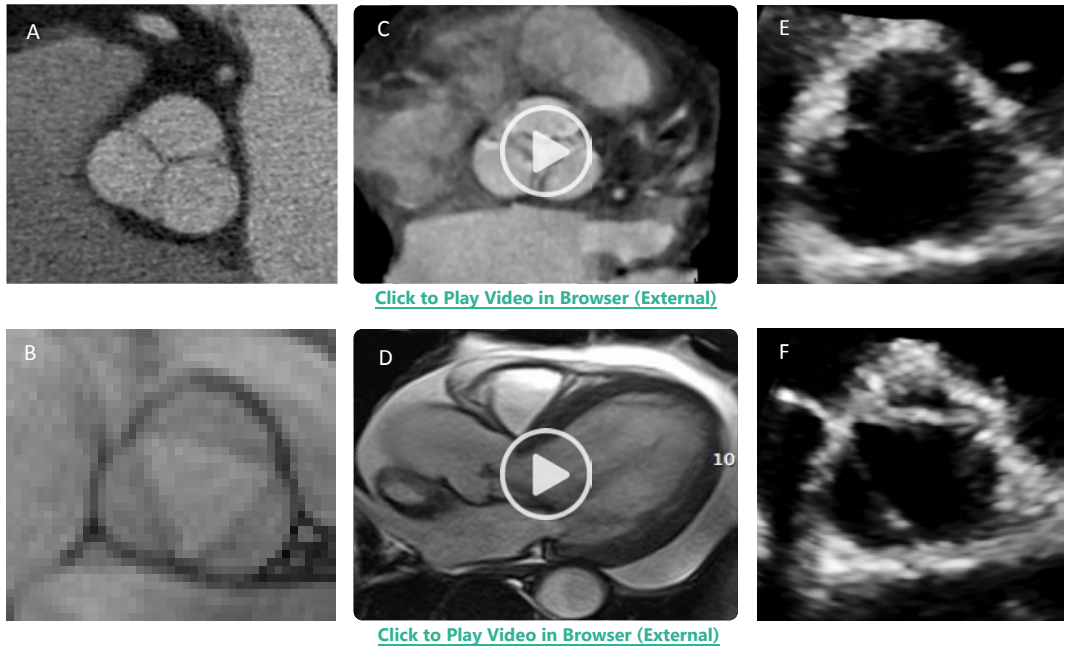

Fig. 7. Aortic valve morphology in CT (A) and MR scans (B). Aortic valve function in cine CT (C) showing cusps movement and cine MR (D) showing transvalvular flow, which appears as a «black jet». Echocardiographic images of a closed (E) and open (F) aortic valve.

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Pericardium

A thin flask-shaped fibroserous membrane, that contains the heart and the roots of the great vessels and is composed of two layers, the inner serosa (also referred as the visceral pericardium) and the outer serosa (parietal pericardium). It forms a complete sac filled with up to 50 mL of plasmatic ultrafiltrate.

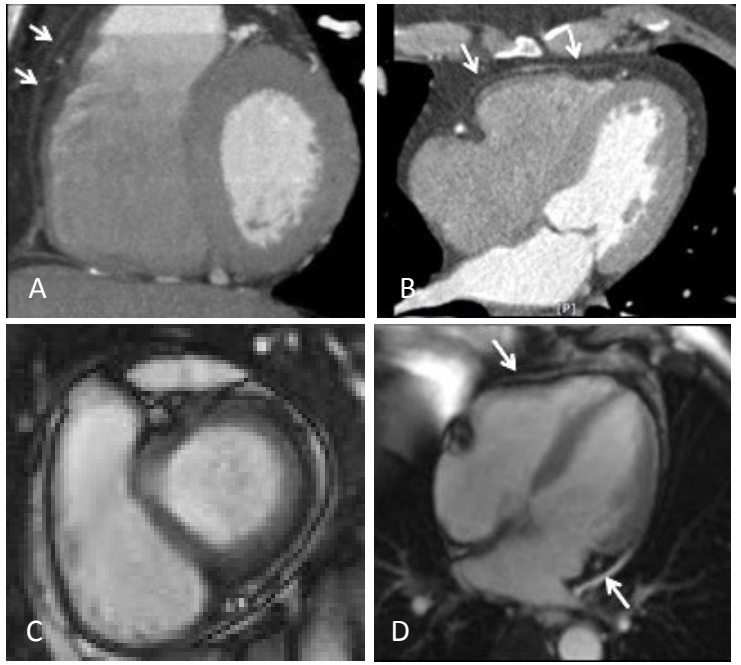

Fig. 8. CT scan (A,B) showing normal appearance of pericardium. Normal pericardium is also shown as it appears in «white-blood» and «black-blood» MRI sequences (C,D).

Innervation

The heart has extrinsic and intrinsic innervation, which stimulate the heartbeat independently and coordinately. The cardiac conduction system consists of a pacemaker centre at the level of the sinus node and conduction pathways that transmit the pulse up to the ventricular myocardium.

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Blood Supply

Coronary Anatomy

Two coronary arteries arise from the sinuses of the aortic root: the right coronary artery (RCA) from the right sinus, the left main coronary artery (LM) from the left sinus.

- RCA descends in the coronary sulcus between right atrium and ventricle, turns posteriorly onto the diaphragmatic surface of the heart still following the sulcus. It gives off atrial and acute marginal branches.
- LM passes between pulmonary trunk and left auricle before entering the coronary sulcus, here it divides into the left anterior descending artery (LAD) and Left circumflex artery (LCX).
    - LAD descends obliquely towards the apex in the anterior interventricular septum while giving off diagonal and septal branches.
    - LCX runs in the coronary sulcus up to the diaphragmatic surface of the heart giving off obtuse marginal branches.

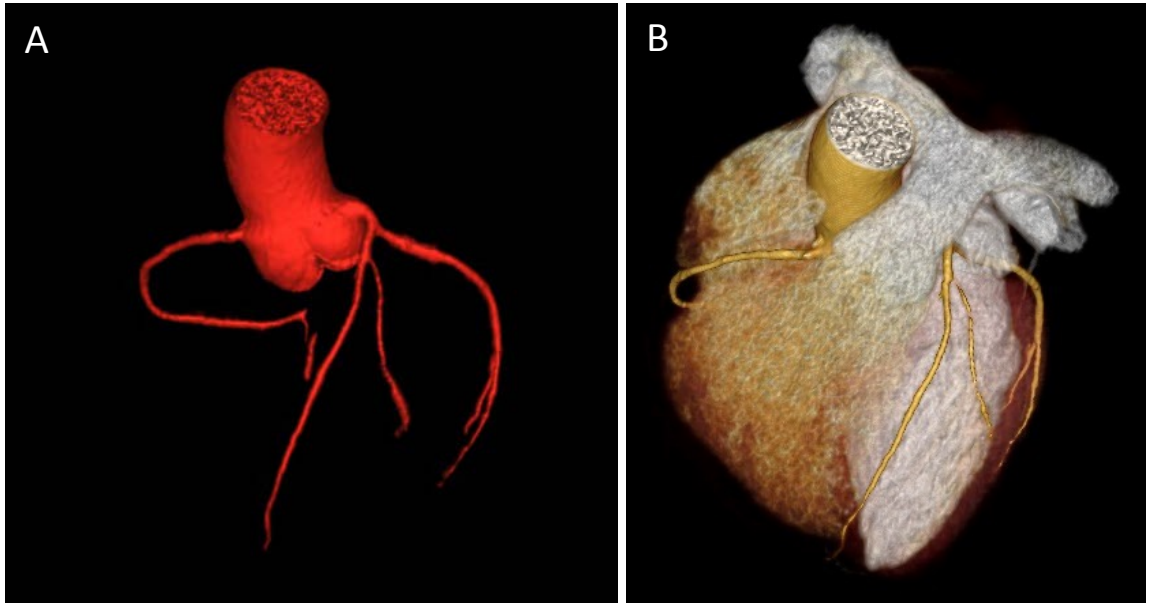

Fig. 9. (A) CT 3D Volume Rendering of the aortic root and coronary tree. (B) CT 3D Volume Rendering of heart and coronary tree

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- RCA supplies the right atrium and ventricle, the sinoatrial and atrioventricular nodes and the posterior one third of the interventricular septum (in cases of right dominance, see below).
- LAD supplies the anterior two thirds of the interventricular septum and the anterior wall of the left ventricle
- LCX supplies the lateral wall of the left ventricle and the left atrium.

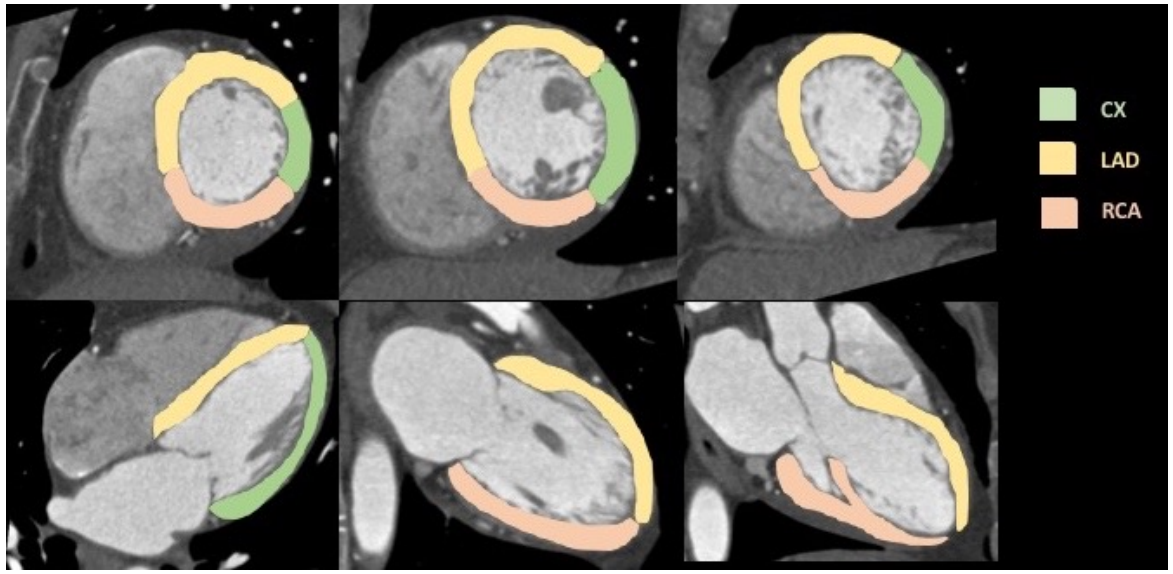

Fig. 10. Graphic representation of the coronary artery territories.

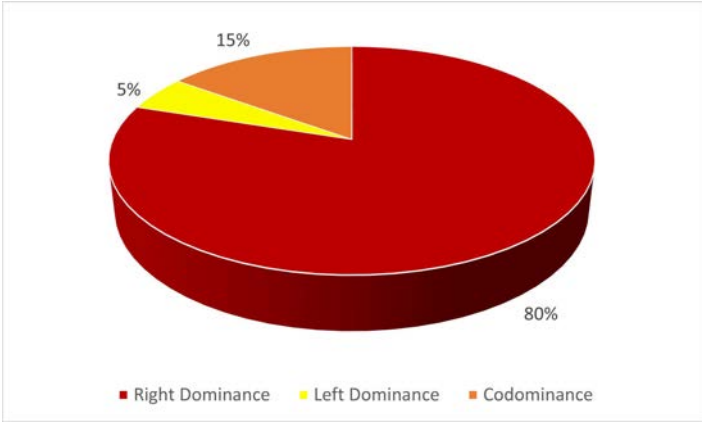

Fig. 11. Coronary dominance refers to the coronary artery giving off the posterior interventricular artery. Right dominance occurs in 80% of the population, left dominance (from the LCX) in 5% and codominance in 15%.

Venous Drainage:

The coronary veins return deoxygenated blood from the myocardium back to the right atrium. Most venous blood returns via the coronary sinus.

Chapter Outline

Chest X-Ray

Chest X-ray can show abnormalities in the size and shape of the heart, which may indicate heart failure, pericardial effusion or heart valve disorders. Moreover, chest x-ray may reveal pulmonary changes as a consequence of heart disease (e.g. pulmonary oedema as result of congestive heart failure).

The main limitation of this modality in the study of the heart is the difficulty in distinguishing the various overlapping cardiac structures, as they share similar radiographic density.

Understanding what makes up the normal contours of heart and mediastinum on a PA chest X-ray is an important skill for most physicians, as it is required to correctly allocate any abnormality that is detected.

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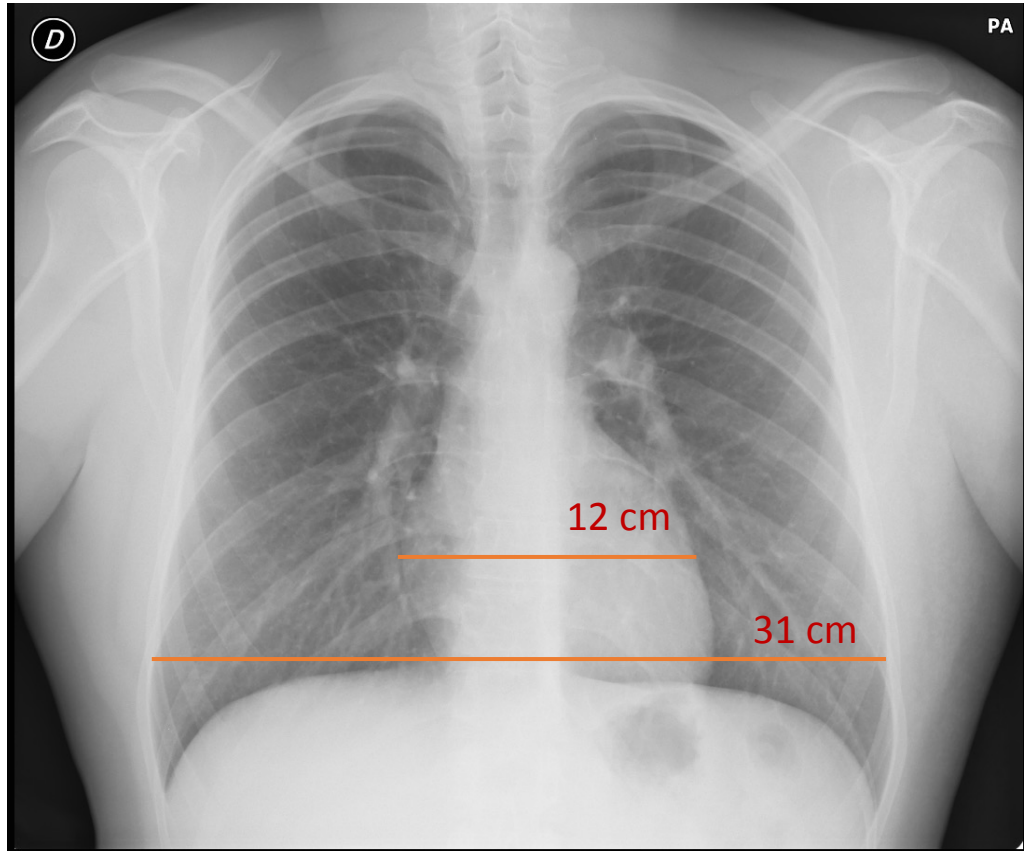
The Cardiothoracic Ratio

The cardiothoracic ratio is a simple yet effective tool to look for cardiomegaly. This ratio must be measured on a PA chest X-ray and is calculated dividing the widest horizontal diameter of the heart by the maximal horizontal diameter of the thoracic rib cage. A normal ratio should be < 0.5, values above this point to cardiomegaly or other pathologies (pericardial effusion).



Cardiothoracic ratio on CXR: You shouldn't measure the cardiothoracic ratio on an AP projection as the cardiac silhouette is typically magnified in these cases. Cardiothoracic ratio is useful to detect eccentric hypertrophy of the heart, concentric hypertrophy will generally go undetected.

Fig. 12. Chest X-Ray (PA) showing a normal cardiothoracic ratio (<0,5)

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In the Patient A the cardiothoracic ratio is 0,41 (<0,5), while in the Patient B it is 0,55 (>0,5), an evidence of Cardiac Enlargement

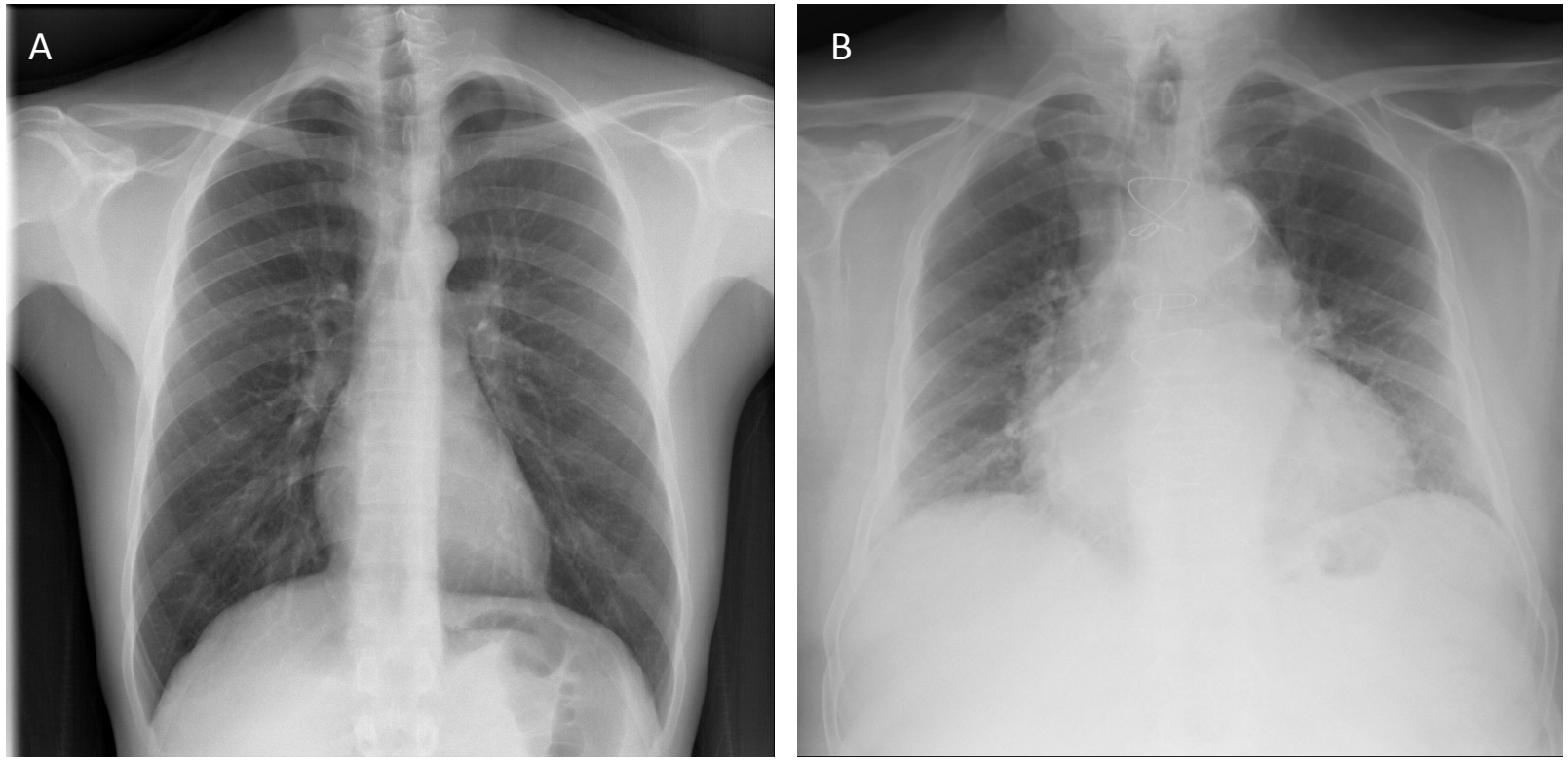

Fig. 13. Chest X-Ray in a 27 years old healthy patient (A) and in a patient affected by post-ischemic heart failure (B)

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Echocardiography

Echocardiography is often used as a first step in the evaluation of cardiac pathologies, as it is a low costs, wide available and non-invasive technique.
Possible pitfalls of echocardiography are the acoustic impedance of the thorax, which can be overcome using a transoesophageal approach, and inter-operator variability.

The main goals of echocardiography are:

- To study cardiac anatomy: characterization of Congenital Heart Disease, evaluation of pericardial effusion and detection of intracardiac masses or thrombi
- To estimate cardiac function: assessment of cardiac motility and cardiac chamber's performance (EF, EDV and ESV)
- To study cardiac valves: evaluation of valves morphology and thickness, estimation of transvalvular flow and detection of valvular stenosis or insufficiency, using the Doppler-US.

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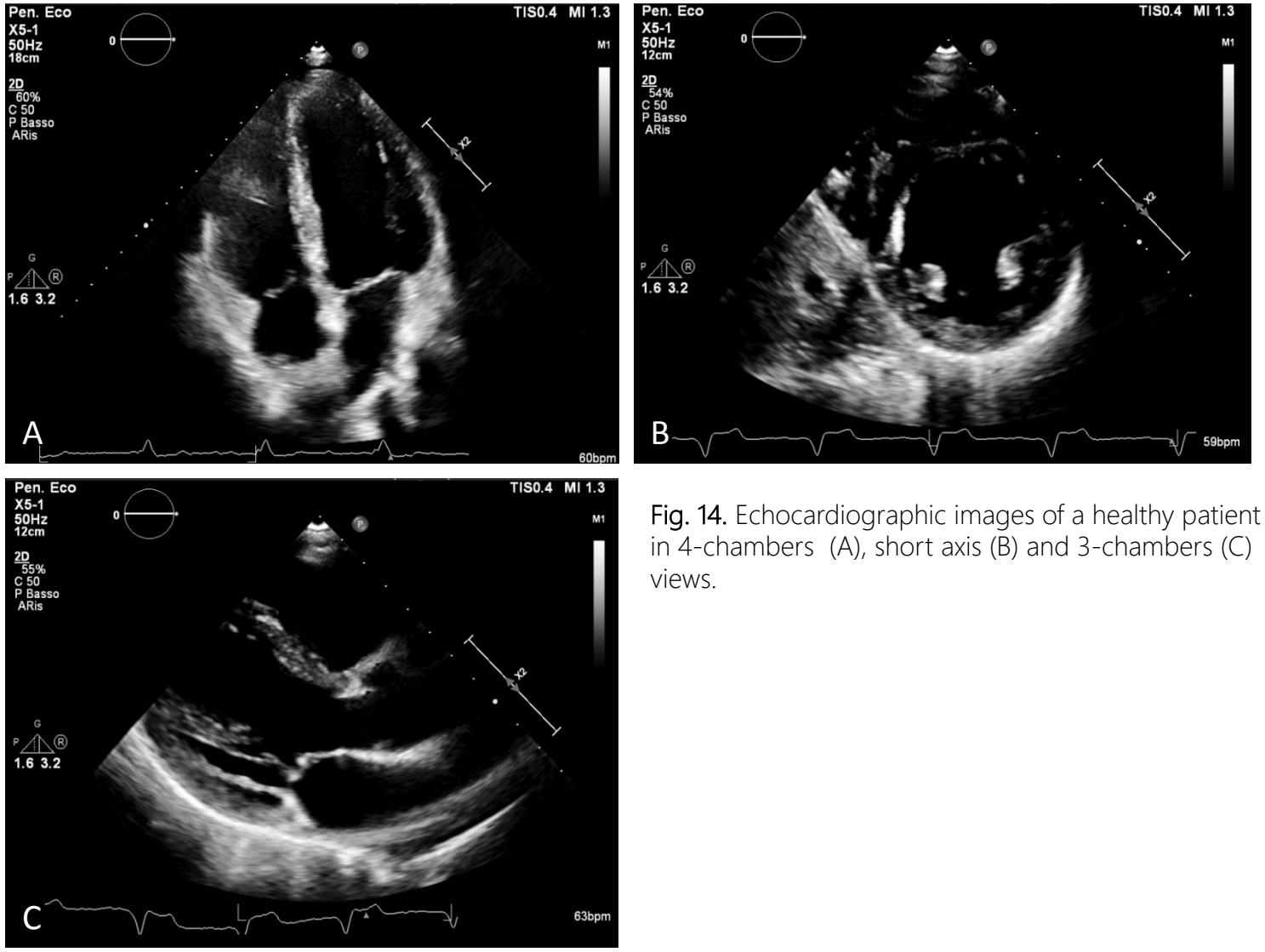

Fig. 14. Echocardiographic images of a healthy patient in 4-chambers (A), short axis (B) and 3-chambers (C) views.

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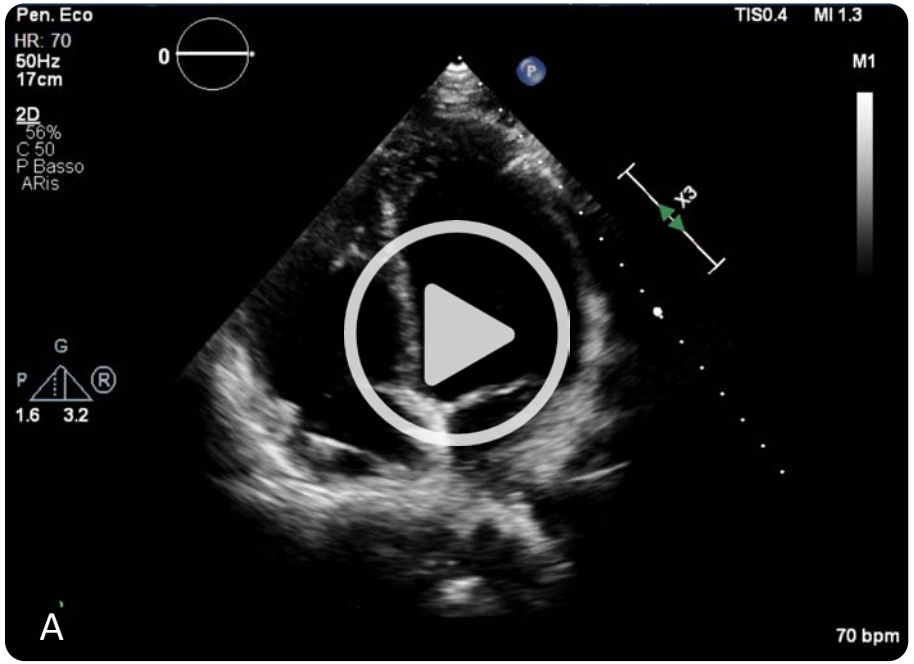

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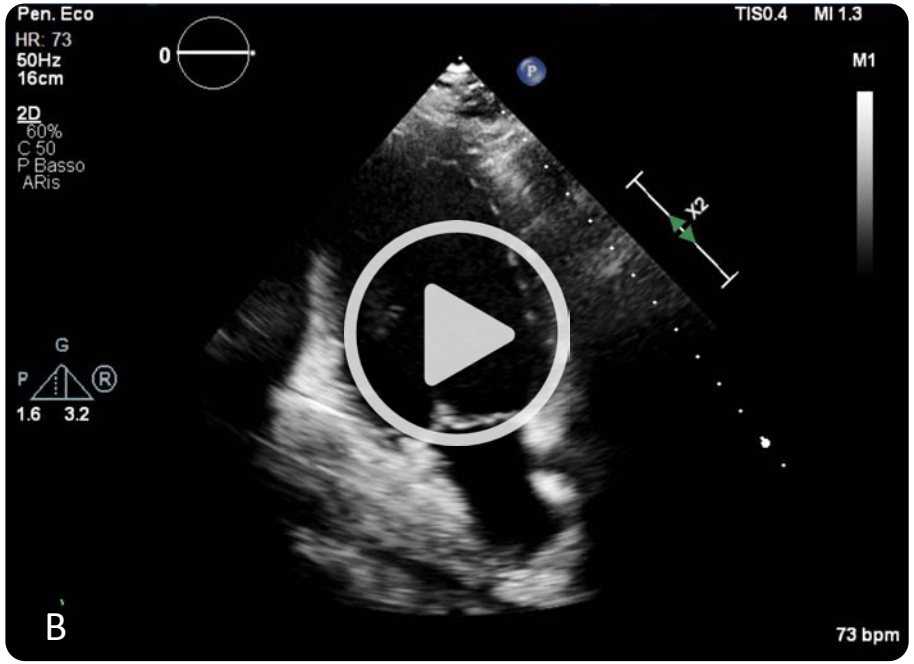

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Fig. 15. Echocardiographic videos of a healthy patient in 4-chambers view (A) and 2-chambers (B) views

Chapter Outline

Cardiac CT

CT scanning of the heart allows precise assessment of heart and coronary anatomy, made possible by the fast image acquisition and by the possibility to synchronize image capture and heart beat (ECG-gating).

Iodinated, intravenous contrast media are used for most cardiac protocols, in order to opacify the blood vessels and heart chambers; the formulations used are typically high-concentration.
Drawbacks of CT scan include radiation dose delivered , increased by ECG-gating, and potential toxicity of iodinated contrast media.

When coronary arteries are being investigated (Coronary CT Angiography) ECG-gating is fundamental to reduce the effects of heart motion. Heart rates that are excessively high (mostly above 70 bpm) lead to image quality that is hardly diagnostic even with the support of ECG-gating, making radiation dose unjustifiable. Such patients cannot undergo Coronary CT Angiography or need reduction of their heart rate through the use of B-blockers.

The accuracy of Coronary CT Angiography can be increased through the use of short – acting nitrates; these drugs cause vasodilation of the coronary arteries and allow better visualization of the coronary lumen.

European Heart Journal (2008) 29, 531–556

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ECG – gating consists in synchronization of image acquisition and cardiac cycle, so to get an image of the heart as if it were still. Gating can be retrospective or prospective, in the first case images are acquired during most of the cycle and subsequently reconstructed in definite phases; in the second case images are only acquired in a single phase of the cycle, usually in diastole. The latter modality allows radiation dose reduction but exposes to the risk of artifacts linked to the heart rhythm, because of this prospective gating is mostly used in patients with slow, regular heart beat. Furthermore valve function and wall motion can only be studied with retrospective gating, as it allows visualization of these structures during the whole heart cycle.

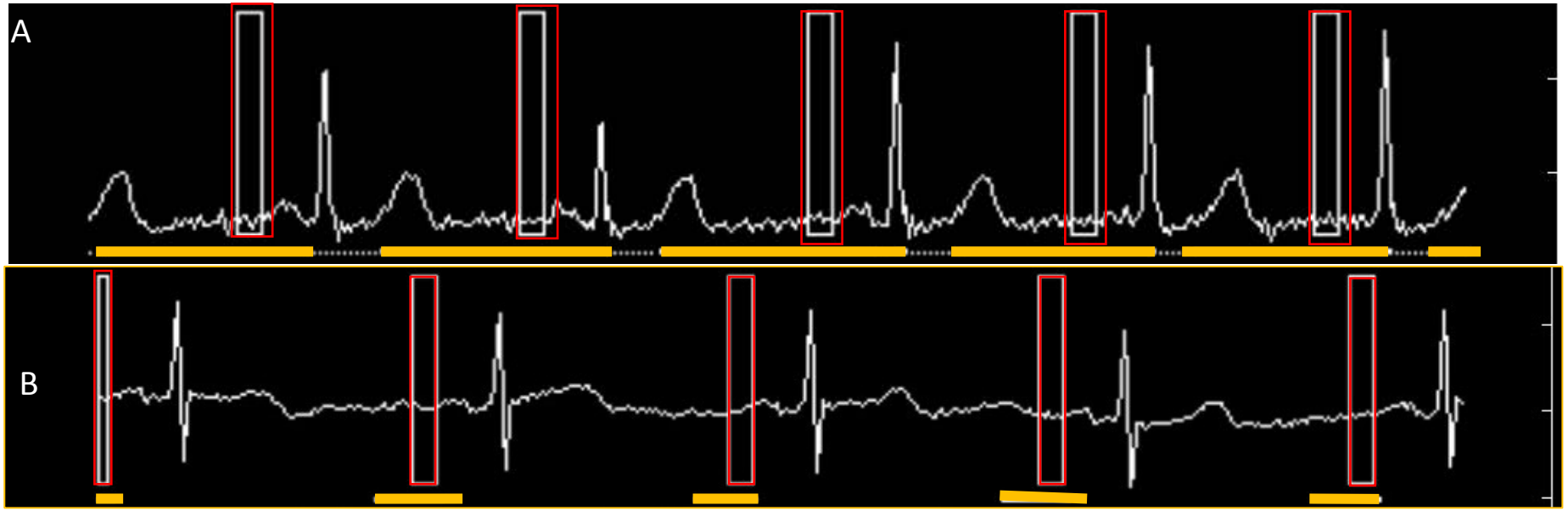

Fig. 16. Graphs showing acquisition technique in retrospective (A) and prospective (B) ECG gating Cardiac CT: the orange lines show the time interval of the cardiac cycle in which the image is acquired, while the red rectangles show the time interval of image reconstruction.

Chapter Outline

Cardiac MRI

Cardiovascular Magnetic Resonance (CMR) can be used in the diagnostic and prognostic evaluation of multiple cardiovascular pathologies; it also provides the most accurate functional information regarding heart physiology (i.e. cardiac volumes and ejection fraction) and allows high resolution anatomical assessment without the drawback of ionizing radiation.

- Unenhanced CMR is useful for morphological and functional studies, but the injection of gadolinium-based contrast media allows tissue characterization, the true strength of this technique, consisting in the detection of vital, suffering (oedematous) and necrotic/fibrotic myocardium.
- CMR is also able to study blood flow dynamics, looking for valvular stenosis and insufficiency, turbulence and shunts.
- ECG-gating can be applied to MRI as well, respiratory motion is reduced by acquiring images in breath holding
- The main drawbacks of cardiac MRI are its costs, the exam duration (it can span from 30 to 60 minutes) and the limited availability of dedicated scans and operators.

Chapter Outline

Cardiac Planes

An advantage of cardiac MRI is that images can be acquired in any plane. Traditional axial, coronal and sagittal planes have little use in the study of the heart, as this organ has a very specific orientation. Some specific planes are used in cardiac MRI to best visualize the heart:

- Horizontal long axis (four-chamber view): this plane is perpendicular to the interventricular septum and passes through the cardiac apex and the atrioventricular valves . It allows complete view of the 4 heart chambers, the interventricular septum, the free walls and the atrioventricular valves
- Vertical long axis (two-chamber view): this plane passes through the apex and the mitral valve as well but is parallel to the interventricular septum, allowing visualization of the left ventricle and atrium.
- Short axis: This plane is perpendicular to the interventricular septum and somewhat parallel to the atrioventricular plane. More of these planes are drawn at different levels along the interventricular septum, allowing visualization of this important structure in between the left and right ventricles or the left and right atria. This view is particularly useful to perform volumetric measurements that allow calculation of stroke volume and ejection fraction.
- Three-chamber view: This plane allows visualization of aortic root and valve, LV outflow and inflow tracts and portions of left atrium and ventricle.

Different MRI sequences will have the blood depicted as hyperintense or hypointense when compare with the myocardium. Morphological sequences will generally be “black-blood”, functional sequences will be “bright blood”.

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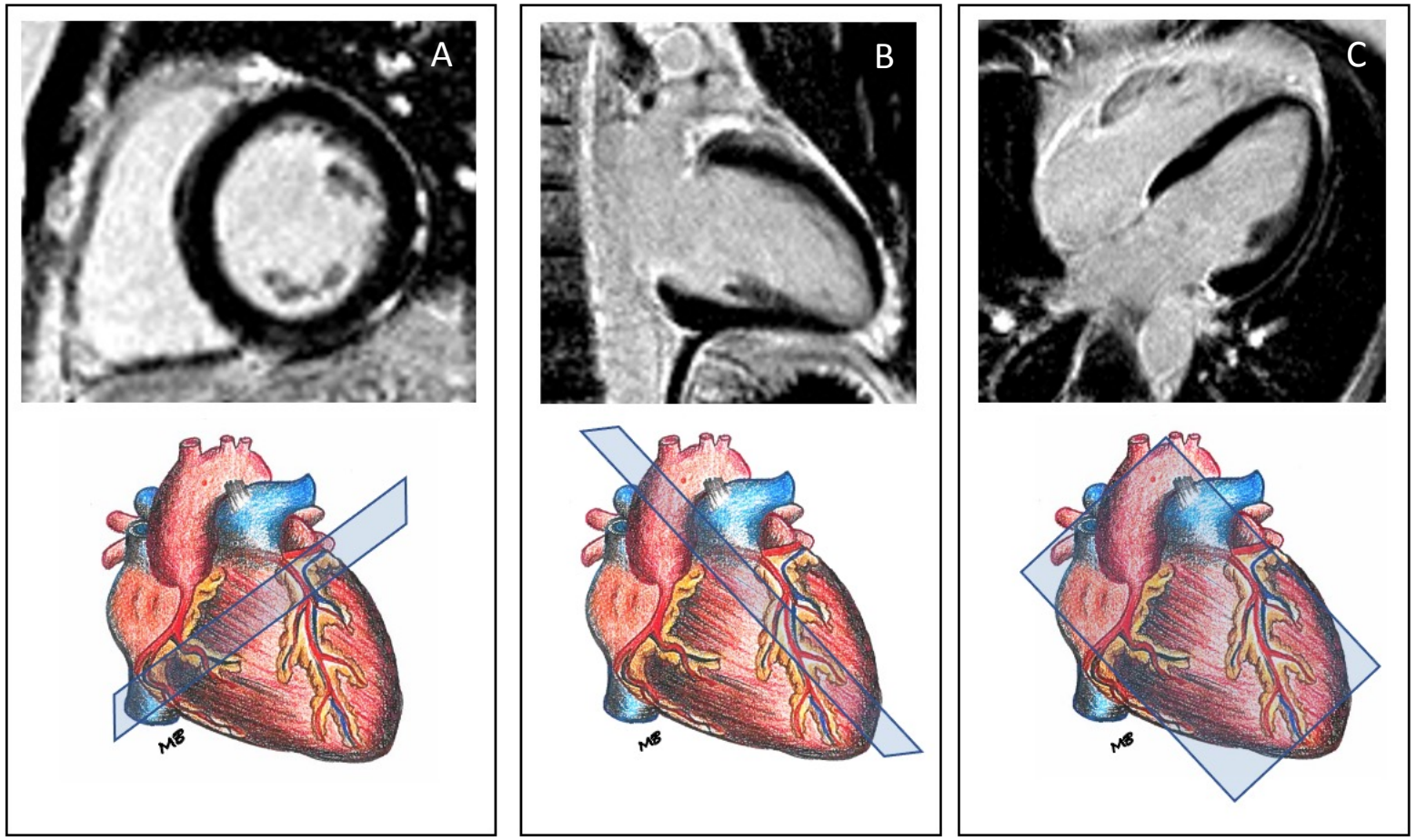

Fig. 17. Late Gadolinium Enhancement (LGE) sequences and corresponding schematic drawings illustrating the short axis plane (A), 2-chambers plane (B) and 4-chambers (C) plane- There is no pathological parietal enhancement (upper rows)

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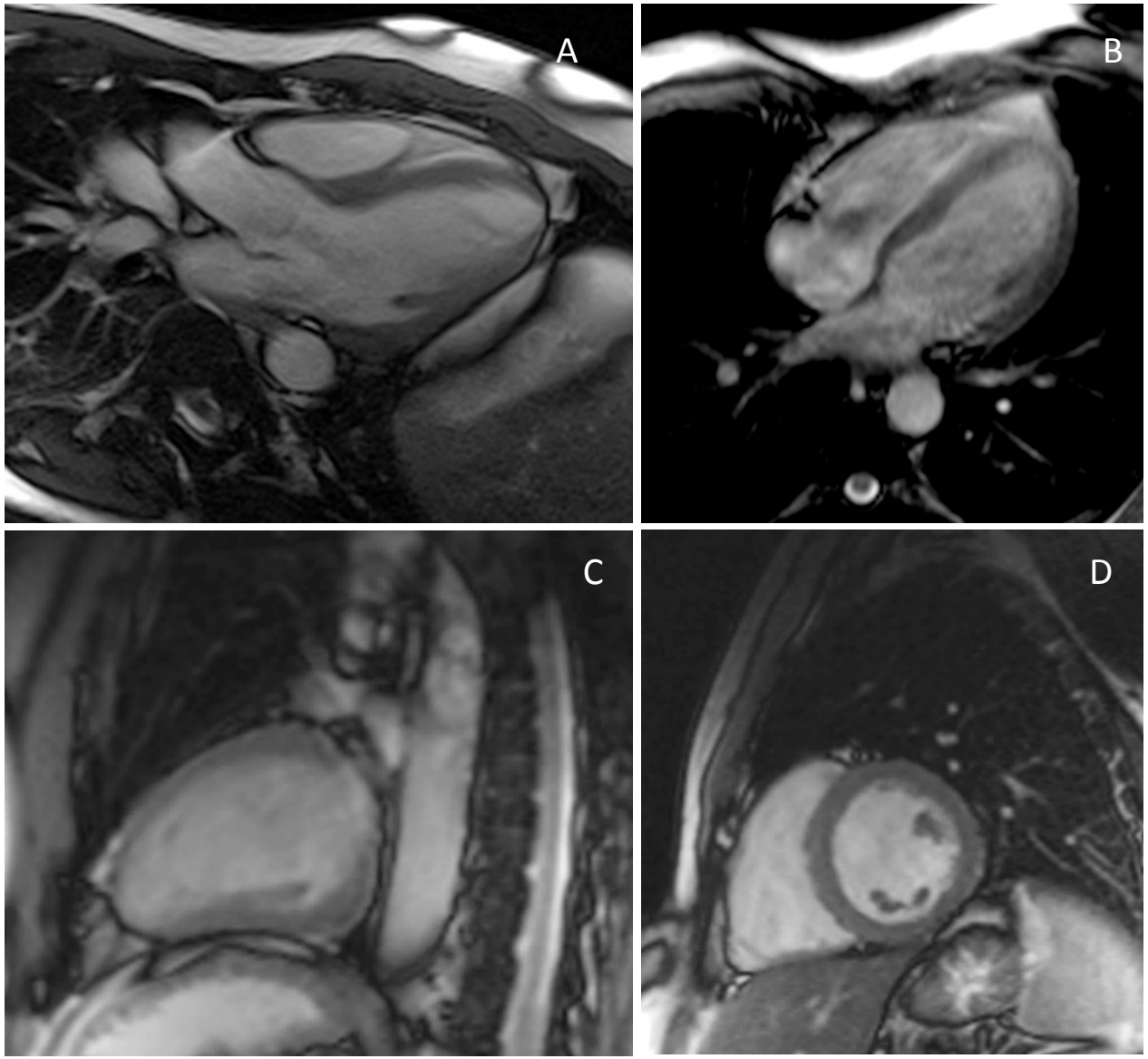

Fig. 18.

- Three chambers view (A)
- Four chambers view (B)
- Two chambers view (C)
- Short axis view (D)

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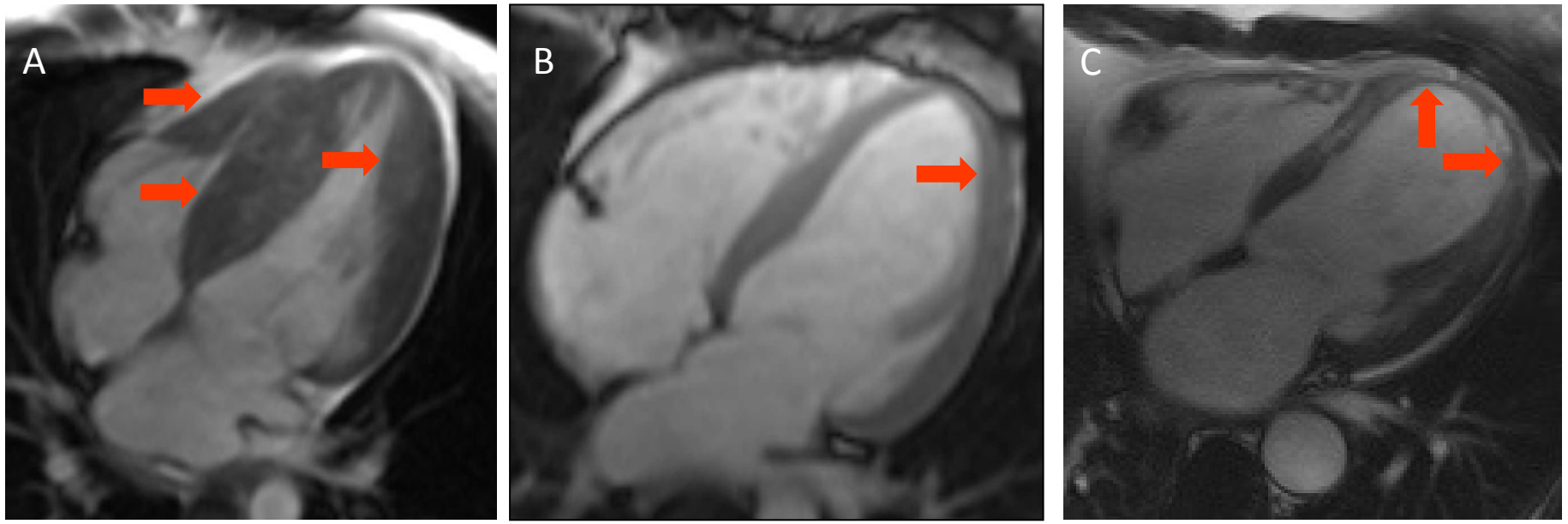

Fig. 19. Cine SSFP MRI in four-chambers view showing increased thickness of ventricular wall (A; red arrows), normal thickness (B; red arrow) and decreased thickness (C; red arrows).

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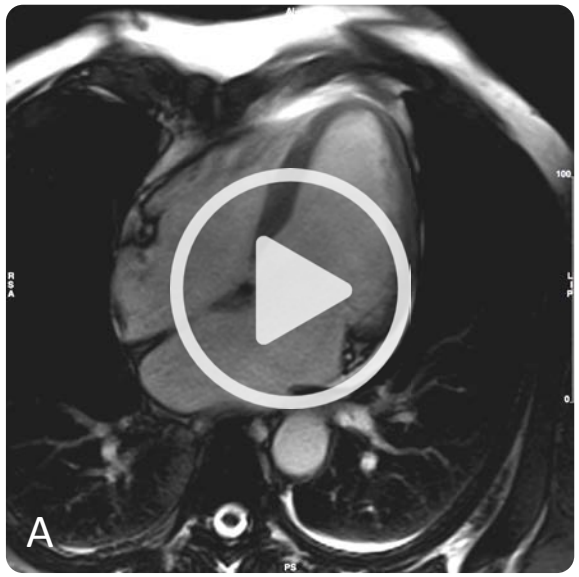

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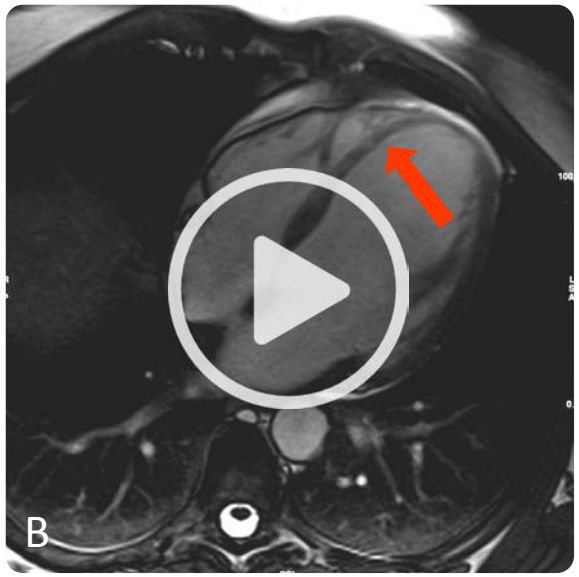
Normal



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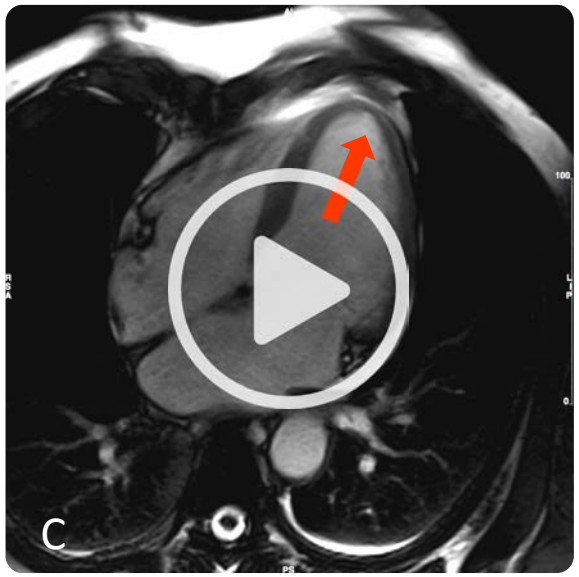
A-/Hypokinetic



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Dyskinetic

Fig. 20. Cine SSFP MR in four-chambers view showing normal wall contraction (A), septal a-/hypokinesis (B; red arrow), and apical dyskinesis (C; red arrow).

Chapter Outline

Nuclear Medicine

Nuclear medicine techniques have a leading role in cardiac pathologies, thanks to their ability to evaluate myocardial perfusion, metabolism and function .
The main techniques used in cardiac evaluation are Single Photon Emission Computerized Tomography (SPECT) and Positron Emission Tomography (PET).

- SPECT imaging, performed at rest and stress state, is used to evaluate myocardial perfusion. The radiotracer (mostly thallium-201 and technetium-99m), administered intravenously, reaches viable cardiomyocytes, where it accumulates proportionally to myocardial perfusion. By using 3D reconstruction techniques, it is also possible to calculate functional parameters, such as End Diastolic Volume, End Systolic Volume and Ejection Fraction, which have an important prognostic role

- PET imaging is important in the evaluation of myocardial viability. The key concept is that hypoperfused but viable cardiomyocytes maintain glucose metabolism (hibernating myocardium): by administering 18-F-FDG, a glucose analogue, PET studies can highlight mismatch between myocardial perfusion and glucose intake, typical of hibernating myocardium

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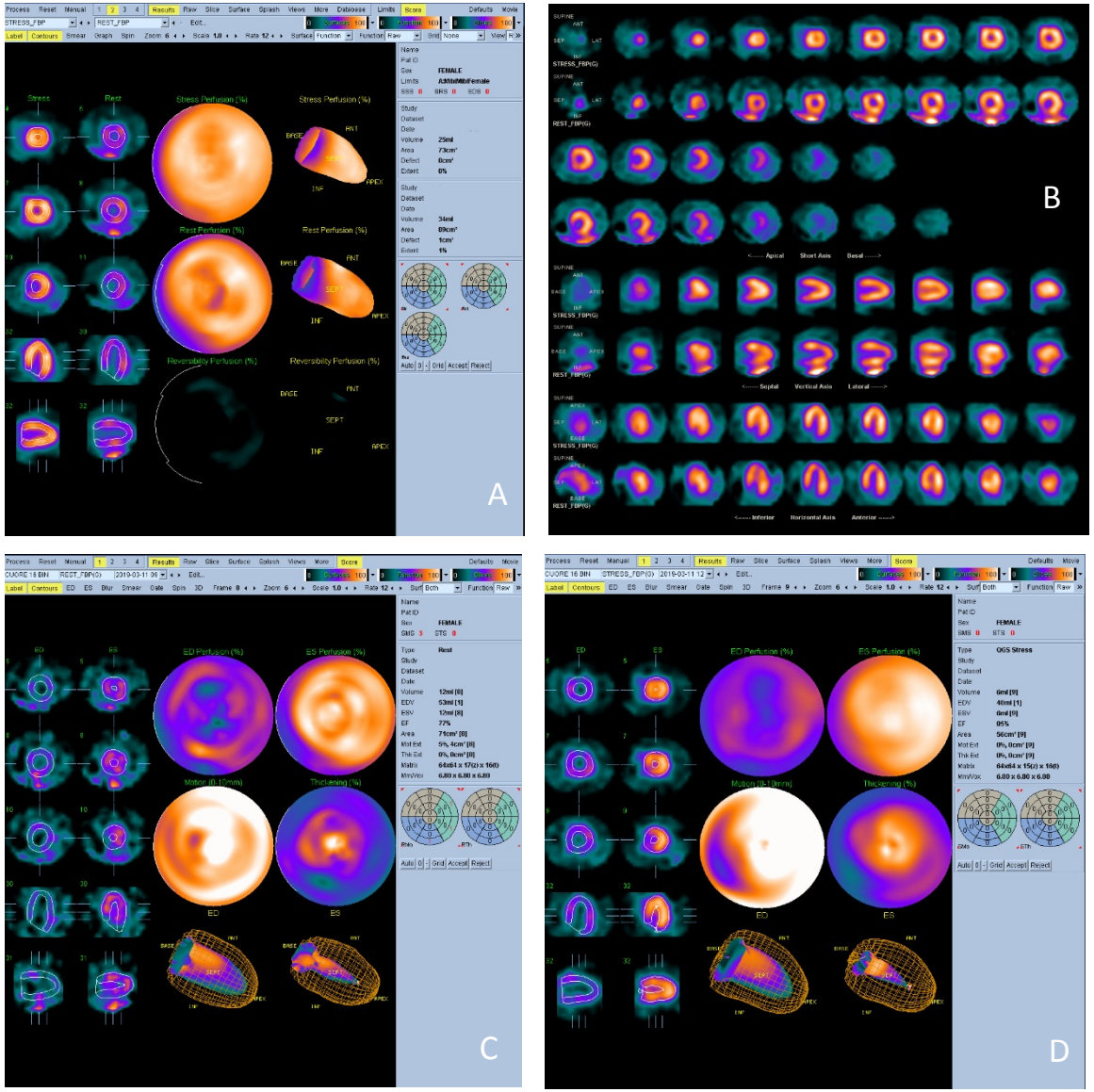


Fig. 21.

A) Myocardial perfusion SPECT study with 99mTc-sestaMIBI at rest and after stress showing images in three orthogonal planes. The radiotracer is evenly distributed in the left ventricle both at rest and after stress.

B) Three-dimensional tomographic reformatted images of left ventricular perfusion with polar maps to evaluate both qualitatively and quantitatively the presence of any perfusion defect, in terms of Summed Stress Score (SSS) and Summed Rest Score (SRS). In this study there is no significant perfusion defect, neither at rest nor under stress.

C and D) Tomographic reformatted images of gated – SPECT acquisitions for evaluation of left ventricular regional function and semiquantitative estimation of ventricular volumes and ejection fraction

Chapter Outline

Ischemic Heart Disease

Suspected coronary artery disease (CAD): the aim of imaging is to identify an obstructive coronary artery disease condition prior to infarct development. The strategies are the direct visualization of the coronary tree (CT) or by functional tests that, by increasing the blood request from the myocardium, can induce a condition of transient ischemia, documented as perfusion defect (Scintigraphy, Stress-MR) or anomalies of the contractility (Echocardiography)

- Stable setting:
  - Echocardiography (contractility defects)
  - Myocardial perfusion scintigraphy (perfusional defects)
  - MRI (perfusional and contractility defects)
    All these tests can be performed as "stress - tests", thus increasing their diagnostic abilities.
  - Cardiac CT
    - Cardiac Calcium Scoring (detection of coronary calcifications): as support to risk stratification
    - Coronary CT Angiography (anatomical search of stenosis) for early detection of obstructive CAD in symptomatic patient with negative functional tests or asymptomatic patient with unconclusive functional tests or patients unable to perform functional tests.

Vasc Health Risk Manag. (2017) 13, 427–437
Curr Cardiol Rep. (2016) 18
Curr Cardiovasc Imaging Rep. (2017) 10
Cardiovasc Diagn Ther. (2017) 7, 189–195.

Chapter Outline

- Acute chest pain (emergency setting)
  - Echocardiography (contractility defects and assessment of complications)
  - Triple-rule-out CT (detection of coronary occlusion, rule out other cardiovascular causes of acute chest pain)
  - Invasive coronary angiography (detection and treatment of an occlusive plaque)

Known CAD:
  - CT (patency of coronary stents and coronary artery bypass grafts)
  - MRI (assessment of cardiac viability mainly for prognostic purposes)

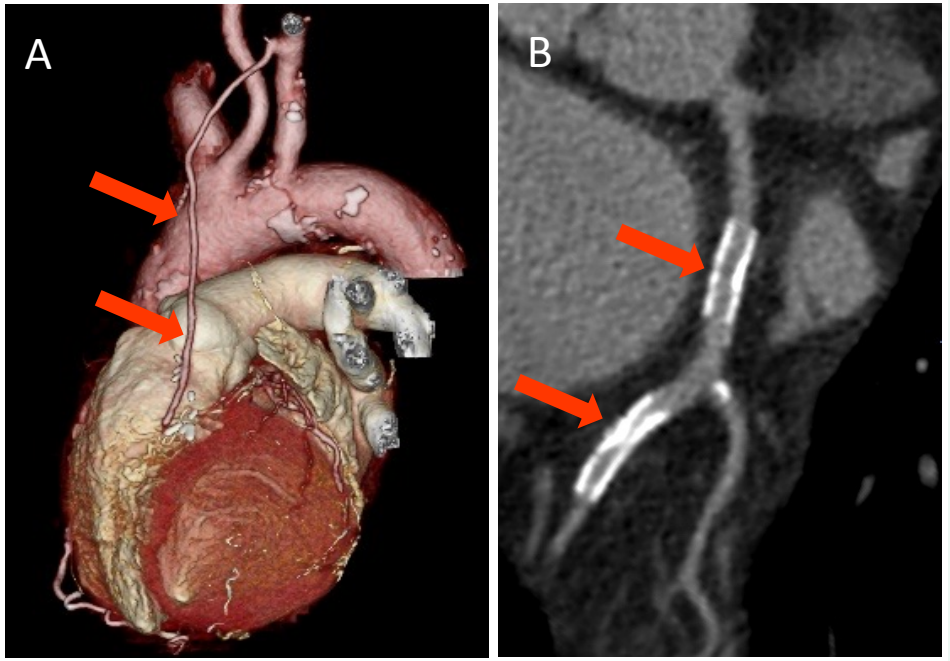


Fig. 22. Coronary artery bypass graft of left internal mammary artery on left descending artery (A, arrows) and 2 stents on the circumflex artery (B, arrows).

Thorac Dis. (2017) 9 (Suppl 4), S283–S288

Chapter Outline

Table 1. Main imaging modalities in suspected and known CAD, with their strengths and weaknesses

			Coronary artery disease: suspected		Coronary artery Disease: known
Modality	Strenghts	Weaknesses	Stable setting	Unstable setting	
Echocardiography	1) Inexpensive 2) Fast 3)Real-time 4) Wide availability	1) Operator-dependent 2) Small acoustic window 3)Low sensitivity and specificity	Detection of contractility defects, at rest and stress state	Detection contractility defects and assessment of complications	
Myocardial Perfusion scintigraphy	1)Relatively inexpensive 2)Functional information	1) Radioactivity 2) Low sensitivity 3) Use of radiopharmaceutical	Detection of perfusion defects		
Computerized Thomography	1) Extremely high negative predictive value 2) Detection of collateral findings	1) Radioactivity 2) Use of contrast agent	1) Cardiac Calcium Scoring can detect coronary calcification and support risk stratification 2) Coronary CT angiography allows plaque detection and charaterization	Triple-rule-out CT to detect coronary occlusion, rule out other cardiovascular causes of acute chest pain)	Assessment of patency of coronary stents and coronary artery bypass grafts
Magnetic Resonance Imaging	1) High sensitivity and specificity	1) Expensive 2) Low availability 3) Radiation free 4) Use of Contrast agent	Can detect perfusional and contractility defects, at both rest and stress state		Assessment of cardiac viability and prognostic study
Invasive Coronary Angiography	1) High sensitivity and specificity 2) Therapeutic	1) Invasivity 2) High radiation dose 3) Use of contrast agent 4) Expensive	Confirmation and treatment of a significative stenosis detected in other modalities. It is still the gold standard in CAD.	Detection and treatment of an occlusive plaque	

Chapter Outline

Table 2. Main imaging modalities in non coronary artery disease.

	Myocarditis	Cardiomyopathies	Valvulophaties	Pericardial Disease	Congenital Heart Disease	Cardiac Masses
Modality						
Echocardiography		Allows first diagnostic and functional evaluation	Diagnostic role and quantification of flow defects	Detection of pericardial effusion	Morphological and functional evaluation	Detection of the abnormality
Myocardial Perfusion scintigraphy						
Computerized Thomography			Morphological study, detection of calcifications, important preoperative role	Detection of pericardial effusion and calcifications	Best anatomical characterization	Best anatomical characterization
Magnetic Resonance Imaging	Provides diagnostic and prognostic information.	Comprehensive diagnostic, functional and prognostic evaluation	Thorough flow rate and functional study	Differential diagnosis of pericardial thickening	Thorough anatomical and functional assessment	Follow-up

Chapter Outline

Coronary CT Angiography

There are a variety of techniques to image coronary artery disease. Coronary angiography has been the main exam for many years, and it is still the gold standard in the evaluation of coronary artery stenosis, but in certain patient groups it may be replaced by coronary CT angiography (cCTA).
Coronary CT angiography can easily evaluate coronary atherosclerosis and classificate it on the basis of:

- Composition of the plaques: calcified, mixed, soft;
- Distribution of the plaques: isolated and diffuse;
- Severity of the stenosis: 0% = no visible stenosis; 1-24% = minimal stenosis; 25-49% = mild stenosis; 50-69% = moderate stenosis; 70-99% = severe stenosis; 100% = occlusion

Cardiac CT is especially important because of its very high negative predictive value, meaning that a negative exam excludes presence of CAD.

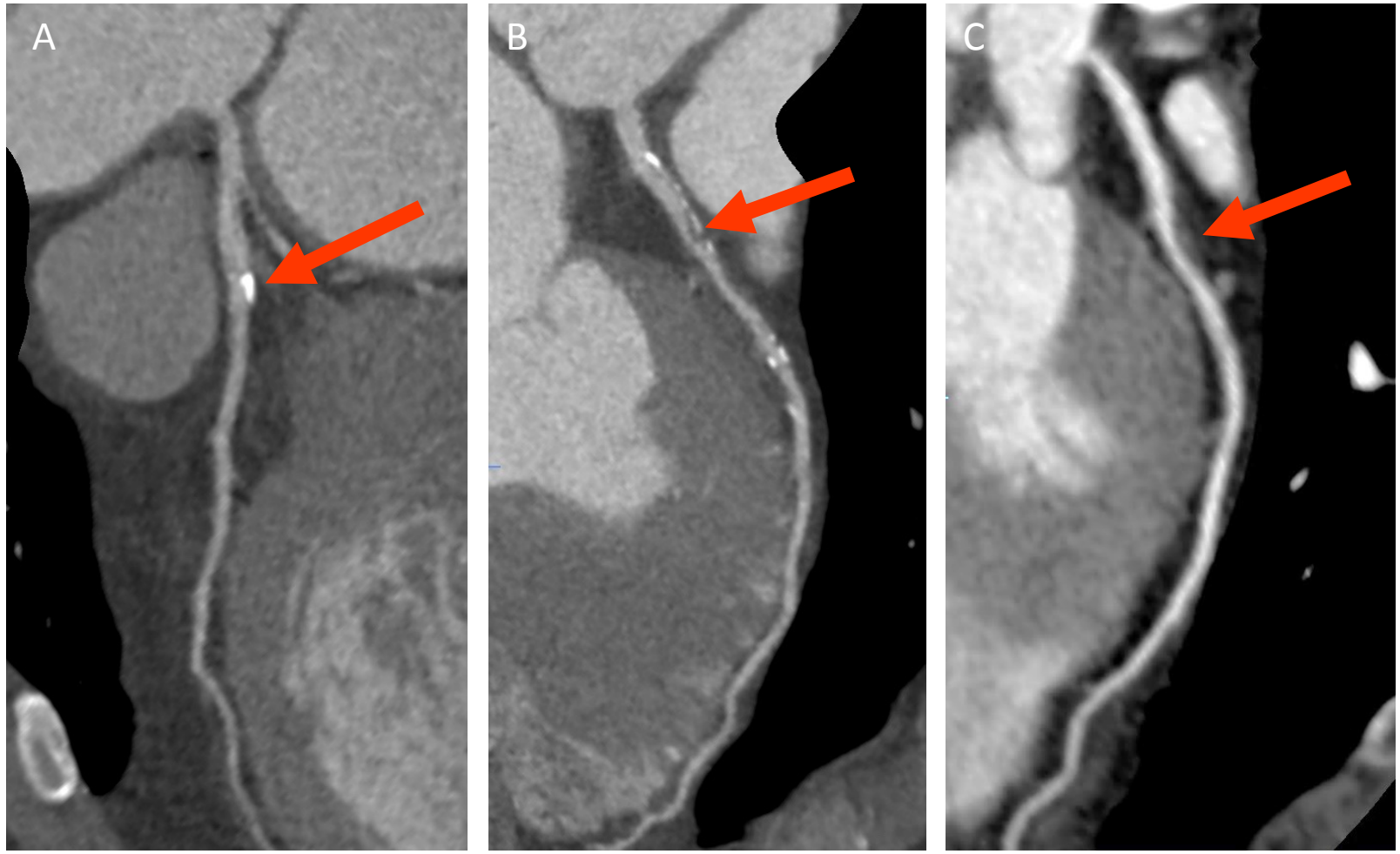


Fig. 23. Classification of coronary plaques (arrows) on the basis of their composition: Calcific (A), mixed (B) and soft (C) plaques.

Chapter Outline

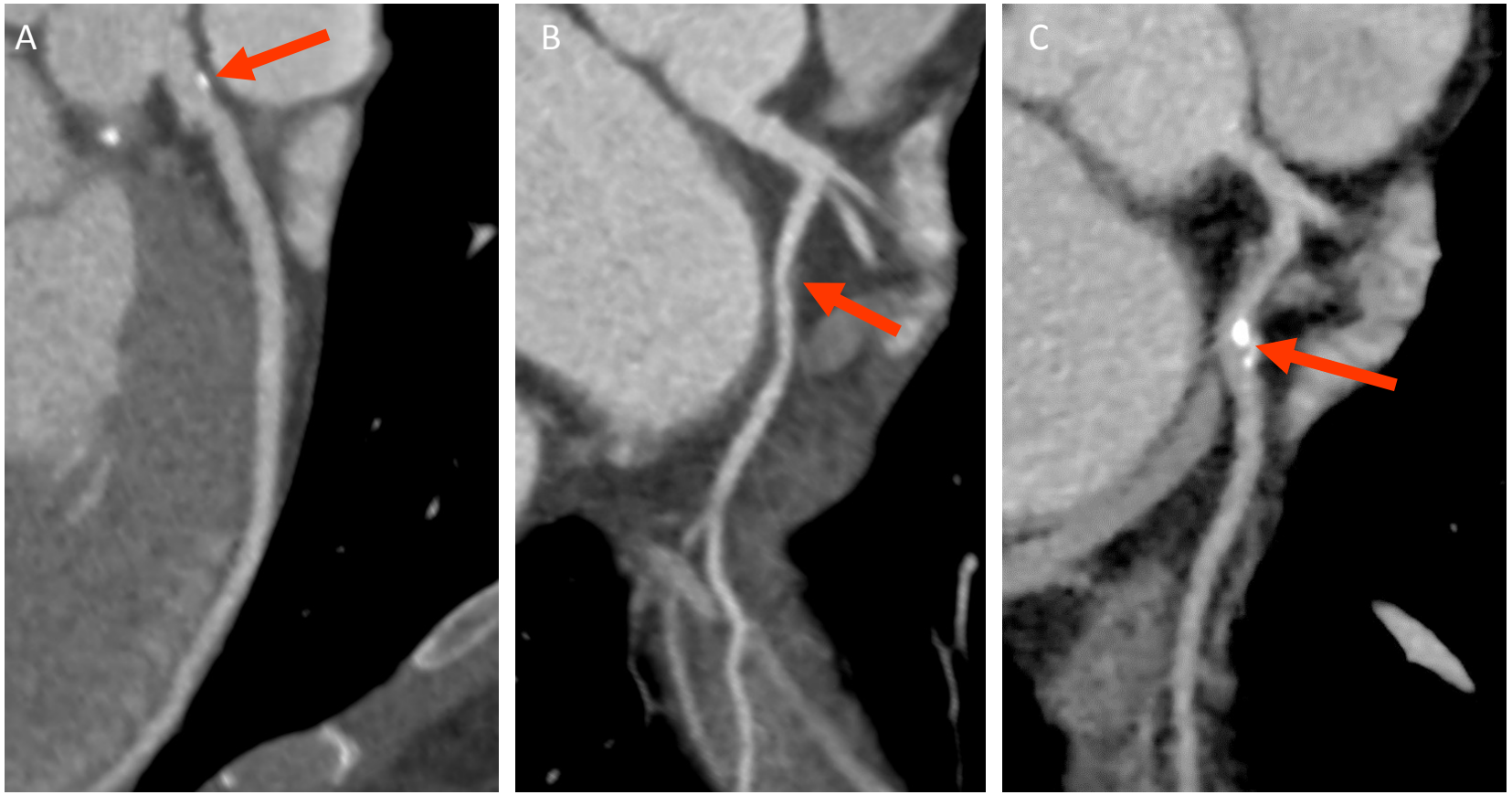


Fig. 24. Classification of coronary plaques on the basis of severity of the stenosis: minimal (A), mild (B) and moderate (C) stenosis

Chapter Outline

Fig. 25. Classification of coronary plaques on the basis of severity of the stenosis: severe stenosis (A) and occlusion(B).

Chapter Outline

MRI can also play a role in the evaluation of CAD, by performing a non-invasive assessment of myocardial perfusion, function and myocardial viability.

In the past decades, SPECT techniques were widely used to evaluate myocardial perfusion. This technique blends i.v. injection of a radioactive isotope with a 3D image acquisition, leading to localization of the disease by comparing image at stress and rest state.

Nuclear perfusion studies are gradually being replaced by MRI stress test, which in conjunction with a dobutamine infusion, can be used to detect wall motion abnormalities induced by ischaemia. The technique has been shown to have a comparable safety profile to dobutamine stress echocardiography. Dobutamine stress cardiac MRI (CMR) may be useful in patients with sub-optimal acoustic windows, especially those in whom pharmacologic perfusion imaging using adenosine is contra-indicated.

Perfusion CMR is more widely used than dobutamine stress CMR. Recent studies have confirmed the good diagnostic accuracy of CMR perfusion imaging at 1.5 Tesla (T), as compared with nuclear perfusion imaging. Finally, quantitative CMR perfusion measurements demonstrate good correlations with FFR measurements.

European Heart Journal (2013) 34, 2949–3003

Chapter Outline

Myocardial Infarction

Myocardial infarction results from obstruction to blood flow in one district of the coronary tree, with resultant myocardial ischemia. It is an acute event typically presenting with severe chest pain. Expedite diagnosis is crucial in this setting as these patient should undergo reperfusion as soon as possible. In this context, time saving modalities are especially useful.

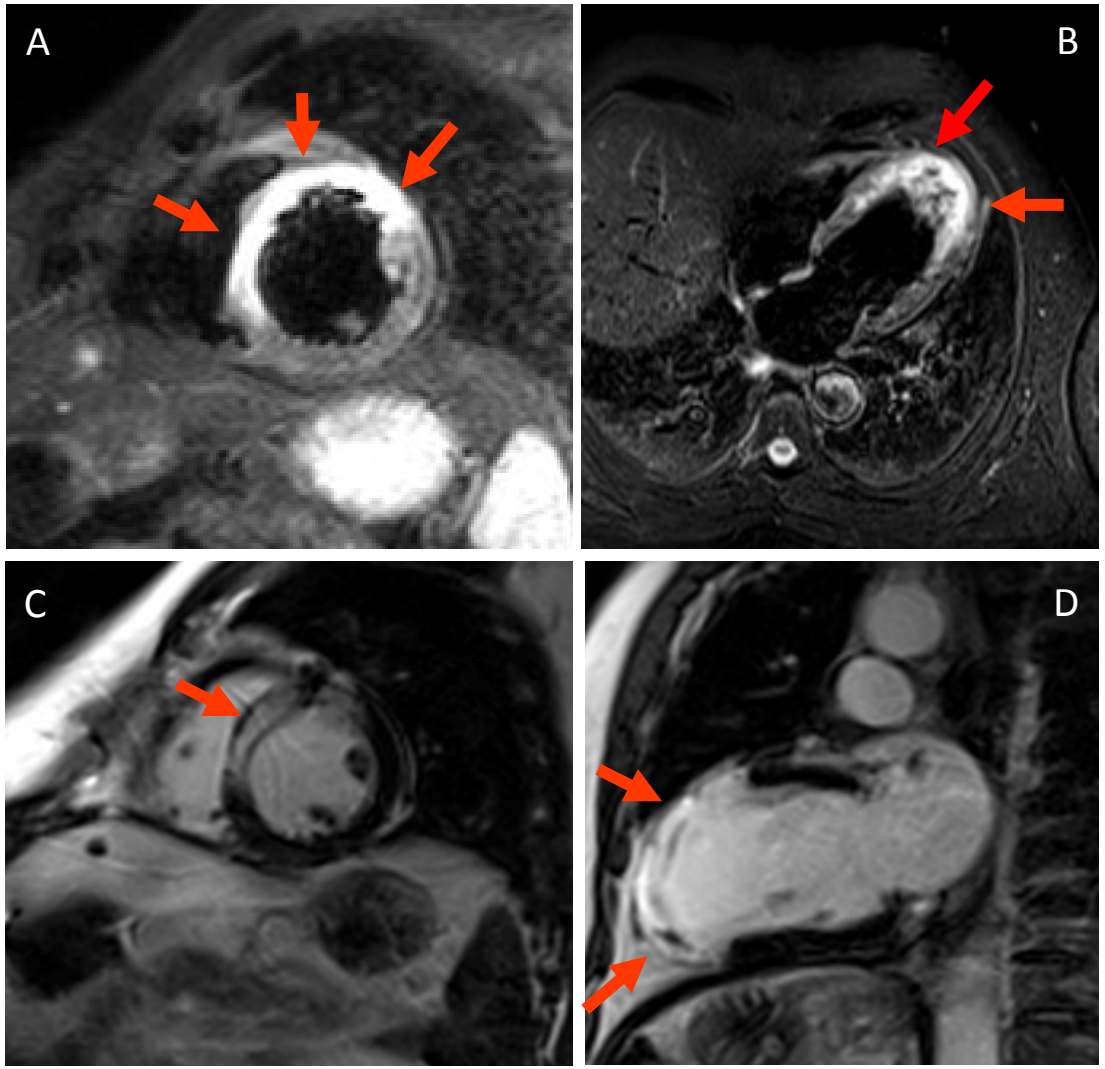
- Chest X-rays is useful to exclude other causes of chest pain (e.g. pneumonia) but not to the direct diagnosis of acute myocardial infarction (AMI); sometimes it can demonstrate indirect and non specific signs of heart failure.
- Echocardiography, is a fast exam that allows a first confirmation of the diagnostic hypothesis of myocardial infarction. The typical finding in the acute setting is a regional wall motion abnormality of the affected walls (those perfused by the occluded coronary artery). Mitral regurgitation can also be seen when the ischemia involves the papillary muscles.
- Coronary CT Angiography in the context of a Triple-rule-out protocol can assess patency of coronary arteries in the setting of acute chest pain, but only when the ECG alone is not enough to have diagnostic certainty.
- Invasive Coronary Angiography allows direct visualization of the obstruction to blood flow. It is a pivotal modality as in the same context it is possible to proceed with primary percutaneous coronary intervention (primary PCI) with angioplasty and stenting to treat the stenosis. Patients with high clinical suspicion of AMI should undergo prompt revascularization with no need for further diagnostic evaluation.

Academic Emergency Medicine (2013) 20, 861– 871
Br J Radiol. (2016) 89.
European Radiology (2009), 19, 789-799.
Circulation Journal (2009) 73, Issue 9, 1577-1588,

Chapter Outline

- Myocardial scintigraphy can assess myocardial viability by detecting reversible perfusion defects through comparison of the images at rest and stress state.
- MRI in the acute setting can detect the presence of oedema in regions of the myocardium that are salvageable ("myocardium at risk"); on the basis of MRI findings it is possible to indicate the likelihood of success of revascularization procedures.
- Perfusion MRI at rest and stress state using a "first-pass" techniques can detect a signal increase in normal myocardium and limited enhancement in the ischemic one.
- MRI is also useful to identify the scar tissue using "delayed enhancement" techniques.
- MRI imaging can also provide information about cardiac function by estimating cardiac volumes (EDV,ESV,SV that can be increased) and contractility (that can be compromised), using cine-MRI sequences.
- In the chronic setting, delayed enhancement cardiac magnetic resonance is particularly useful in identifying patients with ischemic cardiomyopathy and severe left ventricular dysfunction who would benefit from myocardial revascularization.

Chapter Outline



Extremely interesting and useful is the accumulation of contrast medium in areas of necrosis 15-20 minutes after injection, a phenomenon referred to as **delayed (or late) gadolinium enhancement (DGE or LGE)**. Different patterns of delayed enhancement can shed light on the differential diagnosis of several different cardiac pathologies.

Fig. 26. Cardiac MRI in a case of acute myocardial infarction (AMI):
- A and B: T2 weighted with fat suppression images showing an increased signal of the anterior, lateral and anteroseptal wall (arrows), due to the presence of oedema.
- C and D: LGE (late gadolinium enhancement) sequences showing pathological parietal enhancement of the same segments (arrows), due to the presence of necrosis, with a transmural distribution pattern.

Chapter Outline

The pattern of Late Gadolinium Enhancement (LGE) can differentiate infarction (subendocardial or transmural) from non-ischemic dilated cardiomyopathy (mid-wall or subepicardial) and infiltrative diseases (scattered or subepicardial).

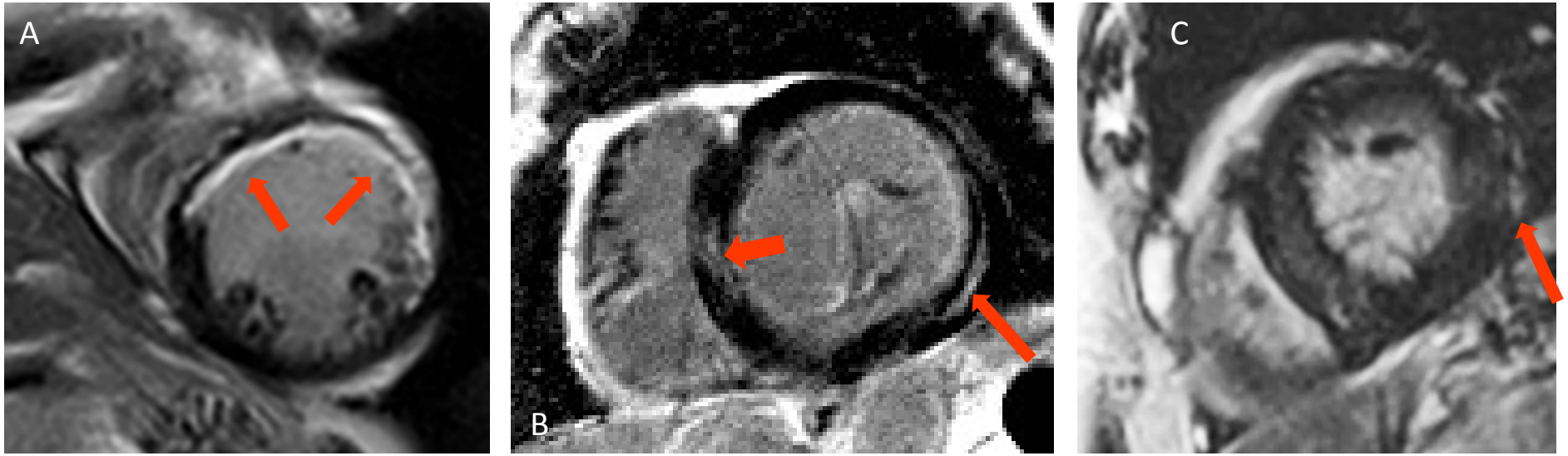


Fig. 27. (A) LGE (late gadolinium enhancement) sequences showing pathological parietal enhancement of the anterior, anteroseptal and lateral wall, due to the presence of necrosis/fibrosis, with a subendo-mesocardial distribution pattern, in a patient with myocardial infarction. (B) LGE sequences showing subepicardial and midwall parietal enhancement in a patient with long-standing dilated cardiomyopathy. (C) Scattered pathological enhancement in a patient with Anderson – Fabry disease.

Chapter Outline

Complications of Myocardial Infarction

The main complication of myocardial infarction are intracardiac thrombi, aneurysm/pseudoaneurysm and heart failure.

- Aneurysm and pseudoaneurysm: chest X-Ray may show a localized bulge along the ventricular wall, with or without a thin rim of calcification. CT, MRI, and echocardiography are more specific in the identification of myocardial morphologic alterations.
- Thrombi: they can be easily detected by echocardiography, which is the first line exam. CT is able to distinguish cardiac masses from thrombi, as the latter lack contrast enhancement. The same information can be provided by MRI with the use of gadolinium contrast.
- Heart Failure: Chest X-ray can demonstrate some indirect features of HF, such as cardiomegaly, pleural effusion, B-Kerley lines and interstitial oedema. Echocardiography is the first-line exam and can evaluate cardiac chambers volumes, valvular function, ejection fraction and pericardial effusion. Cardiac CT also provides information about left and right ventricular structure and function, cardiac venous anatomy and pulmonary venous system. MRI is particularly useful in distinguishing the cause of HF and providing information about prognosis, especially when echocardiographic findings are inconclusive.

Diagnostic and Interventional Imaging (2012) Volume 93, Issues 7–8, 578-585

Chapter Outline

In order to distinguish true aneurysms from pseudoaneurysms (one is surrounded by myocardium and the other is a contained rupture lined by pericardium) MRI is the best option, showing a dyskinetic segment with focal bulging of the pericardium, in the case of pseudoaneurysm.

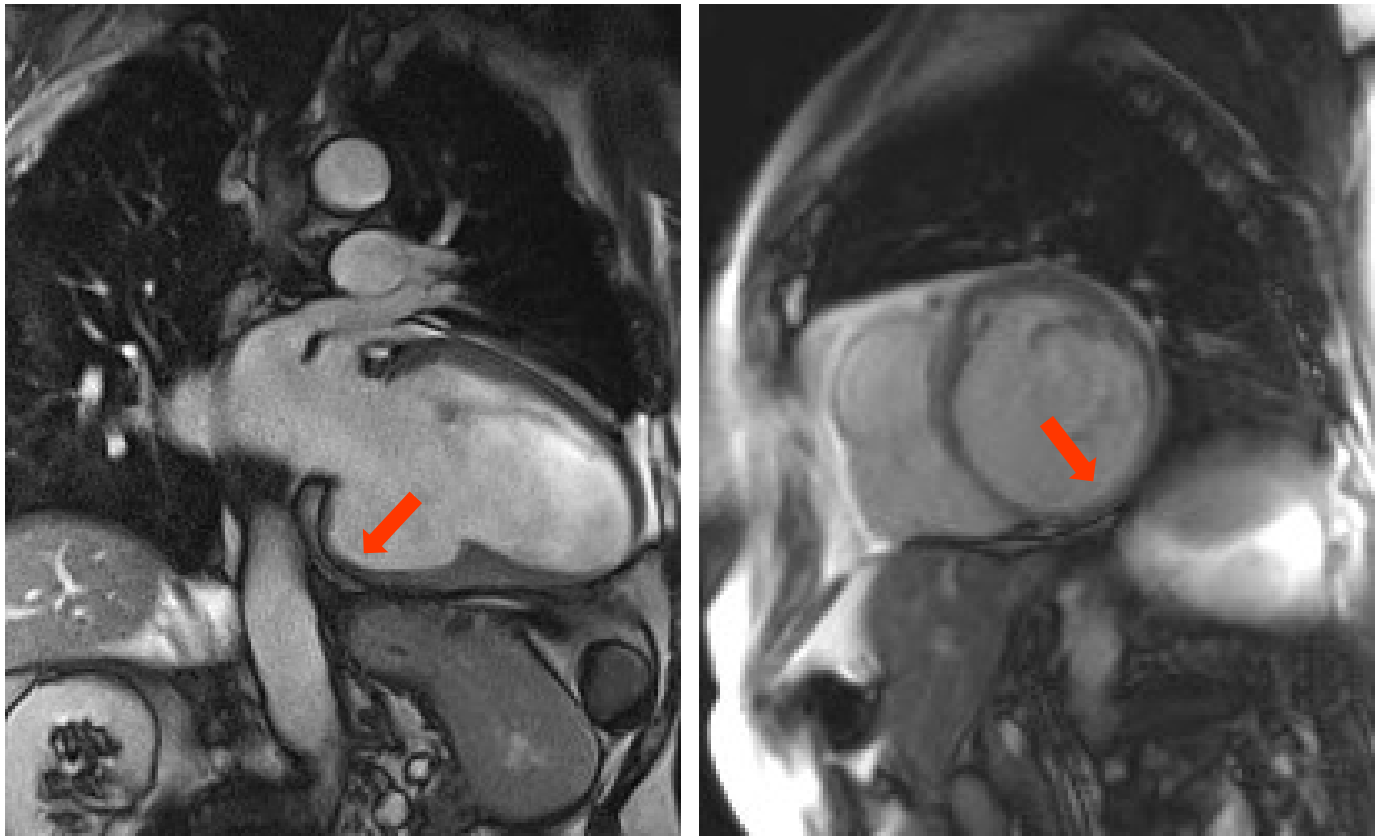
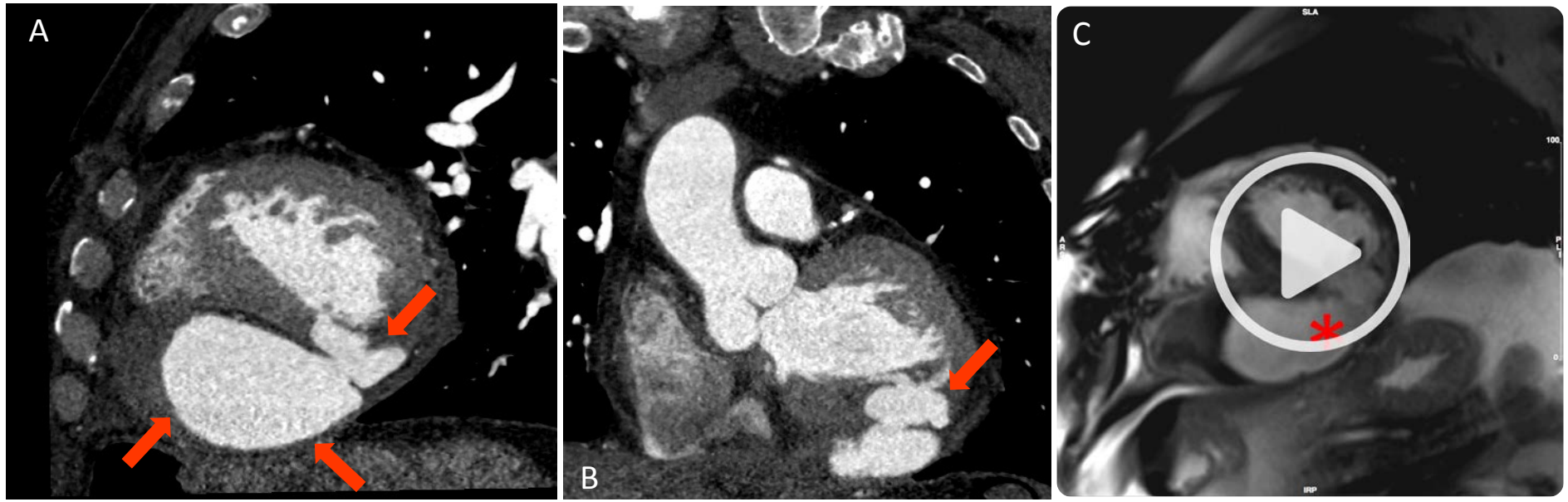


Fig. 28. Cardiac MRI performed one year post AMI, showing presence of an aneurysm of the infero-basal wall.

Chapter Outline



Click to Play Video in Browser (External)

Fig. 29 (A and B) Cardiac CT multi-planar reconstruction of a pseudoaneurysm of the inferior wall (arrows) in a patient with a previous AMI. (C) Cardiac MR movie of the same patient. The pseudoaneurysm is indicated by an asterisk.

Chapter Outline

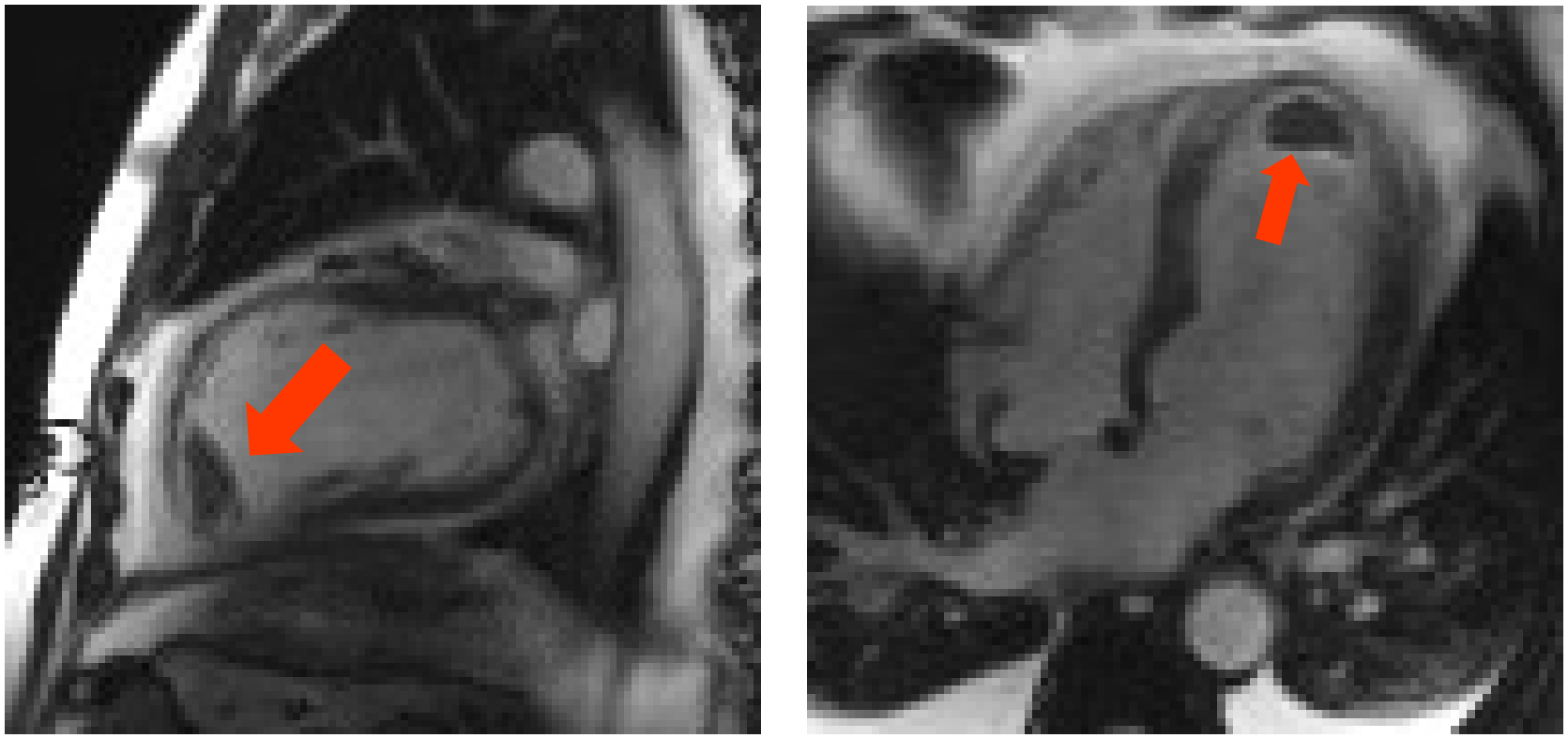


Fig- 30. Cardiac MRI: LGE sequences showing the presence of a sizable apical thrombus (arrows) in a patient with a previous apical AMI

Chapter Outline

Non Coronary Artery Diseases

- Myocarditis
  - MRI (diagnostic and prognostic role)
- Cardiomyopathies
  - Echocardiography (first diagnostic and functional evaluation)
  - MRI (comprehensive diagnostic, functional and prognostic evaluation)
- Valvulopathies
  - Echocardiography (diagnostic role and quantification of flow defects)
  - CT (morphological study, detection of calcifications, important preoperative role)
  - MRI (thorough flow rate and functional study)
- Pericardial diseases
  - Echocardiography (detection of pericardial effusion)
  - CT (detection of pericardial effusion and calcifications)
  - MRI (differential diagnosis of pericardial thickening)
- Congenital Heart Disease
  - Echocardiography (morphological and functional evaluation)
  - Cardiac MRI and Magnetic resonance angiography (thorough anatomical and functional assessment)
  - CT angiography (best anatomical characterization)
- Cardiac Masses
  - Echocardiography (detection of the abnormality)
  - CT (best anatomical characterization)
  - MRI (follow up)

Myocarditis

Myocarditis is inflammation of the myocardium, it is usually either infectious or autoimmune in aetiology and can have a wide spectrum of different clinical presentations, ranging from a completely asymptomatic course to acute cardiac failure, with chest pain being a common symptom in most cases.

The population affected is typically younger than the one more at risk for myocardial infarction, the differential diagnosis between the two conditions is anyway very important, and can be troublesome, as myocarditis typically shows elevation of cardiac enzymes and alterations of the ECG as well. It shouldn't come as a surprise therefore that myocarditis underlies many cases of acute chest pain with completely negative coronary angiograms.

While the gold standard in the diagnosis of myocarditis remains endomyocardial biopsy, Cardiac MRI a fundamental diagnostic tool in this setting.

- In the acute setting Cardiac MRI shows presence of intramyocardial oedema and delayed enhancement. Distinction of myocardial infarction and myocarditis is allowed by the distribution of the enhancement, subendocardial and dependent on coronary artery distribution in myocardial infarction, subepicardial and irrespective of coronary arteries in myocarditis.
- In the chronic setting the oedema will disappear, while the myocardial scar will remain visible as a stripe of delayed enhancement.
- Useful prognostic information comes from Cardiac MRI thanks to several parameters, including extension of the delayed enhancement, degree of functional compromission and involvement of the right ventricle. The utility of designing a follow up scans is still being debated, as several cases heal completely while other go on to develop ventricular dilation and congestive heart failure.

Cardiac CT can only be useful to exclude other causes of analogous clinical presentation.

Chetrit M, Friedrich MG. The unique role of cardiovascular magnetic resonance imaging in acute myocarditis. F1000 Res. 2018;7:F1000 Faculty Rev-1153. Published 2018 Jul 30.

Baeßler B, Schmidt M, Lücke C et al. Modern Imaging of Myocarditis: Possibilities and Challenges. Fortschr Röntgenstr 2016; 188: 915–925

Chapter Outline

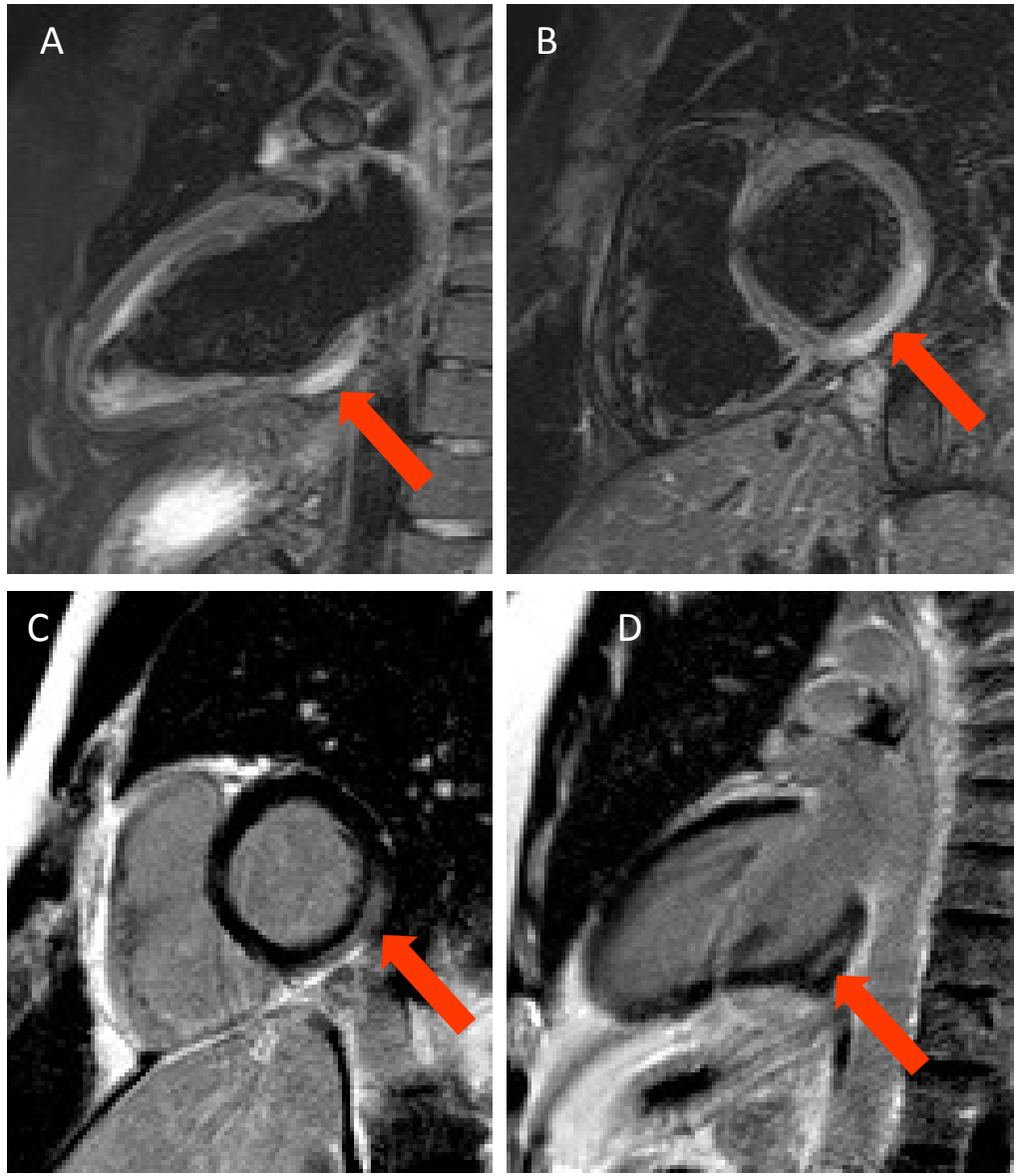


Fig. 31. Cardiac MRI in a case of acute myocarditis:
- A and B: T2 fat suppressed images showing an increased signal of the inferior and infero-lateral wall , due to the presence of oedema, with a subepi-mesocardial distribution pattern.
- C and D: LGE sequences showing pathological parietal enhancement of the same segments, due to the presence of necrosis/fibrosis, with a subepi-mesocardial distribution pattern.

Chapter Outline

Cardiomyopathies

Cardiomyopathies form a heterogeneous group of diseases in which the heart is abnormal in structure or function in the absence of ischemic, valvular, hypertensive and congenital causes.

Cardiomyopathies are most commonly classified according to their phenotype as dilated, hypertrophic, restrictive or arrhythmogenic, irrespective of their true aetiology.

- Echocardiography is commonly the first test used to find abnormalities in these patients, but it can only provide broad morphological and functional information, with no insights on aetiology and prognosis.
- Cardiac MRI is an invaluable tool in many of these diseases, as it gives the best functional evaluation, important morphological information and crucial prognostic and etiological classification.

Hypertrophic cardiomyopathy is most often genetic in origin but can also result from amyloidosis or Fabry disease. It is characterized by increased wall thickness (hypertrophy), characteristically asymmetrical and often associated to outflow tract obstruction. Microscopically we can appreciate fibrosis and disarray of the muscular fibres, which are the likely cause of the increased risk of sudden death.

JACC Cardiovasc Imaging. (2017) 10 1180–1193.

World J Cardiol. (2016) 8, 132–145.

Eur Heart J Cardiovasc Imaging. (2017) 18, 237–253

Chapter Outline

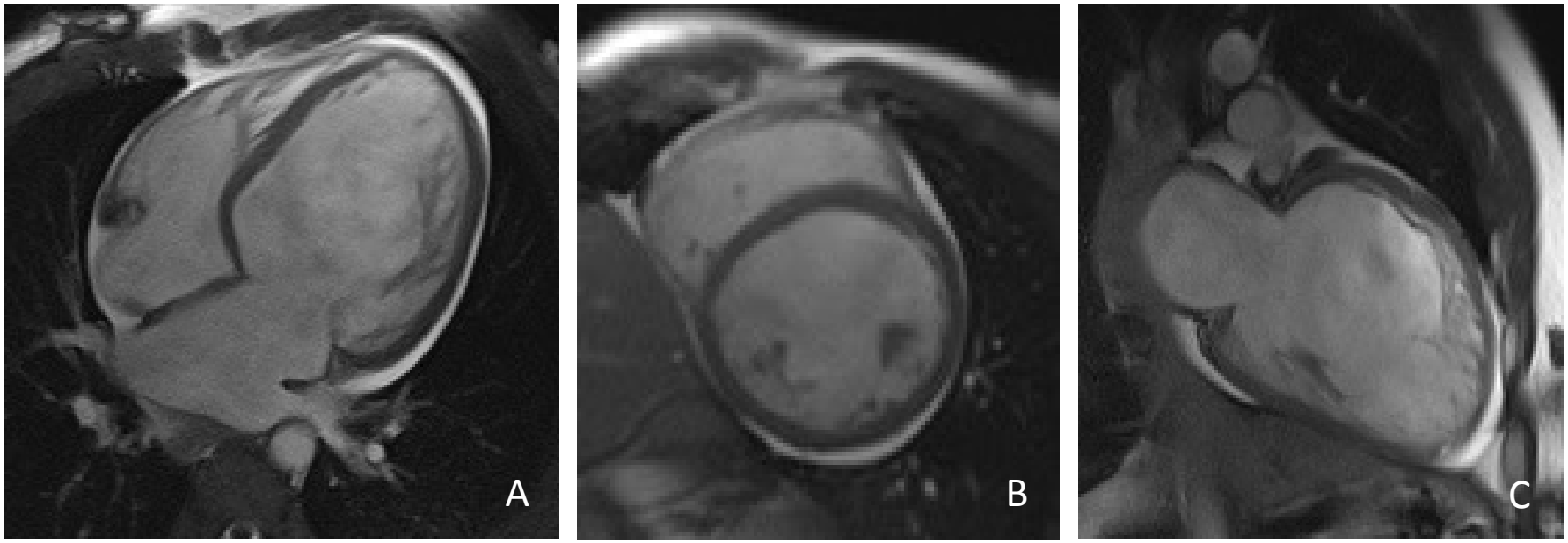


Fig. 32. Cardiac MRI showing increased volumes of the cardiac chambers in a patient with dilated cardiomyopathy (Left ventricle parameters: End-diastolic volume/Body surface area 151 mL/m2; normal values in the same age and sex group: 53-97) on 4-chamber (A), short axis (B) and 2-chamber (C) plane

Chapter Outline

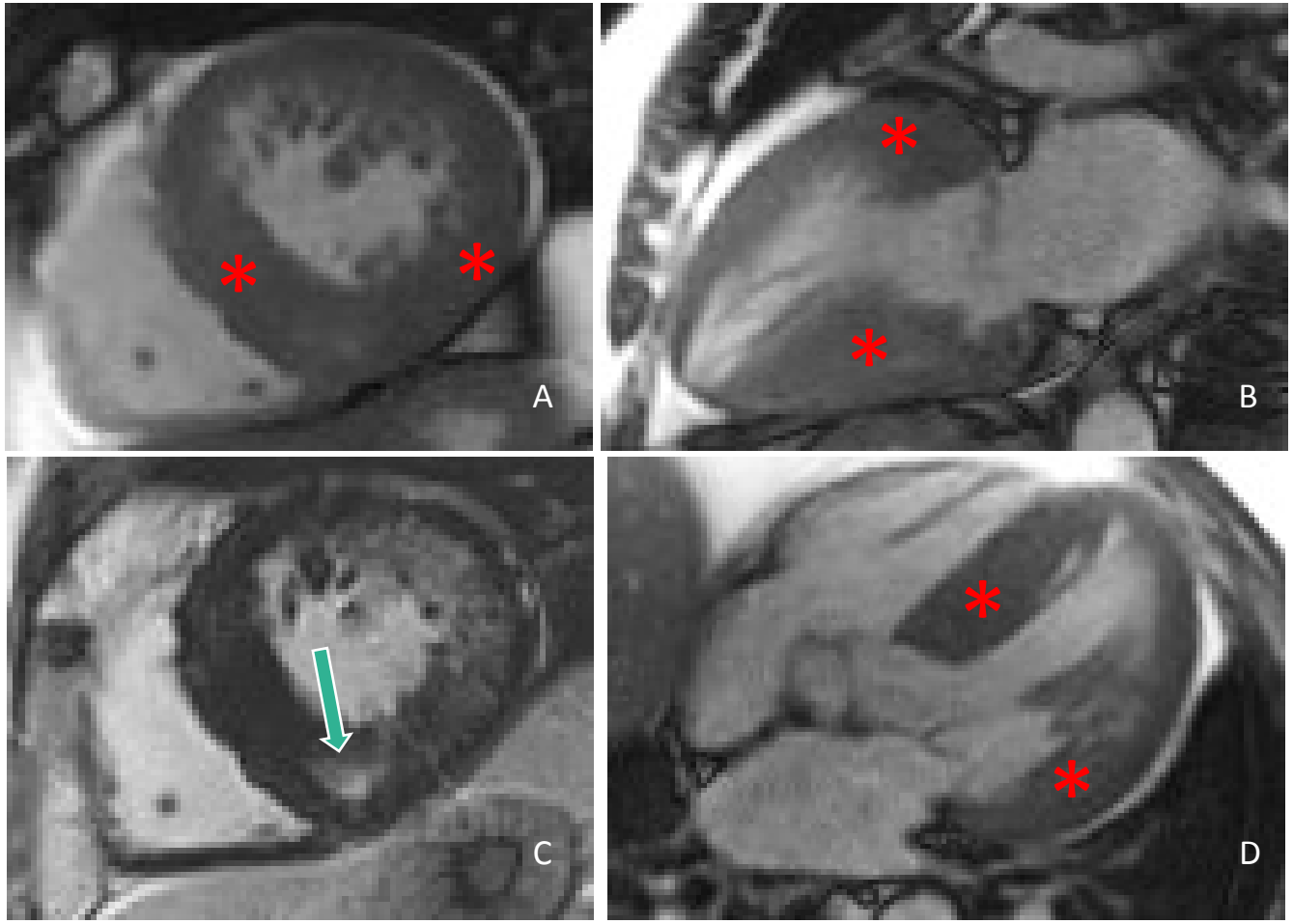


Fig. 33. Cardiac MR of a patient with hypertrophic cardiomyopathy showing ventricular wall thickening (asterisks), mostly affecting septal and inferior wall, in short axis (A and C), 2 chamber (B) and 4 chamber (D) view. (C): LGE sequence showing an area of fibrosis in the inferior interventricular junction (arrow).

Chapter Outline

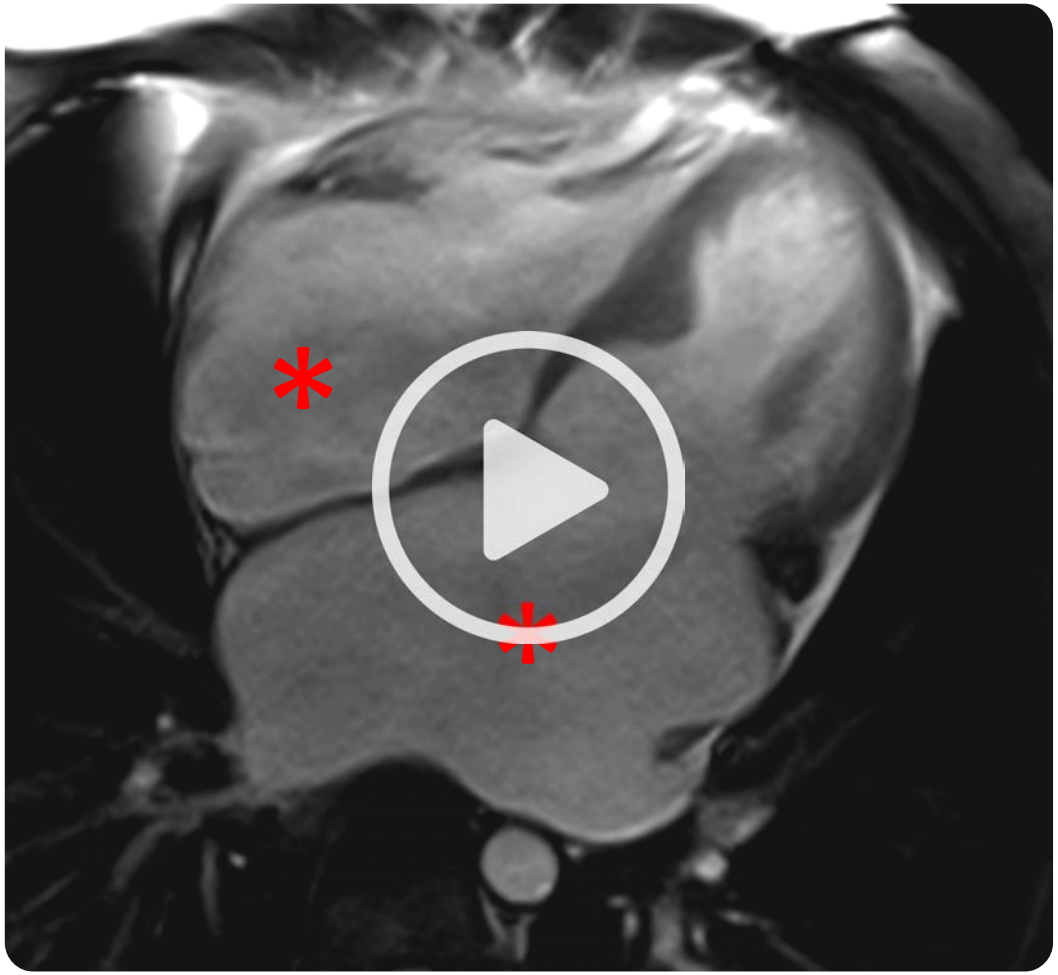


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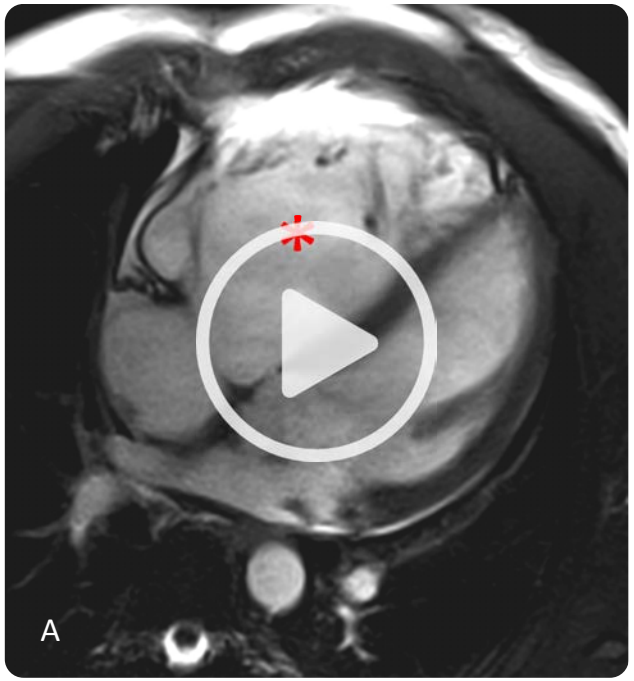
Fig. 34. Cine-MRI in four-chambers view, showing decreased compliance and impaired relaxation of the left ventricle in a patient with restrictive cardiomyopathy. Dilated atria (asterisks).

Chapter Outline



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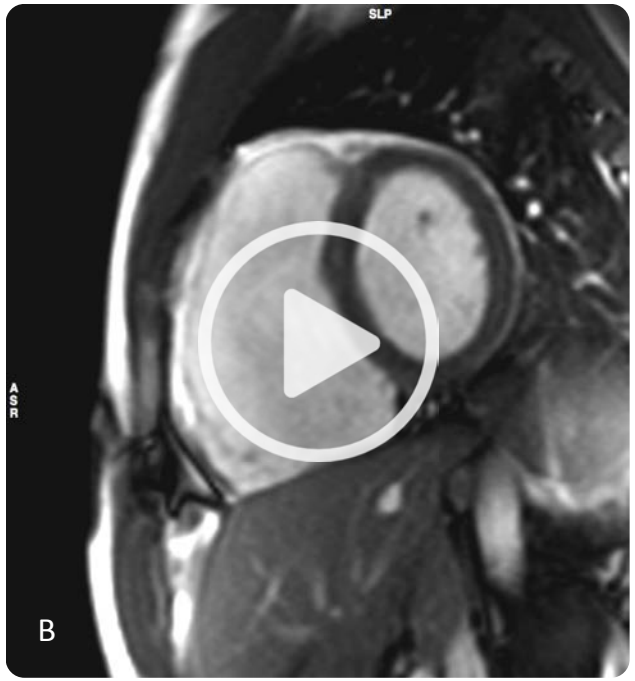

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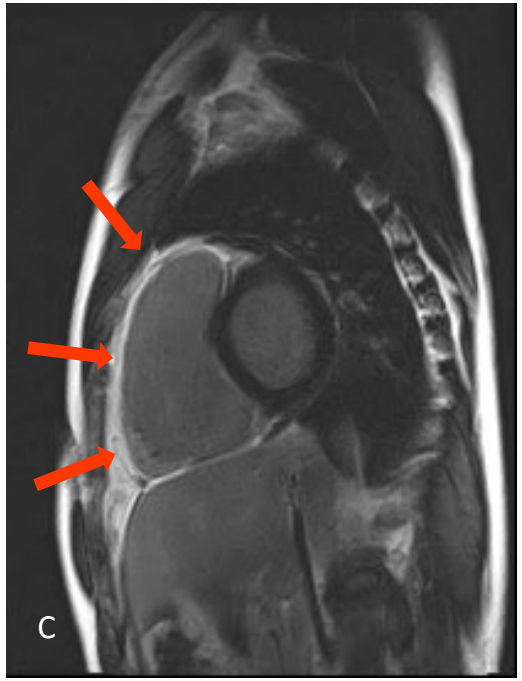


Fig. 35. Cine-MRI (A and B) showing right ventricular dilatation (asterisk, Right ventricle (asterisk) end-dyastolic volume/body surface area: 171.8 mL/m2; normal values for the same age and sex group : 67-111) with decreased Ejection Fraction (EF: 14%). Motility is clearly reduced. C. LGE sequence showing diffuse pathological parietal enhancement of the right ventricular wall, due to fatty infiltration and fibrosis typical of arrhytmogenic right ventricular dysplasia (ARVD).

Chapter Outline

Pericardial Disease

- Pericardial effusion results from accumulation of more than 50mL in the pericardial sac, it is a common finding in a wide spectrum of pathologies.
  - Chest X-ray can detect effusion only when pericardial fluid is more than 200mL, and will be seen as a globular, enlarged cardiac silhouette (water bottle configuration)
  - Echocardiography is accurate in describing the amount of effusion, that will appear as hypoechoic material between the two layers of pericardium, and will also give information on the hemodynamic effect on the heart of such effusion. Echocardiography is also useful to plan and guide pericardiocentesis
  - Detection of effusion at CT is very easy when you see material with the density of water surrounding the heart. CT can also very often give insights on the cause of effusion
  - Effusion at MRI will be easily recognized as hyperintense material surrounding the heart in T2 sequences
- Pericarditis can be seen as a thickening of the pericardium, that will be enhanced by the uptake of contrast
  - CT and MRI are the only two modalities able to reliably identify pericarditis
- Cardiac tamponade is caused by a rapidly developing pericardial effusion that compromises the functionality of the heart
  - Echocardiography is the most important modality in this clinical scenario, as it allows for localization of the effusion, assessment of the heart function and guidance of the pericardiocentesis

Eur Heart Cardiovasc Imaging (2015) 16, 12-31

Insights Imaging. (2019); 10

Quant Imaging Med Surg. (2016) 6, 274–284

Chapter Outline

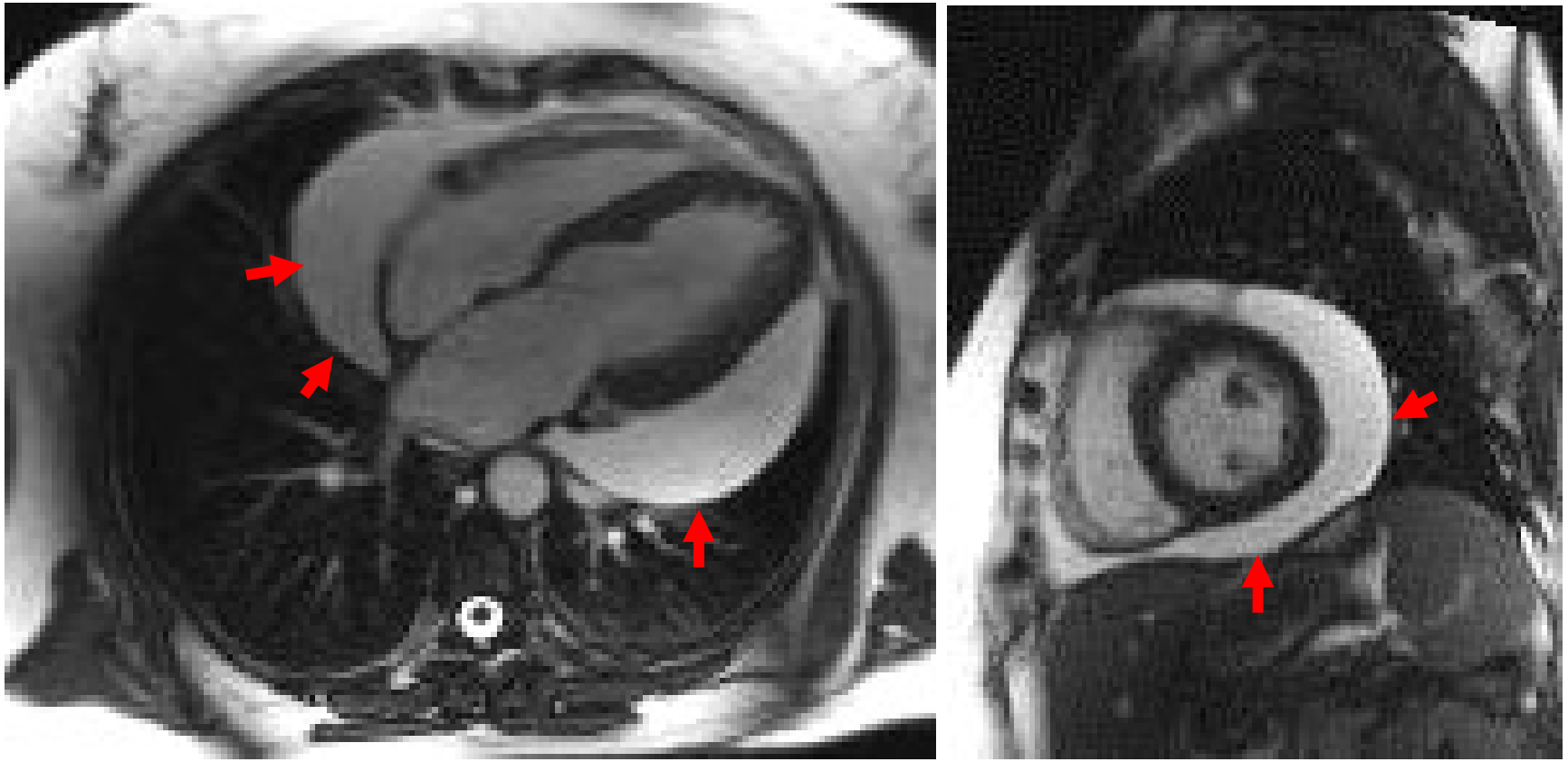


Fig. 36. Cardiac MRI showing profuse circumferential pericardial effusion (arrows) in a patient with systemic lupus erythematosus (SLE).

Chapter Outline

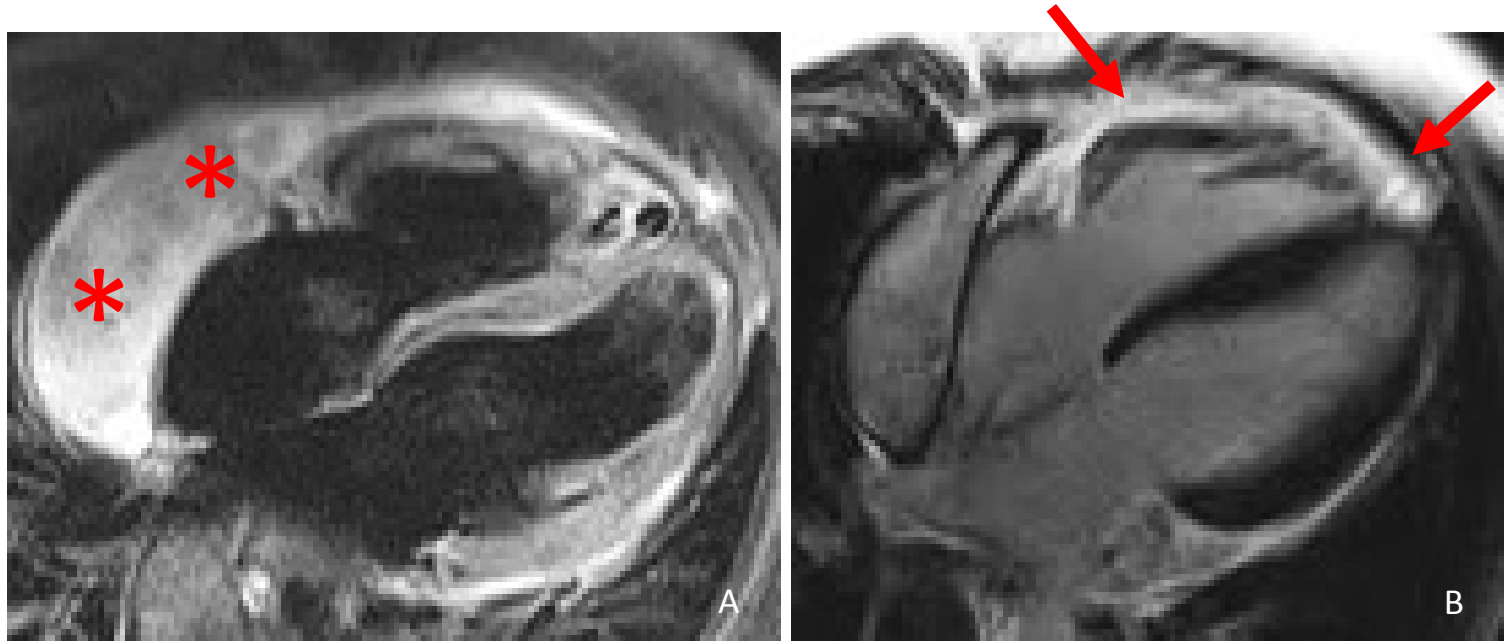


Fig. 37. Cardiac MRI in a patient with pericarditis: A) T2 fat saturated sequence showing massive pericardial effusion (asterisks). B) LGE sequence showing enhancement of pericardial layers (arrows).

Chapter Outline

Congenital Heart Defects

Congenital Heart Defects are alterations in cardiac structures that are present at birth.
There are several congenital defects, mostly involving cardiac wall, heart valves or large blood vessels , with different clinical presentations, ranging from an asymptomatic picture to severe Heart Failure.
They can be isolated, but more often there is an association with other congenital anomalies, in a syndromic clinical picture.
They can be distinguished on the basis of clinical features in Cyanotic and Acyanotic CHD, but the most useful classification is the physiopathological one, which comprehends:

- CHD with increased pulmonary blood flow
- CHD with reduced or normal pulmonary blood flow
- CHD with reduced systemic flow.

The most common CHD is the biscuspid aortic valve, followed by Interventricular Septum Defect and Interatrial Septum Defect.

The first step in evaluation of CHD is echocardiography, but it often detects just indirect signs of CHD, such as altered Qp/Qs values and/or cardiac chambers enlargement, and the suspicion of CHD has to be confirmed by a second-level modality, such as MRI.
MRI is the best modality in evaluating cardiac defects (with morphological sequences) and how they affect cardiac function(cine-MR). It is also useful in the follow-up of patients who underwent surgical correction of CHD.

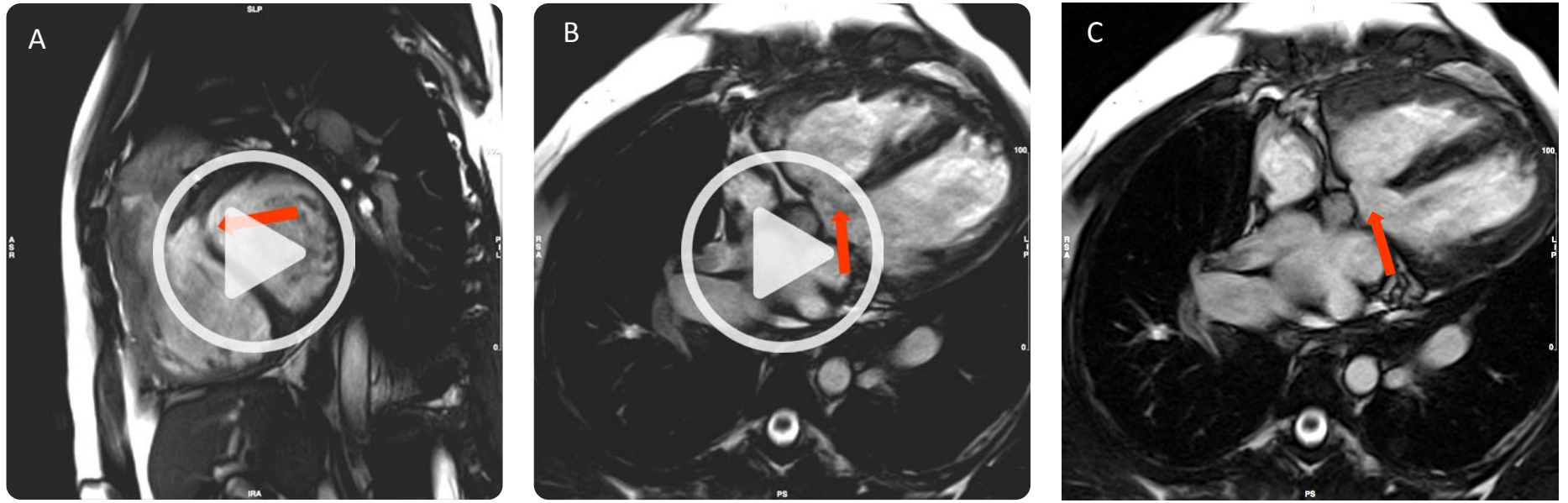
Br J Radiol. (2011) 84, S258–S268.

Diagnostic and Interventional Imaging (2016) Volume 97, Issue 5, Pages 505-512

Chapter Outline

- **Acyanotic**
  - With increase pulmonary blood flow
    - Right Hypertrophy → *Interatrial defects*
    - Left Hypertrophy → - *Interventricolar defects*
      - *Patent ductus arteriosus*
  - Without increase pulmonary blood flow
    - Right Hypertrophy → *Pulmonary stenosis*
    - Left Hypertrophy → - *Aortic stenosis*
      - *Coarctation of the aorta*
- **Cyanotic**
  - With increase pulmonary blood flow
    - Right Hypertrophy → - *Transposition of Great Vessels*
      - *Total Anomalous Pulmonary Venous Drainage*
      - *Hypoplastic left heart syndrome*
    - Left Hypertrophy → *Single Ventricle*
  - Without increase pulmonary blood flow
    - Right Hypertrophy → - *Tetralogy of Fallot*
      - *Ebstein anomaly*
    - Left Hypertrophy → *Tricuspid atresia*

Chapter Outline



Click to Play Video in Browser (External)

Click to Play Video in Browser (External)

Fig. 38. Cardiac MR images in short-axis (A) and four-chambers (B and C) views, showing a large interventricular septum defect (arrows)

Chapter Outline

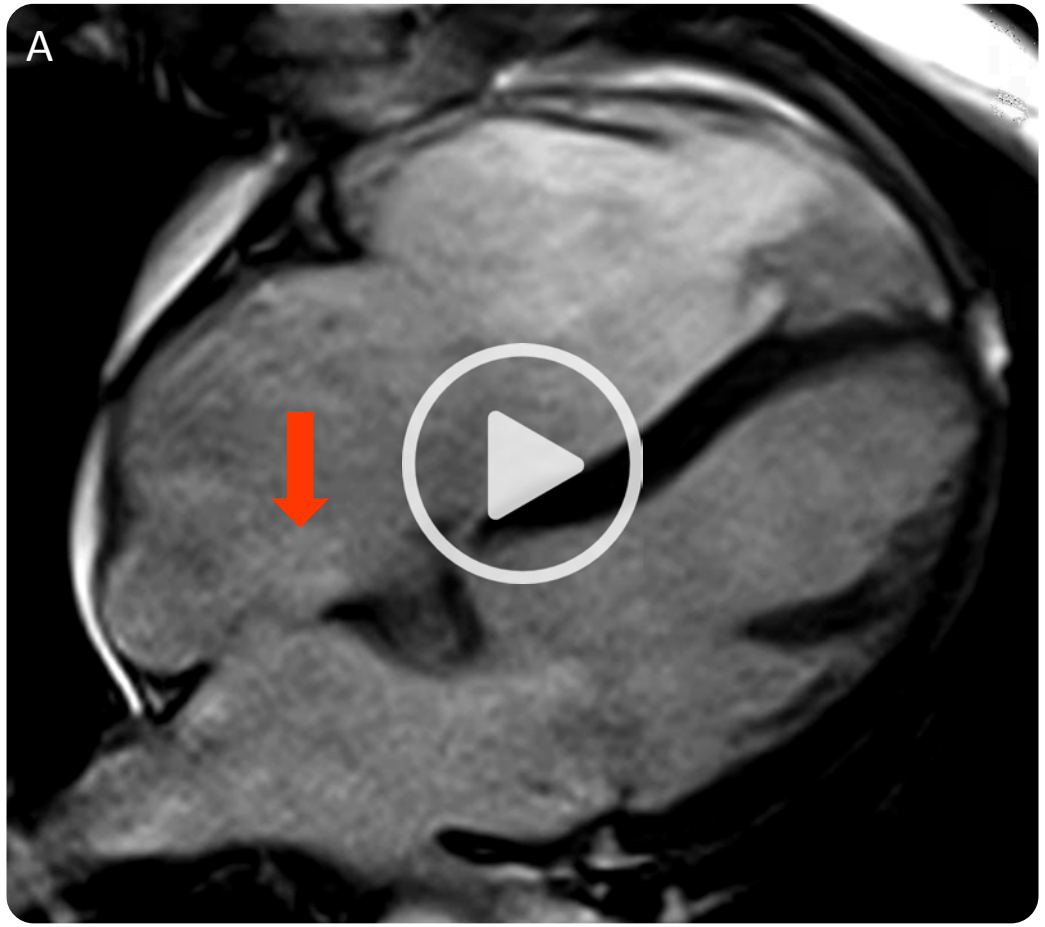


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Fig. 39. Cardiac MRI , in a four-chamber view, showing a large interatrial septum defect (Red arrow points at the jet phenomenon due to blood turbulence on the cine series caused by the defect .

Chapter Outline

Cardiac Masses

Cardiac masses can be divided in tumour and non-tumour ones. The most common finding is non-tumour masses, which comprehend thrombi and misinterpretation of normal variants of cardiac structures.

Tumours can be distinguished in primary cardiac tumours and cardiac metastasis, which are more common. Primary cardiac tumours are exceedingly rare, usually originated from mesenchymal tissue and mostly benign.

The most common benign cardiac tumour is the Myxoma, although the most common malignant tumour is cardiac angiosarcoma. Non-mesenchymal tumours comprehend Teratoma (which can be benign or malignant) and Lymphoma.

Cardiac masses are usually first detected at echocardiography, but cardiac CT and MRI can underlight some characteristics useful in distinguish tumour from non-tumour masses and benign from malignant tumours. These findings mostly comprehend location, size, margins, tissue composition, the presence of a feeding artery, calcification, or pericardial effusion.

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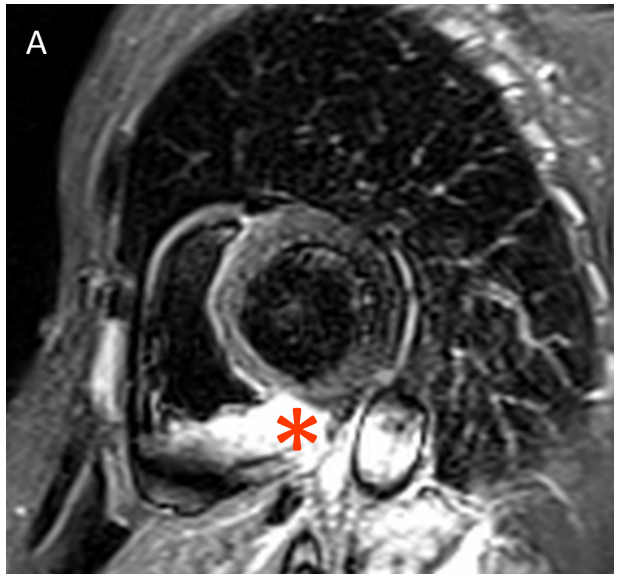
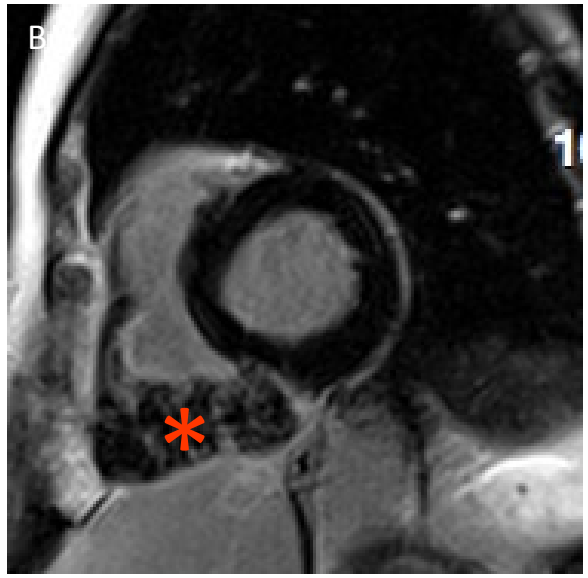
Korean J Radiol. (2009) 10, 164–175.

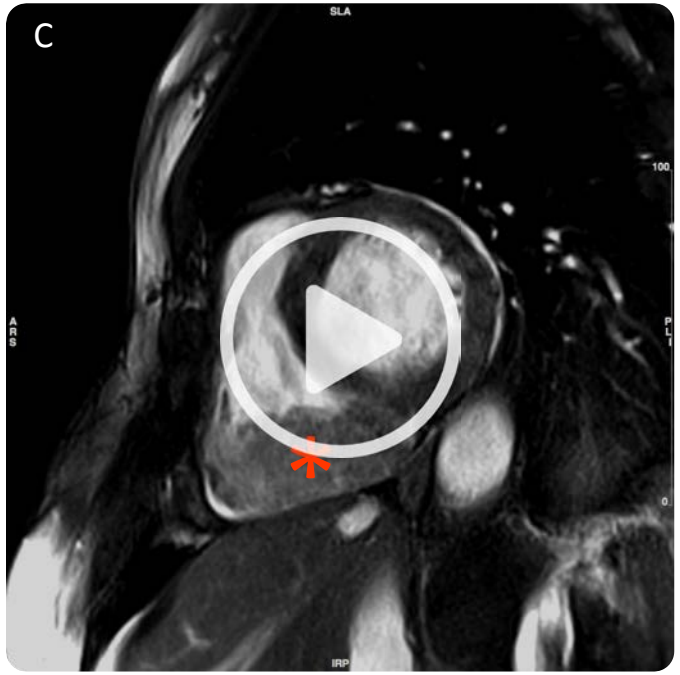
AJR Am J Roentgenol. (2011) 197(5), W837–W841.

Curr Cardiovasc Imaging Rep. (2014) 7(8), 9281.

Chapter Outline







Click to Play Video in Browser (External)

Fig. 40. STIR (T2 fat suppresed) (A) LGE (B) cine-MR (C) and T1-w (D) images in short axis view, showing a large cardiac metastasis (asterisk) in patient with known melanoma

Chapter Outline

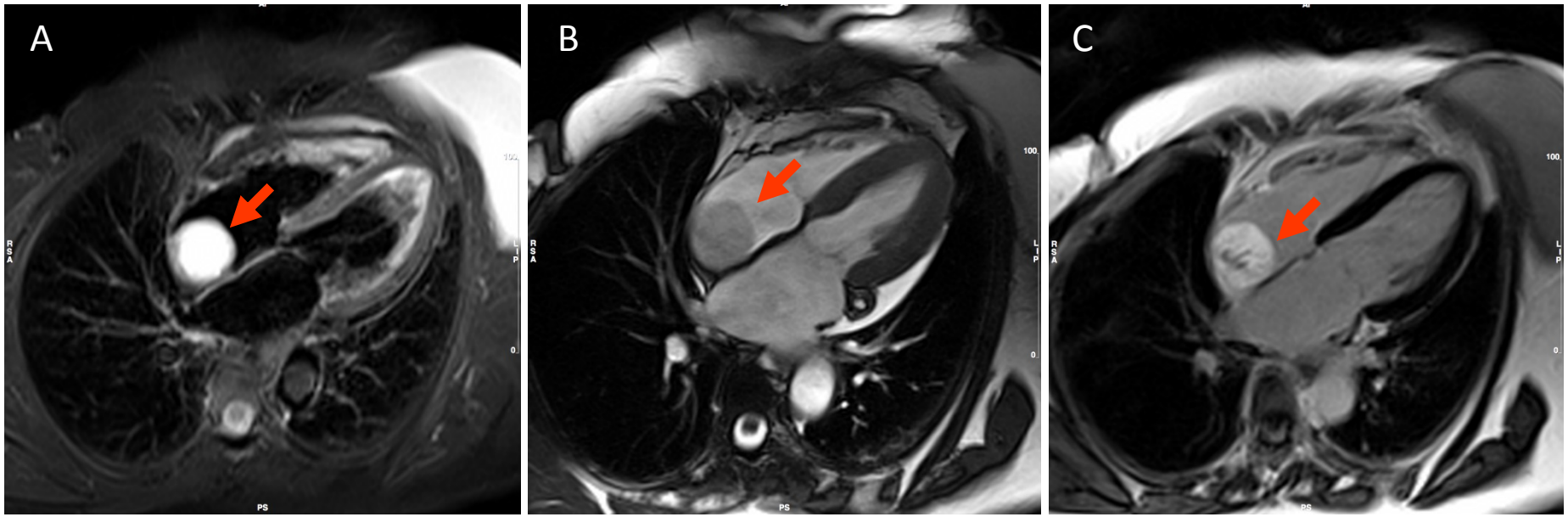


Fig. 41. STIR (A), cine-MR (B) and LGE(C) images on 4-chamber view showing a typical appearance of right atria myxoma (arrows).

Chapter Outline

Test Your Knowledge

1 - Which anomaly do you see in this MRI image?

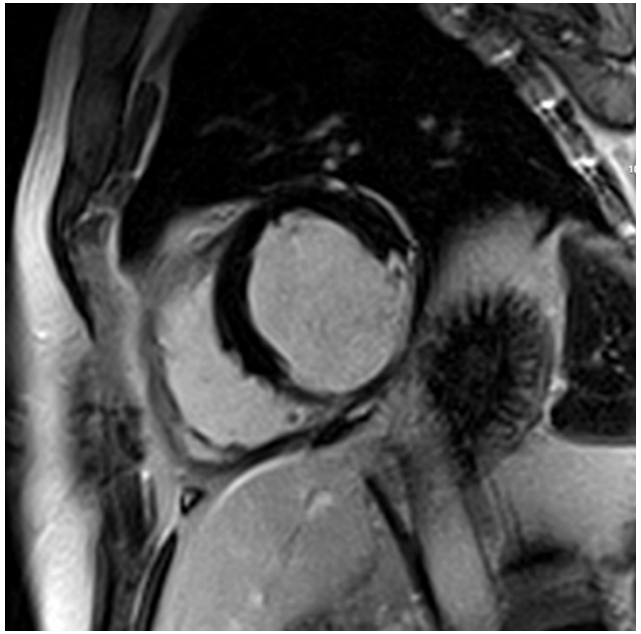
Test Your Knowledge

1 - Which anomaly do you see in this MRI image?

This is a case of situs inversus, as you can see by looking at the position of the different organs and at the directions towards which the heart is pointing.

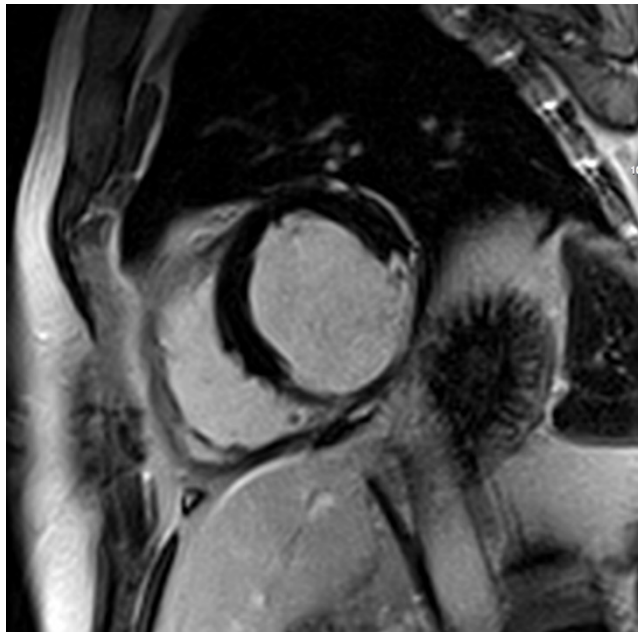
Test Your Knowledge

2 - How would you describe this cardiac MRI image?



Test Your Knowledge

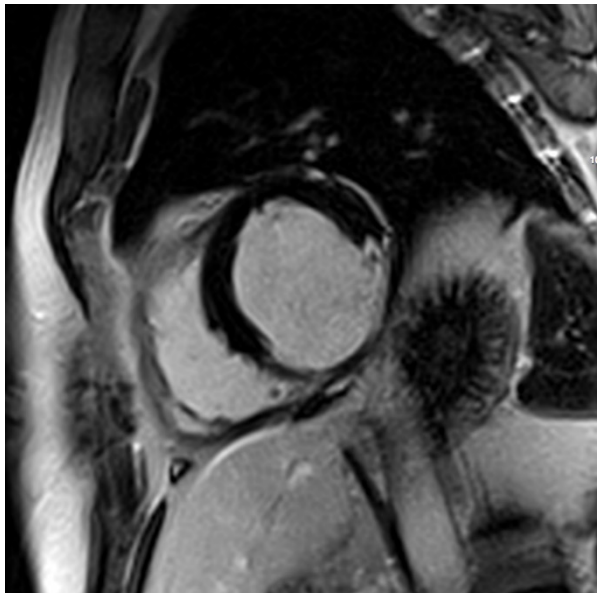
2 - How would you describe this cardiac MRI image?



This is an LGE sequence, short axis view. The inferior wall of the left ventricle is markedly thinned, while the remaining segments seem unaffected.

Test Your Knowledge

3 - Can you give an etiopathological explanation of these findings? Which is the most likely cause?



Test Your Knowledge

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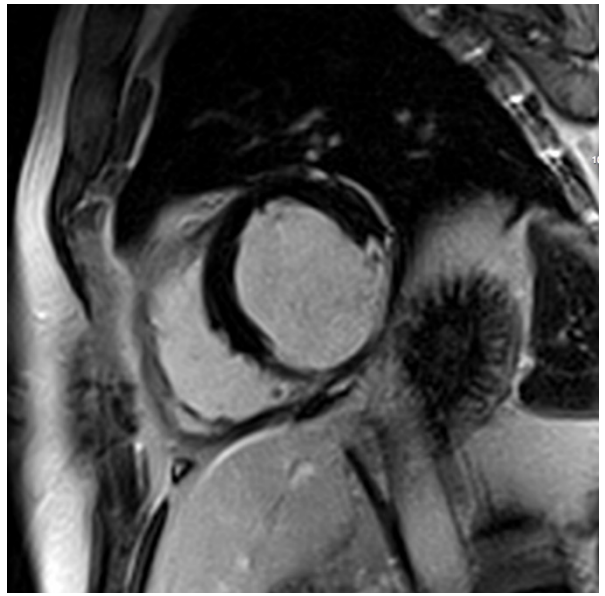
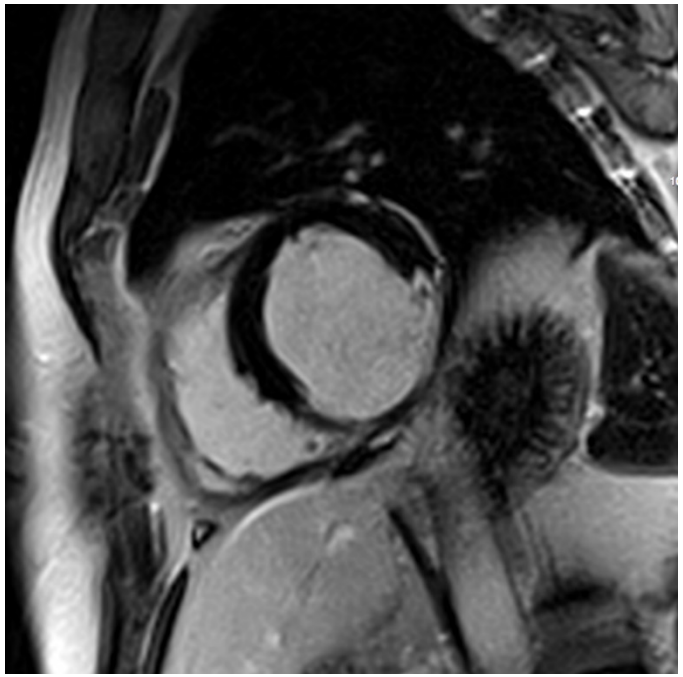


This is the result of long term remodelling of an area of myocardium subjected to ischemia and, subsequently, to fibrosis. The most likely cause is a past myocardial infarction.

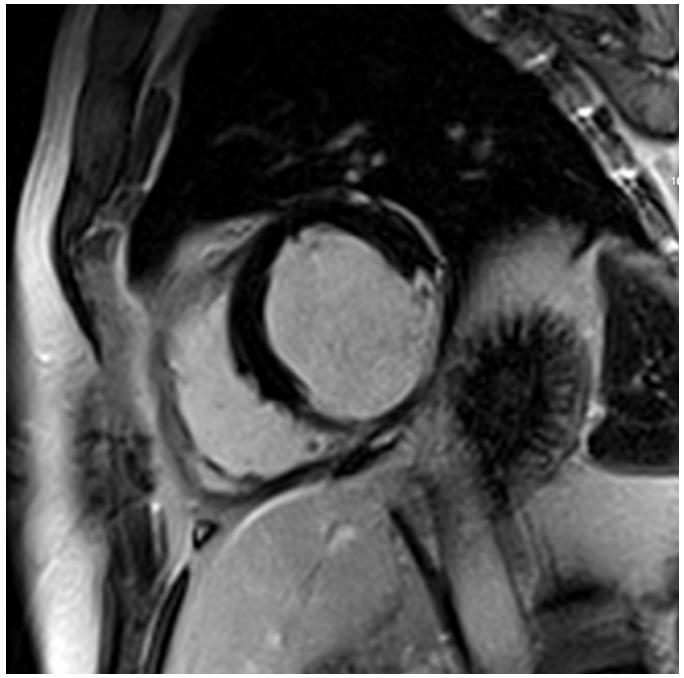
Test Your Knowledge

4 – Can you guess which coronary artery was involved?



Test Your Knowledge

4 – Can you guess which coronary artery was involved?



It was the right coronary artery, which typically perfuses the inferior and inferoseptal walls of the left ventricle.

Test Your Knowledge

5 – A 50-year old male arrives to the attention of his family doctor because of a complain of stable angina and exertional dyspnoea. He doesn't smoke, but is overweight and has a family history of major cardiovascular events.

The physician prescribes an ECG stress test, but the results are inconclusive.
Which is the best next step?

Test Your Knowledge

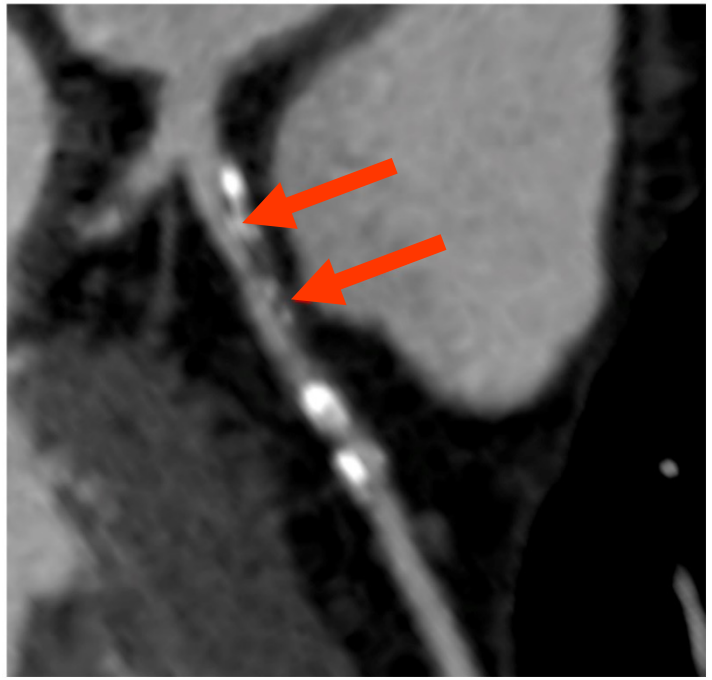
5 – A 50-year old male arrives to the attention of his family doctor because of a complain of stable angina and exertional dyspnoea. He doesn't smoke, but is overweight and has a family history of major cardiovascular events.

The physician prescribes an ECG stress test, but the results are inconclusive.
Which is the best next step?

Given the young age of the patient and the inconclusive ECG stress test, the best next step is to perform a coronary CT angiogram.

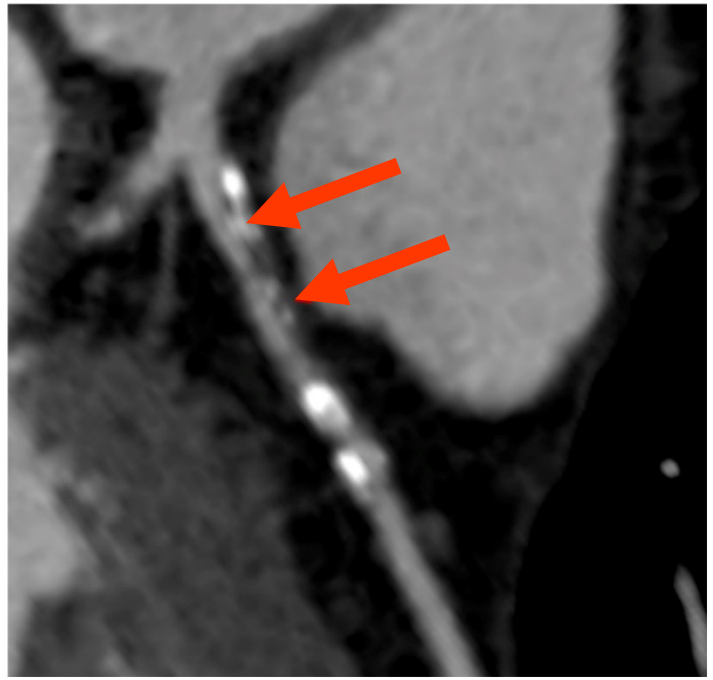
Test Your Knowledge

6 - Here is the major finding of his exam, can you describe it? Do you think it may be the cause of his symptoms?



Test Your Knowledge

6 - Here is the major finding of his exam, can you describe it? Do you think it may be the cause of his symptoms?



This is an atherosclerotic plaque in his left anterior descending artery. The plaque is mixed and causes severe stenosis of the lumen (70%). The patient is at risk and should undergo invasive coronary angiography for further characterization and possibly treatment of the stenosis.

Test Your Knowledge

7 - A 32-year old male arrives to the ED complaining acute, compressive, chest pain radiating to the left arm, LV function is depressed at echocardiography. the main clinical suspicion is acute myocardial infarction, but the ECG only shows a specific anomalies of ventricular repolarization. This finding, together with the young age of the patient, convince the physicians to perform a Triple-rule-out CT scan.

The only pathological finding can be seen here, affecting the left anterior descending coronary artery, can you spot it?

Chapter Outline

Test Your Knowledge

7 - A 32-year old male arrives to the ED complaining acute, compressive, chest pain radiating to the left arm, LV function is depressed at echocardiography. the main clinical suspicion is acute myocardial infarction, but the ECG only shows a specific anomalies of ventricular repolarization. This finding, together with the young age of the patient, convince the physicians to perform a Triple-rule-out CT scan.

The only pathological finding can be seen here, affecting the left anterior descending coronary artery, can you spot it?

There is a small calcified plaque on the left anterior descending artery.

Chapter Outline

Test Your Knowledge

8 - The only abnormality seen on CT angiography was a small calcified plaque of the left anterior descending artery. Could it be responsible for the clinical presentation?

Chapter Outline

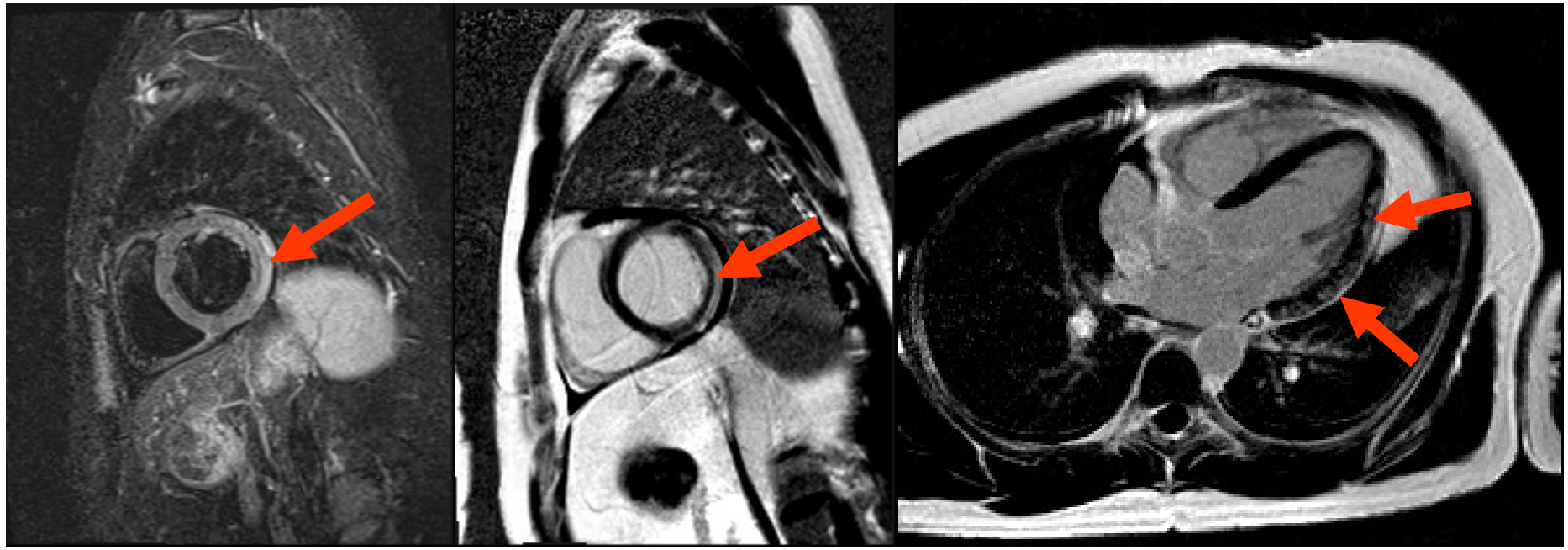
Test Your Knowledge

8 - The only abnormality seen on CT angiography was a small calcified plaque of the left anterior descending artery. Could it be responsible for the clinical presentation?

The small calcified plaque is very unlikely to be responsible for the patient's symptoms

Test Your Knowledge

9 - The acute symptomatology subsides, but the heart function remains depressed. The patient undergoes Cardiac MRI 6 days after the acute episode. Here are some selected images from the MRI exam. What are the main findings?



Test Your Knowledge

9 - The acute symptomatology subsides, but the heart function remains depressed. The patient undergoes Cardiac MRI 6 days after the acute episode. Here are some selected images from the MRI exam. What are the main findings?

The STIR image (left) shows myocardial oedema in the inferolateral wall. LGE images (centre and right) show subepicardial enhancement, which has a patchy distribution. These findings are most likely consistent with myocarditis.

Chapter Outline