European Heart Journal Supplements (2025) **27** (Supplement 1), i22–i26
The Heart of the Matter
https://doi.org/10.1093/eurheartjsupp/suae112

ESC
European Society
of Cardiology

The era of interventional imaging has arrived: what role for computed tomography and magnetic resonance?

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KEYWORDS
Coronary computed tomography angiography;
Fractional flow reserve by CCTA;
Percutaneous coronary intervention;
Cardiac magnetic resonance

Coronary computed tomography angiography (CCTA) is the first-line investigation test to 'rule out' significant coronary artery disease in low-risk patients. By performing blood flow simulations using computational fluid dynamics, it is possible to derive fractional flow reserve (FFR) from CCTA (FFRCT) images. Coronary computed tomography angiography and FFRCT are now utilized in higher-risk patients to choose the revascularization mode. Furthermore, new applications of CCTA and FFRCT include a planning tool for percutaneous coronary intervention (PCI), which allows the cardiologist to assess lesion-specific ischaemia, plan stent locations and sizes, and use virtual remodelling of the lumen (virtual stenting) to assess the functional impact of PCI. Moreover, CCTA can assist in planning surgical and percutaneous revascularization by determining the disease complexity, vessel size, lesion length, and tissue composition of the atherosclerotic plaque, as well as the best fluoroscopic viewing angle; it may also help in selecting adjunctive percutaneous devices (e.g. rotational atherectomy) and in determining the best landing zone for stents or bypass grafts. Coronary computed tomography angiography has become also the gold standard for pre-procedural annular assessment, device sizing, risk determination of annular injury, coronary occlusion or left ventricular outflow tract obstruction, calcification visualization and quantification of the target structure, and prediction of a co-planar fluoroscopic angulation for transcatheter interventions in patients with structural heart disease. Coronary computed tomography angiography and cardiac magnetic resonance could be used also in electrophysiology procedures of atrial fibrillation and ventricular arrhythmias ablation (imaging during clinical evaluation and pre-procedural evaluation and intra-procedural live integration). The era of interventional imaging has arrived, and it is based on the cooperation of different figures with specific competences (cardio-imagers, electrophysiologists, cardiac surgeons, and invasive cardiologists)

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Coronary computed tomography angiography to guide surgical revascularization

In patients with three-vessel disease and/or left main disease, the SYNTAX III REVOLUTION trial demonstrated that selecting revascularization strategy based on coronary computed tomography angiography (CCTA) has a high level of virtual agreement with treatment decisions based on invasive coronary angiography (ICA) (93% concordance and Cohen's kappa 0.82), a finding which prompted the hypothesis that CCTA might provide sufficient, or even superior, information to ICA in planning and performing coronary artery bypass graft (CABG).[1] However, the SYNTAX III REVOLUTION trial was virtual, as prior to treatment, each Heart Team (ICA and CCTA) was ultimately unblinded. In FAST TRACK CABG trial, the key question was: it is feasible and safe to skip ICA before CABG? The trial showed that planning and execution of CABG based on CCTA alone was feasible in a cohort of 114 patients with chronic coronary syndrome and low surgical risk.[2] The 30-day follow-up CCTA in 92% of patients showed an anastomosis patency rate of 93%, similar to other previous studies.[3]

With its 3D nature and physiological assessment of fractional flow reserve (FFRCT), CCTA allows to assess Syntax Score and Syntax Score II, which provide the Heart Team with a recommendation on the mode of revascularization [percutaneous coronary intervention (PCI) or CABG] for patients with complex disease based on long-term mortality. The identification of haemodynamic significance of a lesion, visualization of landing zone for the distal surgical anastomosis, and distal run-off emerged as the most important factors supporting the feasibility of this approach. Coronary computed tomography angiography identifies non-diseased target segments for grafting. In addition, it provides insights into vessel course including an intra-myocardial coronary path, presence of coronary anomalies, and target vessel size. In case of chronic total occlusion, assessment of the vessel distal to the occlusion proves usually feasible also providing information not always readily available with ICA, where only in case of well-developed collateral flow the course and size of the distal coronary bed are evaluable. Moreover, the amount of subtended myocardium and identification of potential myocardial scar by CCTA can help omit futile grafting or optimize CABG strategies when limited grafting material is available.

Coronary computed tomography angiography 3D volume rendering also facilitates the assessment of coronary anatomy. The course of and distance between the left anterior descending artery and diagonal branches is relevant for planning sequential bypass grafting. Furthermore, CCTA can also assess the anatomy, calibre, and length of the left and right internal mammary arteries by using the curved multiplanar reconstruction and then lumen visualization view. The presence of disease in the ascending aorta may prompt alternative surgical approaches such as no-touch aorta technique with the potential to minimize cerebral embolization during surgery. Maximal intensity projection (MIP) is particularly useful for the evaluation of aortic calcifications eventually changing cannulation or impacting the selection of a good location to sew the origin of the bypass graft.[4]

Figure 1 shows an example of a CABG procedure planning by CCTA.

Coronary computed tomography angiography to guide percutaneous revascularization

Using CCTA, the location of the coronary ostia can be ascertained and knowledge of ostia position informs the operator on distinct manoeuvres or special coronary catheter shapes required for selective cannulation.[5] Thanks to its 3D nature, CCTA can be potentially useful also to select the best angiographic projection that is of upmost importance in bifurcation and ostial lesions. In coronary bifurcations, correct visualization of the side branch ostium is crucial to define PCI strategy and the need of additional interventions at the level of the side branch. Likewise, in ostial lesions, the precise demarcation of the ostium is essential for correct stent positioning and deployment. In these scenarios, a CCTA-guided approach may save time, may contrast, and reduces unnecessary radiation exposure. Based on CCTA, complex interventions can be better prepared.

Coronary computed tomography angiography allows visualizing the atherosclerotic plaque and determining plaque burden and extension. Plaques can be qualitatively and quantitatively characterized.[6] It has been shown that CCTA helps identify high-risk plaques (HRP) and also allows the characterization of lesions through their Hounsfield units (HU). Calcified plaques can be visualized as structures with high HU, and their thickness, length, and circumference can be evaluated. A high calcium burden is associated with lower stent expansion, leading to higher rates of device-related adverse events after PCI. Therefore, in vessels with high calcium burden detected by CCTA, the use of additional techniques such as rotational or orbital atherectomy and intracoronary lithotripsy may improve stent expansion. In the other spectrum of the atherosclerotic disease (as HRP), PCI has been associated with periprocedural myocardial infarction and no-reflow phenomenon.[7] Thus, plaque characterization by CCTA may help in stratifying the risk of periprocedural complications. Moreover, pre-PCI assessment is based on lesion length that is assessed as the distance between healthy (i.e. plaque free) landing zones proximal and distal to the coronary stenosis.[7]

Fractional flow reserve from CCTA has been an accurate method for determining the haemodynamic significance of coronary artery disease (CAD) compared with invasive fractional flow reserve (FFR).[8] The PCI planning tool is a new application of CCTA and FFRCT, and it has been validated in the P3 trial.[9] FFRCT allows the interventional cardiologist to assess lesion-specific ischaemia and to assess the phenotype of CAD (focal or diffuse), whereas the CCTA data set is used to measure stenosis, lesion length, minimal lumen diameter, and reference diameter and to plan stent selection. Unique features of the PCI planning tool include the ability to use virtual stenting and FFRCT to assess the physiological response to various PCI strategies, even before ICA is performed; the application is mobile for use on a tablet or cellular device and interactive with near real-time assessment of various PCI strategies. The PCI planning

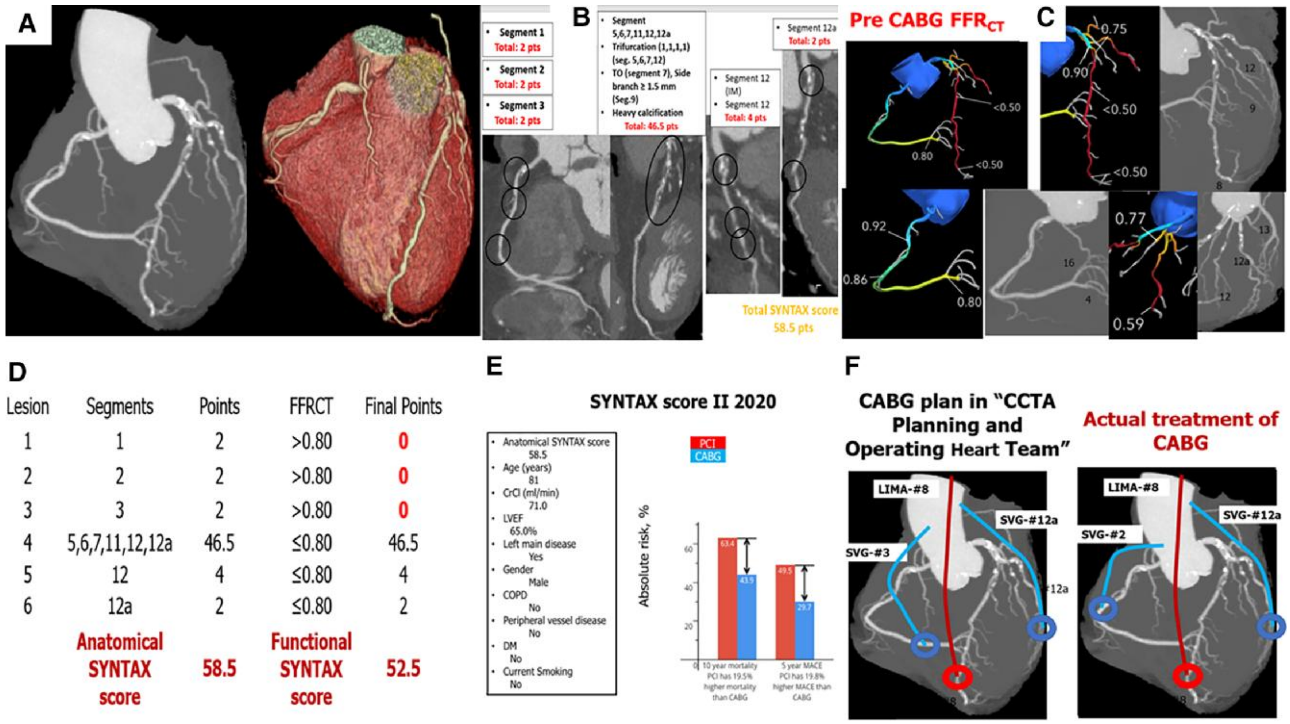

Figure 1 Example of a planning of coronary artery bypass graft procedure by coronary computed tomography angiography. A case of 81-year-old male with stable angina with three-vessel disease by coronary computed tomography angiography. The maximal intensity projection and volume rendering images in *A* show the extent of disease and allow identifying the distal bed of coronary arteries. (*B*) The coronary computed tomography angiography-derived anatomical Syntax Score and (*C*) the fractional flow reserve from coronary computed tomography angiography images. (*D*) The functional Syntax score (in particular the lesions on right coronary artery were derubricated from the score because of normal fractional flow reserve from coronary computed tomography angiography images). (*E*) The calculation of Syntax Score II has been assessed, which provides the Heart Team with a recommendation on the mode of revascularization (percutaneous coronary intervention or coronary artery bypass graft). (*F*) The planning of coronary artery bypass graft procedure based solely on coronary computed tomography angiography. In this case, although there is a normal fractional flow reserve from coronary computed tomography angiography images on right coronary artery, the surgeon decides to make a bypass also on right coronary artery.

tool is currently a research application and is not available for commercial use.

The ongoing P4 trial is an investigator-initiated, multicentre, randomized study with a non-inferiority design of patients with an indication for PCI aiming at comparing clinical outcomes between two imaging strategies to guide PCI: a computed tomography (CT)-guided PCI strategy and IVUS-guided PCI strategy (NCT05253677).

Figure 2 shows an example of a CCTA-guided PCI.

Currently, several technical and logistical limitations exist that limit the use of FFRCT. The primary technical limitation is its dependence on quality source data. Artefacts related to motion, metal, body habitus, arrhythmia, or gating may degrade the source coronary CTA acquisition, which may render the post-processed FFRCT data not evaluable or inaccurate. Moreover, the cost associated with FFRCT and the computational fluid dynamics method, currently the only approved by the Food and Drug Administration, limits the routine use.

Computed tomography and magnetic resonance in structural diseases

Coronary computed tomography angiography has become crucial in the diagnosis of structural heart disease as well as in the selection of patients for interventional procedures, pre-procedural planning, device sizing, and post-procedural follow-up.[10] Apart from CAD evaluation, the severity of aortic valve stenosis can be estimated by the calcium load of aortic valve calculated according to the Agatston method on non-enhanced cardiac CT, and this is particularly useful in the reclassification of the low-flow low-gradient aortic stenosis. Cardiac CT provides information on aortic root and thoracic aorta measurements, aortic annulus sizing optimizing the selection of aortic prosthesis as well as distance of the coronary ostia from the aortic valve plane, and the number and length of aortic cusps and provides optimal fluoroscopic projection as well as the grade and distribution of annular and sub-annular calcifications. Finally, CCTA offers information regarding the optimal vascular access route providing detail on vessel size, tortuosity, course, calcifications, and stenosis which are the main determinants of vascular complications during the procedure.[11]

Also in the pre-procedural work-up of patients with mitral valve disease, CCTA is playing an increasing role, helping determine device suitability evaluating the mitral annulus size and geometry, the relationship of the mitral valve with the circumflex coronary artery, and the distribution of mitral annular calcifications. Moreover, pre-procedural CCTA-based simulation has

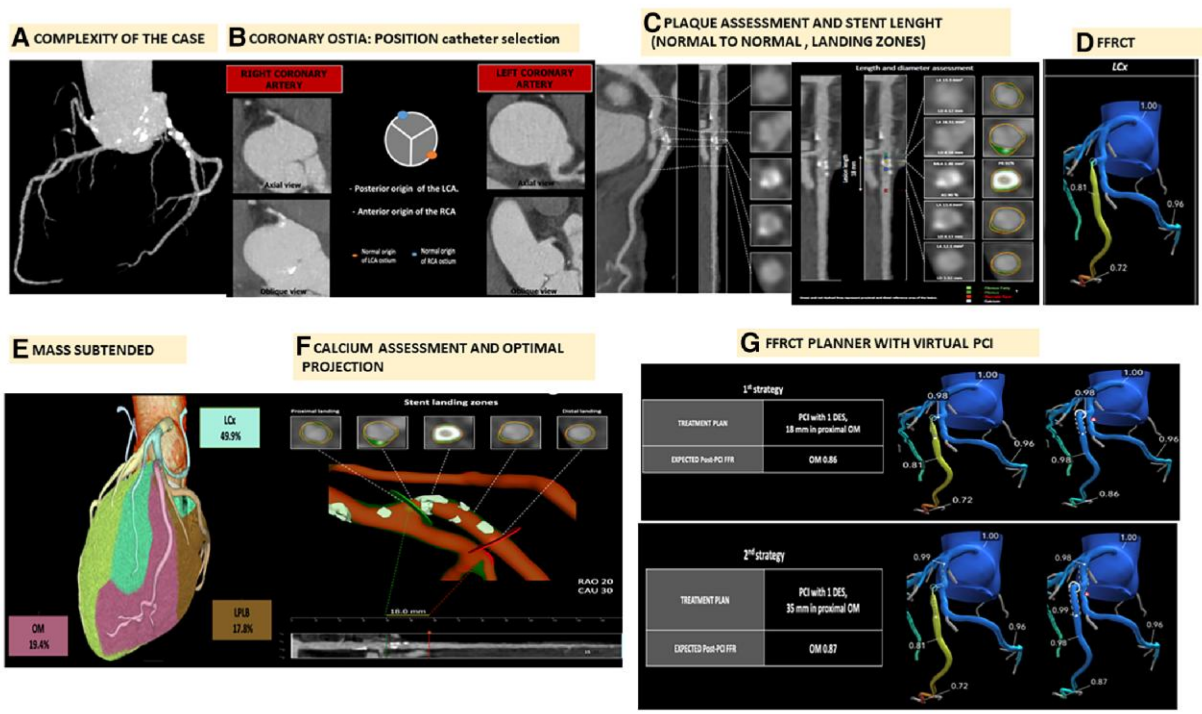

Figure 2 Example of a planning of percutaneous coronary intervention procedure by coronary computed tomography angiography. A case of 78-year-old male with angina symptoms and a severe stenosis on marginal branch. The different phases of planning percutaneous coronary intervention by coronary computed tomography angiography are shown: (*A*) the maximal intensity projection images anticipate the complexity of case and calcium burden; (*B*) the axial images showed the coronary ostia position (in this case anterior for right coronary artery and posterior for left main artery) suggesting the catheter to use during ICA; (*C*) plaque assessment with evaluation of the lesion length (stent length) considering stent landing zone in normal vessels; (*D*) functional evaluation by fractional flow reserve from coronary computed tomography angiography images showed an fractional flow reserve of 0.72 on marginal and a delta-fractional flow reserve of 0.27; (*E*) the mass subtended by the marginal branch is big 19.4%; (*F*) calcium assessment showed circumferential deposition but short in length suggesting a preparation of the lesion with a NC balloon 1:1; moreover, optimal projection for the lesion assessment has been shown before ICA; (*G*) fractional flow reserve from coronary computed tomography angiography images planner and virtual percutaneous coronary intervention shows two possible strategies: one with a short stent of 18 mm with a fractional flow reserve from coronary computed tomography angiography images post-percutaneous coronary intervention expected of 0.86 and a longer stent of 35 mm with a fractional flow reserve from coronary computed tomography angiography images post-percutaneous coronary intervention of 0.87. CCTA, coronary computed tomography angiography; ICA, invasive coronary angiography; PCI, percutaneous coronary intervention; LM, left main artery; MIP, maximum intensity projection; RCA, right coronary artery.

shown to be helpful in identifying patients at higher risk of post-implant left ventricle outflow tract obstruction.[12]

Magnetic resonance (MRI) that can be used for quantification of the aortic valve opening area and transvalvular velocities using planimetry and phase-contrast imaging with simultaneous LV ejection fraction calculation is the gold standard for cardiomyopathy phenotyping with mapping techniques and late gadolinium enhancement.[13] In particular, the assessment of late iodine enhancement and CT-derived extracellular volume (ECV) had a good correlation with late gadolinium enhancement and MRI-derived ECV. ECV by CT during routine CT for transcatheter aortic valve replacement evaluation can reliably detect subclinical amyloidosis, and the measured ECV by CT tracks the degree of infiltration[14]

Computed tomography and magnetic resonance for electrophysiological procedures

In the context of atrial fibrillation, CCTA has been widely used in the pre-procedural planning of catheter ablation, providing detailed anatomic delineation of left atrium and pulmonary veins, in ruling out left atrial appendage (LAA) thrombus, and in planning the LAA closure.[10]

Targeting atrial fibrosis detected by electroanatomical mapping or using diagnostic imaging to treat patients with atrial fibrillation (AF) has shown promise in some studies.[15] Using regions of delayed enhancement to identify fibrotic remodelling, Akoum *et al.*[15] demonstrated that patients with persistent AF and more fibrosis targeted during ablation based on late gadolinium enhancement MRI had significantly less AF recurrence after the procedure. Recently, DECAFF II trial investigated the efficacy and adverse events of targeting atrial fibrosis detected on MRI in reducing atrial arrhythmia recurrence in persistent AF showing no significant difference in atrial arrhythmia recurrence between MRI-guided fibrosis ablation and pulmonary vein isolation (PVI), compared with PVI catheter ablation only.[16]

In the context of ventricular arrhythmias, the role of MRI in the risk stratification is well known, with precise and reproducible assessment of scar and detailed tissue characterization.[17] Beyond accurate localization of substrate, CMR has been used to predict the location of re-entrant circuits within the scar to guide ablation.[17]

However, the results of radiofrequency ablation cannot be extended to all patients with recurrent ventricular tachycardia; the possibility to effectively treat the arrhythmogenic substrate is indeed limited by several factors, including the complexity, extent, and depth of the arrhythmogenic substrate. This evidence clearly explains the suboptimal percentage of patients successfully treated for ventricular tachicardya (VT).

In the STRA-MI-VT trial, safety and efficacy of stereotactic body radiation therapy (SBRT) for the treatment of recurrent VT in patients not eligible for catheter ablation have been investigated and CCTA with also late iodine enhancement technique for the characterization of the substrate and the definition of the anatomical target has been used.[18] Stereotactic body radiation therapy, guided by imaging techniques as CCTA, partially integrated by electrocardiographic and/or electroanatomical data, significantly reduced the arrhythmic burden in these patients, in the absence of major adverse events correlated with the treatment applied.

Conclusions

The era of interventional imaging has arrived, and it is based on the cooperation of different figures with specific competences (cardio-imagers, electrophysiologists, cardiac surgeons, and invasive cardiologists) and on a multimodality imaging approach that is necessary for planning and guiding procedures, encouraging the expert radiologists to be the part of the decision-making process.

Funding

None declared.

Conflict of interest: none declared.

Data availability

No new data were generated or analysed in support of this research.

References

1. Collet C, Onuma Y, Andreini D, Sonck J, Pompilio G, Mushtaq S *et al*. Coronary computed tomography angiography for heart team decision-making in multivessel coronary artery disease. *Eur Heart J* 2018;**39**:3689-3698.
2. Serruys PW, Kageyama S, Pompilio G, Andreini D, Pontone G, Mushtaq S *et al*. Coronary bypass surgery guided by computed tomography in a low-risk population. *Eur Heart J* 2024;**45**:1804-1815.
3. Sousa Uva M, Cavaco S, Oliveira AG, Matias F, Silva C, Mesquita A *et al*. Early graft patency after off-pump and on-pump coronary bypass surgery: a prospective randomized study. *Eur Heart J* 2010;**31**:2492-2499.
4. Nykonenko A, Feuchtner G, Nykonenko O, Chmul K, Makarenkov A, Naumova D *et al*. Feasibility of coronary CT angiography for guidance of CABG. *J Cardiovasc Comput Tomogr* 2021;**15**:281-284.
5. Pursnani A, Jacobs JE, Saremi F, Levisman J, Makaryus AN, Capunay C *et al*. Coronary CTA assessment of coronary anomalies. *J Cardiovasc Comput Tomogr* 2012;**6**:48-59.
6. Maurovich-Horvat P, Ferencik M, Voros S, Merkely B, Hoffmann U. Comprehensive plaque assessment by coronary CT angiography. *Nat Rev Cardiol* 2014;**11**:390-402.
7. Uetani T, Amano T, Kunimura A, Kumagai S, Ando H, Yokoi K *et al*. The association between plaque characterization by CT angiography and post-procedural myocardial infarction in patients with elective stent implantation. *JACC Cardiovasc Imaging* 2010;**3**:19-28.
8. Norgaard BL, Leipsic J, Gaur S, Seneviratne S, Ko BS, Ito H *et al*. Diagnostic performance of noninvasive fractional flow reserve derived from coronary computed tomography angiography in suspected coronary artery disease: the NXT trial (analysis of coronary blood flow using CT angiography: next steps). *J Am Coll Cardiol* 2014;**63**:1145-1155.
9. Sonck J, Nagumo S, Norgaard BL, Otake H, Ko B, Zhang J *et al*. Clinical validation of a virtual planner for coronary interventions based on coronary CT angiography. *JACC Cardiovasc Imaging* 2022;**15**:1242-1255.
10. Pontone G, Rossi A, Guglielmo M, Dweck MR, Gaemperli O, Nieman K *et al*. Clinical applications of cardiac computed tomography: a consensus paper of the European Association of Cardiovascular Imaging-part II. *Eur Heart J Cardiovasc Imaging* 2022;**23**:e136-e161.
11. Blanke P, Weir-McCall JR, Achenbach S, Delgado V, Hausleiter J, Jilaihawi H *et al*. Computed tomography imaging in the context of transcatheter aortic valve implantation (TAVI)/transcatheter aortic valve replacement (TAVR): an expert consensus document of the Society of Cardiovascular Computed Tomography. *JACC Cardiovasc Imaging* 2019;**12**:1-24.
12. Weir-McCall JR, Blanke P, Naoum C, Delgado V, Bax JJ, Leipsic J. Mitral valve imaging with CT: relationship with transcatheter mitral valve interventions. *Radiology* 2018;**288**:638-655.
13. Francone M, Budde RPJ, Bremerich J, Dacher JN, Loewe C, Wolf F *et al*. CT and MR imaging prior to transcatheter aortic valve implantation: standardisation of scanning protocols, measurements and reporting-a consensus document by the European Society of Cardiovascular Radiology (ESCR). *Eur Radiol* 2020;**30**:2627-2650.
14. Scully PR, Patel KP, Saberwal B, Klotz E, Augusto JB, Thornton GD *et al*. Identifying cardiac amyloid in aortic stenosis: eCV quantification by CT in TAVR patients. *JACC Cardiovasc Imaging* 2020;**13**:2177-2189.
15. Akoum N, Daccarett M, McGann C, Segerson N, Vergara G, Kuppahally S *et al*. Atrial fibrosis helps select the appropriate patient and strategy in catheter ablation of atrial fibrillation: a DE-MRI guided approach. *J Cardiovasc Electrophysiol* 2011;**22**:16-22.
16. Marrouche NF, Wazni O, McGann C, Greene T, Dean JM, Dagher L *et al*. Effect of MRI-guided fibrosis ablation vs conventional catheter ablation on atrial arrhythmia recurrence in patients with persistent atrial fibrillation: the DECAAF II randomized clinical trial. *JAMA* 2022;**327**:2296-2305.
17. Nelson T, Garg P, Clayton RH, Lee J. The role of cardiac MRI in the management of ventricular arrhythmias in ischaemic and non-ischaemic dilated cardiomyopathy. *Arrhythm Electrophysiol Rev* 2019;**8**:191-201.
18. Carbucicchio C, Jereczek-Fossa BA, Andreini D, Catto V, Piperno G, Conte E, *et al*. STRA-MI-VT (STereotactic RadioAblation by Multimodal Imaging for Ventricular Tachycardia): rationale and design of an Italian experimental prospective study. *J Interv Card Electrophysiol* 2021;**61**:583-593. doi:10.1007/s10840-020-00855-2