REVIEW

Role of non-invasive imaging in the management of coronary artery disease: an assessment of likely change over the next 10 years. A report from the British Cardiovascular Society Working Group

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Coronary angiography has been the gold standard for determining the severity, extent and prognosis of coronary atheromatous disease for the past 15–20 years. However, established non-invasive testing (such as myocardial perfusion scintigraphy and stress echocardiography) and newer imaging modalities (multi-detector *x* ray computed tomography and cardiovascular magnetic resonance) now need to be considered increasingly as a challenge to coronary angiography in contemporary practice. An important consideration is the degree to which appropriate use of such techniques impacts on the need for coronary angiography over the next 10–15 years. This review aims to determine the role of the various investigation techniques in the management of coronary artery disease and their resource implications, and should help determine future service provision, accepting that we are in a period of significant technological change.

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It is generally accepted that coronary angiography (CA) plays a central role in the management of patients with coronary artery disease (CAD) and is currently the gold standard for confirming the presence of atheromatous coronary obstruction. Increasingly however, developments in non-invasive test are beginning to challenge the primacy of the coronary angiogram, with established functional studies such as stress echocardiography and myocardial perfusion imaging being considered as more than screening tests, as they can provide valuable information on disease severity and patient prognosis. Additionally, there have been innovative developments in MRI (or cardiovascular magnetic resonance (CMR)) and CT (or multi-detector *x* ray computed tomography (MDCT)). Such developments are likely to increase further the current shift from CA.

The extent to which any developments in newer non-invasive imaging techniques have an impact on the need for CA will, however, depend on multiple factors such as the additional information they provide, the cost/benefit ratio of full national uptake, the user-friendliness of the investigation (including patient convenience), the degree to which personnel training (especially developments in junior doctor training programmes) can keep pace, and, importantly, a fundamental understanding of both the additional benefits and the limitations provided by non-invasive imaging in general terms. It is clear however that the rapid development of technology, particularly in MDCT, and also in CMR and 3D echocardiography, makes confident assessment difficult and to a certain extent speculative.

The brief for this British Cardiovascular Society (BCS) Working Group was to assess the impact that non-invasive investigations are likely to have on the need for CA over the next 10 years or so, and will encompass both the newer and the more established modalities. The current use of established tests and future uptake of new modalities are likely to have important implications for resource allocation and hospital facility configurations, and for the design of training programmes at all staff levels. In an attempt to assess as accurately as possible any shifts in practice, we set out to establish the current status of non-invasive imaging, to place any new developments in clinical context, and attempted to determine how useful the different investigations are at different points in a patient-management pathway. We have also considered the overlap of information provided by the various non-invasive tests. Addressing issues around training have also been important considerations.

Developing a seamless process for the management of patients with suspected CAD, with efficient and appropriate use of all available non-invasive tests, perhaps keeping the invasive tests for when they are absolutely required (eg, as a prelude to coronary revascularisation), should remain the basic premise of future planning. This report is mainly concerned with the investigation of stable patients, but there is an increasing probability that non-invasive imaging, particularly MDCT, may have a role in acute situations.

Abbreviations: BCS, British Cardiovascular Society; CA, coronary angiography; CAD, coronary artery disease; CMR, cardiovascular magnetic resonance; ETT, exercise tolerance test; LV, left ventricular; MDCT, multi-detector *x* ray computed tomography; MPS, myocardial perfusion scintigraphy; PCI, percutaneous coronary intervention; PET, positron emission tomography; SE, stress echocardiography; SPECT, single photon emission computed tomography; SpR, specialist registrar

CORONARY ANGIOGRAPHY

To be useful in the management of patients with CAD, non-invasive testing must match the low-cost (both financial and in terms of patient risk) to high-information ratio provided by CA. Since its introduction in the late 1960s, CA has increasingly been considered as the gold standard for confirming the presence and extent of coronary heart disease, and also for indicating those angiographic features in longitudinal studies that influence prognosis. The most recent figures (from 2004) indicate that 201 000 catheterisations (excluding percutaneous coronary intervention) were undertaken in the UK, a 7% increase in the 2003 figure.

CA is generally safe, is routinely undertaken as a day case procedure, not infrequently in mobile catheter laboratories, and provides important information for revascularisation options. Overall, it has a low associated mortality (0.07%)[1] and low arterial risk (<0.25%). Although patients and operators are exposed to radiation risk, this is generally lower than other imaging procedures such as myocardial perfusion scanning and CT imaging, and can be considered acceptable for patient and staff, during a single diagnostic procedure, even when undertaken by non-physician staff.[2] The premise that CA has a central role in patient investigation has been reflected in the expansion of catheter laboratory facilities throughout the UK, with 90 new labs funded by New Opportunities Funding since 2003. Consequently, more patients have access to the procedure, embedding it further into the management algorithm of those with suspected CAD. The ease of being able to undertake multiple procedures in a session together with increased generic working of catheter laboratory staff has led to increased efficiency.

The consensus is that CA provides important clinical information safely, efficiently and at relatively low cost. Whether the anatomical and simple functional information provided by CA is sufficient or can alternatively be provided without the need for such an invasive procedure is an important question. Currently CA is a prerequisite to ensure appropriate decision making prior to revascularisation, particularly for percutaneous coronary intervention (PCI) (now the dominant form of revascularisation). "Ad hoc" or "follow-on" angioplasty (ie, angioplasty undertaken immediately after, and using the same procedure as, the diagnostic coronary angiogram) remains attractive, especially with the increasing numbers of patients presenting with acute coronary syndromes. Establishing catheter laboratories in district general hospitals together with the roll-out of PCI from tertiary centres has meant that there has been less need for patients and relatives to travel long distances, and consequently a major reduction in waiting lists.

The questions to be addressed are what percentage of any future coronary angiograms can be deemed unnecessary through the alternative use of non-invasive testing to establish which patients actually need CA and, additionally, which tests may provide anatomical information equivalent to CA, either as stand alone or in addition to any functional information they provide. Any such considerations must necessarily be speculative, but may be suggested by current trends in numbers of both non-invasive and invasive tests undertaken, the estimated current shortfalls in non-invasive imaging, and the more obvious future technical developments that will shape the newer non-CA investigations. The appropriate training of personnel to run any increase in the number of studies will be central to any potential expansion of tests.

Driving some of the shift away from CA is the unproven suggestion by some in the imaging field that current availability of catheter laboratory facilities already leads to excess and potentially unnecessary angiography, with stress echocardiography and myocardial perfusion imaging being underused in the algorithm of predicting which patients will benefit most from revascularisation. It has been suggested that the presence of a catheter laboratory may be a stronger determinant of the use of angiography rather than any of the standard clinical factors...[3] As such, some consider that there may be "unacceptable" numbers of patients undergoing CA who are then found to have normal coronary arteries, and even some patients at times undergoing "unnecessary" stenosis-driven revascularisation as a result. After myocardial infarction, for example, angiography and intervention rates are significantly higher in the USA compared with Canada, but outcomes at 1 year are no different.[4] Thus, the expansion in availability of district general hospital catheter labs should in theory be supported by an equal expansion in access to non-invasive investigations to determine the appropriateness of the invasive investigation.

Finally, CA as a procedure has downsides. These include the radiation exposure, the fact that it underestimates the extent of coronary disease (as the procedure is essentially a luminogram and provides little or no information on the amount of atheroma in the vessel wall), and, most importantly, its failure to provide adequate information on cardiac function and viability, and an assessment of the amount of ischaemia present. Furthermore, it is an invasive procedure carrying a small but finite risk, including death. Also, in terms of future developments, even accounting for the development of the new *x* ray imaging technology, CA is unlikely to see major advances in the foreseeable future.

The magnitude of any shift from CA to non-invasive tests will be influenced by all such considerations, as well as the context in which any questions are being asked and at what point in the patient management strategy such questions arise. It may be important to know about myocardial function, ischaemic tolerance, hibernating myocardium, contractile reserve and future risk assessment, as well as coronary anatomy relating to a particular patient.

We have structured this report to include current use of the various investigations, and have tried to predict the likely future use and need. We have attempted to highlight the similarities and the differences between the various tests, in order to indicate potential overlap and conflict (see table A1 in the supplementary Appendix).

The aims for this working group were thus to:

1. understand the advantages and limitations of the various non-invasive and invasive tests for CAD;
2. compare and contrast them where appropriate;
3. assess current indications and status;
4. attempt to predict future developments in order to gain an understanding of what will be needed to facilitate any changes in current practice;
5. headline what is likely to be the sequence of investigation for CAD in the next 5–10 years, and identify cost, resource and personnel implications;
6. identify any issues related to training;
7. address models of care to indicate how the appropriate investigation should be delivered.

INVESTIGATIONS FOR MANAGING THE PATIENT WITH CAD—CURRENT STATUS

When a patient presents with chest pain, the symptom will be considered by the doctor, to be likely due to CAD, to be clearly not cardiac in origin, or to fall into the "uncertain" group. According to our understanding of out-patient referrals, those who have a very convincing story or those who have had recent in-hospital admission for suspected angina are likely to be prescribed anti-anginal medication (or have their therapy enhanced) and to be listed directly for a coronary angiogram. Some patients may in certain circumstances still undergo an exercise tolerance test (ETT) (eg, when symptoms have settled completely on medication). If this is abnormal, they will then proceed to angiography, but if equivocal, they may then be listed for another non-invasive test, either myocardial perfusion scintigraphy (MPS) or stress echocardiography (SE). Those patients in whom there is uncertainty (eg, an equivocal ETT), or whose ECGs are difficult to interpret (eg, left bundle branch block) and those who have reduced mobility (weight, peripheral vascular disease, arthritic disability) are also likely to be listed for SE or MPS, although increasingly CMR is being considered and used in such patients.

Patients with a clear history of cardiac pain but with a negative ETT may also be investigated using further non-invasive tests, but often they will be listed directly for angiography, not least because current waiting times for MPS and SE in many hospitals are unacceptably long, negating in some respects the value of the test. Sometimes patients, when given the option of waiting for a non-invasive test or having an invasive investigation earlier, will choose the latter. Our perception of the management plan for suspected CAD is shown in figure A1 the supplementary Appendix.

It is clear that the relationship between the presentation of the patient, the availability of current non-invasive tests and the stage at which they undergo CA sometimes fails to follow a logical sequence and tends to be driven by the perception that the CA is the final arbiter of the presence of CAD. This is compounded by a limited understanding of the value of MPS and SE in predicting CAD severity and prognosis: such tests should be able to tell us which patients truly need CA. As the sensitivity and specificity of CMR and MDCT improve in being able to identify and stratify CAD, their use will increase and as such they are likely to become increasingly important players in the diagnostic process; understanding the place and timing of all the various tests becomes, as a consequence, even more of a challenge. Furthermore, although identification of ischaemia and viability is important for determining prognosis and helping in decisions regarding revascularisation, identifying atheroma may be important in its own right—for example, in determining the use of cardioprotective therapy. Both anatomical and functional imaging are therefore important.

Finally, it is important to note that the sensitivity of any test to be able to detect CAD is highly dependent on the type of the patient undergoing the test. This may become more important if periodic congenital heart disease screening becomes increasingly popular in an attempt to identify those at risk at an early stage of the disease. Identifying a disease becomes easier the more likely it is that the patient has it in the first place.

FIRST-LINE TESTS

The information obtained from non-invasive first-line tests should be sufficiently accurate to allow efficient patient screening, and should also be robust enough to have an important role in their management. Such tests should improve resource utilisation, and should determine with a high degree of sensitivity and specificity whether the presenting chest pain is likely to be cardiac or not, and whether revascularisation may improve symptoms and prognosis.

Currently, these first-line tests comprise ETT, MPS and SE, with each providing sometimes overlapping and at times different information according to the patient group being tested. At present, they are mostly used (some would consider underused) to determine which patients are most likely to need CA, but may also be used to screen individuals without symptoms, such as those with a strong family history or those holding a Driver and Vehicle Licensing Agency licence. Overall, the greatest challenge to such investigations is likely to come from CMR.

CURRENT USE

In general terms, ETT is inexpensive and safe, but has limited positive predictive value (~75%) for CAD. Most understand how it should be used, including its limitations, and it is therefore likely to remain a broad screening test. No ECG changes and no symptoms at high work loads indicate low probability of ischaemic heart disease. Early ECG changes with or without symptoms indicate a need for another test to confirm and determine the extent and severity of the disease; currently, this confirmatory investigation tends to be CA.

It is generally accepted that functional imaging with MPS or SE is underused in the UK, despite echocardiography machines and gamma cameras being available in almost every hospital. These modalities have the potential for directing CA more effectively towards those patients most likely to require invasive intervention. Addressing the current underprovision of MPS and SE will be an important consideration when assessing the reduction in required CA over the next 10 years.

Both techniques can predict the presence of significant coronary stenoses and of stratifying coronary risk. The cardiac risk associated with a normal MPS study is remarkably consistent across different protocols and populations, with an annual rate of cardiac death or non-fatal myocardial infarction of <1% (0.6% in most studies).[5] This low risk applies in the short-term to otherwise high-risk individuals such as patients with diabetes or those with previously documented coronary disease, although such factors tend to reduce the period for which the low risk persists (the so-called ''warranty period'' of a normal study).[5 6] For patients with abnormal MPS, the exact risk depends on the patient population being assessed, as well as on the severity and extent of the perfusion abnormality.[7] Data from large patient cohorts have even identified which scintigraphic variable predicts which element of risk, cardiac death being chiefly a function of gated single photon emission computed tomography left ventricular ejection fraction, and non-fatal myocardial infarction being a function of the amount of inducible hypoperfusion.[8]

Similarly, a normal SE suggests a low annual risk of 0.4–0.9% on the basis of a number of studies, including one study involving 9000 patients,[9–14] and in such patients, CA can be safely avoided. An abnormal stress echocardiogram is associated with a far higher risk of events directly related to the extent of wall motion abnormality in patients with[13] and without diabetes.[10] In a study of 3156 patients followed for 9 years,[13] ischaemia and the extent of abnormal wall motion were independent predictors of cardiac death. In 7333 patients,[11] an abnormal pharmacological stress echocardiogram provided independent and incremental value over and above the clinical data. In a subgroup of 4037 patients who underwent CA without an intervention, the results of the coronary arteriogram did not add significant predictive power to the model.

Although diagnosis and prognosis in coronary disease are important, the main practical goal of investigation is to identify which patients will benefit symptomatically and/or prognostically from revascularisation—that is, which patients warrant angiography and then angioplasty or bypass surgery. In a recent Danish study, 384 patients referred for angiography also underwent MPS, with the cardiologists blinded to the results of the functional imaging.[15] The additional value of revascularisation on symptomrelief was seen only in patients with inducible hypoperfusion on MPS. MPS and SE may also define specific ischaemic coronary territories, and so allow a targeted approach to percutaneous revascularisation.[16 17]

Thus, recent studies have demonstrated the ability of MPS and SE to predict the likely symptomatic and prognostic outcome after revascularisation. Patients with normal MPS can be reassured that further invasive investigation is unlikely to lead to either symptomatic or prognostic benefit, even if they do in fact have coronary stenoses.

Furthermore, SE can provide valuable information on the detection of hibernating myocardium (84% sensitivity, 81% specificity), whereby its function is likely to improve following revascularisation. Again, although not routinely used in a clinical setting in the UK, SE can distinguish between stunned and necrotic myocardium following myocardial infarction. In the context of attempting to achieve appropriate re-perfusion with the most appropriate means (lytic vs primary angioplasty) and with most patients merely undergoing late assessment (4–6 weeks) using post-infarct ETT, we may still be a long way from determining in the early post-infarct period just how much myocardium is necrotic or hibernating, with little understanding of what to do about it. However, recent studies have shown that in patients who are stable and asymptomatic after thrombolysis, the finding of an absence of myocardial viability as assessed by SE correlates with mortality irrespective of findings on CA.

The main disadvantages of MPS are the need for ionising radiation and issues around who undertakes the investigation and who controls the data. Supporters would point out that there is little excess radiation exposure compared with CA, and thus would confer an additional lifetime cancer risk of 1 in 3000 for a typical 10 mSv technetium-based study. Other problems with MPS include the potential for attenuation inferior artefacts, anterior artefacts in women and limited spatial resolution, although poor image windows can result in tests that are technically poor and difficult to interpret in some patients.

Echocardiography has also been limited by suboptimal image quality in the past due to poor echo windows which can result in tests that are technically poor and difficult to interpret in some patients, although this problem may largely be obviated by the use of second harmonic imaging and trans-pulmonary blood pool contrast. Three-dimensional imaging is rapidly becoming routine and can provide volumetric data similar to stress CMR.[18]

Generally, MPS is an underused tool in the management of patients with CAD, the reasons for which are complex and to some extent lie within the discipline itself. Whether MPS can undergo a resurgence to play a more central role in the management of those with CAD over the next 10 years, particularly in the light of the recently increased popularity of SE and the emergence of CMR, remains unclear. The advantage of the additional spatial resolution of CMR will need to be offset by the potential for prognostic information from MPS. If used appropriately with sufficient resource input, MPS can indicate which patients truly need to be referred to some form of coronary artery imaging investigation, but this is also applicable to SE and increasingly to CMR.

Many trusts have made some investment in both modalities. The balance between the two may have implications for the workforce required in that MPS is predominantly performed by technical staff and reported by consultants, whereas SE is a physician-led service.

Recommendation regarding MPS/SE

There is little difference in the clinical information provided by well-conducted MPS/SE, or in the resources and expertise required. In units where MPS/SE are already established, such resources should be maintained and expanded to match current national recommendations. A recent BSE survey showed that only 49% of all cardiac departments in the UK and Northern Ireland currently perform SE with an annual total of about 10 000. This suggests a figure of only 165 stress echocardiograms per million population as compared with an estimated demand of 4000 per million (BCS workforce document[19]).

In centres without access to functional imaging of any sort, the decision whether to establish MPS, SE or CMR should be determined by local factors such as the availability of support from a local centre of excellence, and the training potential and enthusiasm of local medical and technical staff. Although possibly challenged by developments in CMR, MPS and SE should continue to be considered important tools in determining the need for CA. Decisions on further investment in gamma cameras should however probably await clarification of the potential advantages of the alternative, developing non-invasive imaging modalities. Certainly, until it is clear what advantages tests such as CMR have over established investigations, and most importantly until it is clear what the added value is of having imaging facilities that cover over more than one discipline, double investment in MPS/SE and CMR will need considerable thought. The value and limitations of these investigations should be understood and promoted during cardiology training.

Neither SE nor MPS will replace ''anatomical'' coronary imaging in the future, but if such non-invasive imaging techniques are used to their full potential, they should downgrade the number of patients requiring some form of anatomical coronary imaging. If fully resourced and utilised, and provide CMR does not become an indispensable investigation, some proponents of these tests believe that the use of SE and MPS could reduce the need for CA by up to 50%.[20–23]

This working group recommends appropriate provision of either MPS or SE according to published recommendations, but concludes that current evidence does not indicate that one is any better than the other at screening appropriate patients. Ongoing comparative evaluation between established non-invasive imaging and CMR is imperative.

Imaging the coronary arteries

The two relatively new and not-fully evaluated investigations for use in the assessment of patients with CAD and for imaging the coronary arteries are CMR and MDCT*x* ray*x* ray.

Although not currently regarded as optimal for imaging of coronary arteries, CMR can provide important additional information on many cardiological conditions,[24] including the functional assessment of myocardium in patients affected by CAD. CMR can also reproduce quantification of cardiac volume and mass (as in patients with cardiac failure) in addition to detection and sizing of myocardial necrosis and scars (with gadolinium). Increasingly, data are available to support reliable assessment of viability.[25 26] Furthermore, multicentre clinical data are becoming available to support its use in myocardial perfusion imaging.[27 28] As a non-invasive test in this regard, CMR has an about 85% predictive rate for detecting CAD.

An important advantage of CMR is that it is a radiation-free procedure. As such there has been interest in CMR-guided intervention using specially designed catheters and guide wires.[30] Selective coronary intubation has been reported in a porcine model, with real-time visualisation of the coronary arteries using gadolinium injection. CMR guidance for intervention in humans has recently been reported.[31] However, even for those with an interest in CMR there is the view that the likelihood of CMR-guided intervention in coronary arteries is only moderate for the next 10 years.

One current problem in the development of coronary CMR for the anatomical assessment of coronary arteries is the need for acquisition to be averaged over several cardiac and breathing cycles, with most patients unable to hold their breath for the required 15–20 s or more. The use of navigators that compensate for the breathing cycle can somewhat attenuate the problem. This area has been addressed in a recent paper[32] which demonstrates that 83% of all coronary segments were evaluable. The sensitivity, specificity and diagnostic accuracy of this ''state-of-the-art'' CMR were 78%, 91% and 89%, respectively. In future, the combination of an intrinsically high-contrast imaging sequence with a sophisticated navigator technique may produce high-quality, high-resolution imaging of the whole coronary arterial tree within a short duration of examination. However, application to more complex anatomical situations will certainly need confirmation. These and other recent advances have, however, raised the profile of CMR, and of course the potential advantages of this technique over MDCT in terms of radiation risk may drive its development further. However, at this time, it seems unlikely that it will replace CA for coronary artery imaging, as the spatial resolution of CMR is significantly lower. While there are ongoing technology improvements (such as parallel imaging), these are unlikely to be sufficient to fully challenge CA, although there are some as yet not fully assessed technical advances that may well have an impact such as use of hyperpolarised ^{13}C, which may boost the signal by a factor of ~10 000.[29] Although it is difficult to estimate the probability of such developments entering the clinical arena, it may be prudent to plan for future options by expanding the development and installation of CMR scanners, with the potential for them to be adapted if and when developments in CAD imaging become available.

Currently, MDCT as a non-invasive coronary imaging test still has the edge in terms of quality.

Certain other cardiac procedures may well be possible under CMR guidance, including defect closure in children, where avoidance of radiation is particularly important, and assessment of anatomy and function in patients with grown-up congenital heart disease. It is thought that there will be a high probability of such procedures being routine within 5–10 years. Additional roles for CMR-guided cardiac procedures include electrophysiology ablation techniques,[33] with the greater anatomical localisation and assessment of results making the use of CMR in such cases attractive.

Apart from the limitation in adequate visualisation of the whole of the coronary tree, the downside to CMR includes those of patient discomfort in some, potentially long acquisitions and analysis times, and image degradation from gating problems in patients with irregular rhythms. The increasing use of pacemakers in the management of heart failure is another important potential limitation. Availability of trained and skilled staff to undertake post image analyses may become a real issue, but options such as distant site reporting through electronic media transmission to reporting centres of excellence are being considered, and are beginning to be implemented.

It is more likely that CMR will challenge viability and perfusion imaging rather than become the technique of choice to define the coronary anatomy, although even this, at current rates of development, is likely. The spread of CMR will depend on considerations as to what it has to offer in addition to the established, less expensive, more rapidly undertaken current non-invasive procedures (MPS and SE). The fact that CMR has multidisciplinary uses clearly works in its favour.

Recommendations for CMR

We speculate that CMR is likely to have an increasingly important role in the non-invasive assessment of CAD. We support its development, but recognise the need for potentially major resource inputs and also the likelihood of training issues. We believe that full implementation of CMR would reduce the number of coronary angiograms required by up to 15%, and that its growth may be at the expense of MPS and SE, as there may well be additional benefits from CMR over MPS and SE. It is likely that CMR will lead to improved decision making for those potentially needing CA. In such a rapidly changing field, we recommend a further review of the state of development of CMR in 3 years' time. However, in the meantime, we recommend that the specification of all new MRI scanners should include the ability to perform CMR in order to future proof the investment.

MULTI-DETECTOR *X* RAY COMPUTED TOMOGRAPHY

Currently, the major challenge to CA comes from MDCT. Traditionally, CT (electron beam computed tomography and MDCT) has been used for ''calcium scoring'', a measure of the amount of calcification in the coronary arteries. This technique is widely used as a screening technique for CAD in the USA, but has had only a limited acceptance in Europe, mainly due to its very limited role in the older population. CT coronary angiography has greater spatial resolution than CMR (>0.5 mm), although it has worse temporal and spatial resolution than CA. Its positive aspects are its speed, simplicity and reliability, with potential additional information being provided on left ventricular (LV) function and the character of the vessel wall and plaque, which thus may make it a valuable tool in the assessment of plaque vulnerability. Critics of MDCT point out that although this procedure avoids the invasive nature and potential complications of CA, the resolution is less, it is applicable to fewer patients, there is high radiation exposure (although similar to MPS), and as an imaging modality it cannot be used with a follow-on revascularisation strategy. Patients with tachycardia or an arrhythmia are more difficult to image. However, reported problems around training and education should be resolvable with appropriate planning.

To date, the best images have come from the evaluation of arterial and venous grafts. Here MDCT is able to both identify their presence and determine patency. This is also true, although to a lesser extent, for the proximal and mid segments of the coronary tree. Some centres currently use this technique if, for example, CA has been unable to clearly determine the presence of an ostial coronary lesion (particularly in the left main stem). Many would propose that outside these areas, MDCT is less applicable, although it may have a role in confirming the absence of significant proximal native coronary disease in those patients with low likelihood of flow limiting narrowings on non-invasive testing: again aiding decision making about who should or should not go on to CA.

The radiation exposure (~10 mSv compared to <5 mSv for CA) needs to be considered when assessing the place of MDCT. The associated potential additional lifetime risk in cancer will need to be weighed against the potential to influence management that could improve cardiac prognosis. Furthermore, spatial (0.25 mm vs 0.16 mm for CA) and temporal resolution (gantry half turn = 125 ms vs acquisition window<10 ms for CA) are worse than CA. Calcification within the coronary arteries continues to be a real challenge to the full evaluation of any underlying coronary narrowing with MDCT, as does the presence of stents, although this is to a lesser degree. Use of specialised techniques such as ''double oblique reconstruction'' of lesions beneath calcification can overcome some of the problems but inevitably such specialised MDCT techniques require increased expertise, experience and dedication. More recently, there have been developments which will allow MDCT to provide information on LV function similar to that obtained with CMR,[34] and there are early reports on its use in detecting viability and hypoperfusion.

It is clear that MDCT will need to offer significantly more in terms of specific coronary artery imaging if it is to fully overcome the real disadvantages of providing little of the additional information that is available with CMR (function, infarct size, perfusion) and CA. A recent paper and editorial in the *European Heart Journal* provides a little more light and hope for supporters of MDCT.[35] Erbel's editorial is titled: ''Non-invasive computed tomographic coronary angiography: the end of the beginning''. He reiterates that MDCT will only ever be able to provide coronary imaging that competes with CA when the best quality images are obtained using the best techniques (beta blockers to achieve HR<60 beats/min and use of vasodilators), and best equipment (at least 64 slice and rotation times<400 ms) especially if the aim is to visualise distal segments and branches. With such techniques, Leschka's paper[36] to which Erbel's editorial refers reports the correct detection of 165 of 176 stenoses (overall sensitivity per segment was 94% and specificity 97%). Most of the missed stenoses were in calcified segments, as were most of the false positive reports. Furthermore, the false positive findings were predominantly in distal arterial segments, with no left main stem or proximal lesions being missed or falsely identified. As such, the increasing proportion of presenting patients who are elderly, and who are generally recognised as having more heavily calcified coronary arteries, may despite such messages continue to present real challenges to MDCT.

However, the current rate of development of CT makes predicting the future extremely difficult. The very recent introduction of new technology such as dual source CT has shown considerable promise in removing the limitations of the technique (fast heart rate, radiation dosage, spatial and temporal resolution), and the speed of acquisition means that this technique may well be a serious competitor to established techniques in the future.[37]

Electron beam computed tomography is currently being promoted (predominantly by commercial companies) as a useful screening tool. Although the radiation dose is low, no information concerning coronary stenoses is provided, but high calcium scores might select out a group of patients who should be further evaluated with some form of non-invasive functional test. Conversely, those with very low scores have an extremely low risk of clinical events over the ensuing five years.[38]

Recommendations for MDCT

Currently, the role of MDCT in clinical practice is reserved for patients who following other non-invasive investigations remain a diagnostic problem, or where the angiogram has failed to identify proximal coronary anatomy, for example, failure to obtain detailed assessment of the coronary ostia or grafts. However, those with low likelihood of disease as determined from other non-invasive testing will probably not need this investigation and those with a very high probability of a significant stenosis should currently undergo CA. Inappropriate use of MDCT as a first-line investigation at its current state of development is likely to result in an unwanted expansion in the need for non-invasive functional tests and even CA. In selected patients, the disadvantage of the radiation dose can be balanced by specific valuable information it provides. The number of patients likely to fulfil such criteria (confirmation of suspicion of CAD) is probably in the order of <10% of all those presenting to the cardiologist/cardiovascular physician. We would emphasise that expansion of MDCT should not lead to increased numbers of unnecessary confirmatory coronary angiograms being performed.

Recently, it has been proposed that another area in which MDCT may play an increasing important role is in the diagnosis of patients presenting with acute chest pain. The ''triple scan'' in which pulmonary embolus, acute coronary syndromes and aortic dissection are excluded in a single examination performed in less than 10 mins from start to finish is an exciting concept, and may well have a major impact on management in the future.[39] Added to the ability to assess LV function, this technique may well become the first-line investigation in A&E in the future.

As previously pointed out, the technology is advancing rapidly and MDCT capability should also be re-reviewed in 3 years. In the meantime, it is recommended that all new CT scanners should have the appropriate software to be able to perform the gated scans necessary for CT coronary angiography.

Non-invasive imaging and training issues

Irrespective of the current status of the established and developing non-invasive investigations and their limitations, their potential future developments, or final impact in the assessment of patient with CAD over the next 5–10 years, there are and will be issues around training that require serious consideration. Even with established techniques (MPS and SE), current training is poorly formalised, patchy, and there is little assessment of whether trainees understand the place and value of the various tests available. During the current major change that is taking place in the programme of trainees' assessments, it will be vital to ensure that evaluation of competency includes an assessment of their understanding of the importance of non-invasive testing in the management of patients with CAD.

Recent workforce proposals suggest that more than one imaging specialist might be necessary in large centres. Filling these posts will clearly require an expansion in number of specialist registrars (SpRs) who choose a career in non-invasive cardiac imaging. The training curriculum for SpRs is being revised to increase the profile of non-invasive imaging. It is also important that year 5 and 6 specialist Imaging Training Posts continue to expand. Regional training schemes should ensure that these are filled by suitably motivated SpRs.

We therefore believe there should be clearly defined and focussed imaging modules throughout SpR training. Such modules should cover MPS and/or SE, depending on local expertise, and as such would be in keeping with the ethos of equivalence between the tests. An introduction to the concepts of cross sectional imaging, and benefits and limitations of MDCT and CMR will be mandatory and likely to become increasingly important.

Formal assessment of trainees' understanding of the role, value and limitations of the various non-invasive investigations is mandatory, and should include the need to be ''signed-off'' for reporting accuracy.

If CMR and MDCT are unavailable in the trainee's centre, we also recommend rotation during mid-training modules to centres undertaking these investigations. We recognise the complementary expertise cardiology and radiology teams bring to CMR and MDCT, and recommend, wherever possible and depending on local circumstances, that there should be training available to both cardiology and radiology SpRs who aim to become experts in the field, and this should be organised through close collaboration between cardiology and radiology consultants who have specialist expertise in these modalities. This should be achieved with a standardised programme of objectives, the attainment of which would be formally assessed at the end of the period of training.

A final module in cardiac imaging is recommended for all those who have decided this is their career path and should be offered in all units training SpRs. It should be open to SpRs from cardiology or radiology. A curriculum for such a final year is considered essential, but should be flexible and regularly reviewed in what is likely to be an area of rapid change. Training of one year in imaging may well be coupled with adults with congenital heart disease, heart failure or device implantation, which would occupy the anticipated 2 years of subspeciality training.

Furthermore, we strongly support an expansion in the number of imaging fellowships over and above the few that are currently available. Such fellowships should be advertised nationally, be open to all with appropriate background, and be based on a curriculum designed to develop innovators of the future rather than mere service providers.

However, the aim should be that training programmes are flexible, and deliver to National Training Numbers holders the skills that they will imminently require as consultants. Training programmes should therefore develop sufficient imaging subspecialty posts to satisfy demand within programme, and fellowships should not reflect a failure to keep the National Training Numbers programme up to date.

There are also ongoing discussions about the development of a 2-year imaging model. However, thoughts are still being formulated that it may involve 3 years each of cardiology and radiology followed by a 2-year imaging module.

The number of trainees with expertise in non-invasive imaging will need to match the national requirements for personnel who will be needed to undertake such tests (see below).

RESOURCE IMPLICATIONS

Facilities

The true impact of these newer techniques on the future need for CA is clearly difficult to predict in such a changing environment (table 1). It will be important to fulfil the potential and shortfall of stress echocardiography and MPS, as these are already clinically proven, relatively inexpensive and currently available. Any impact from the newer cross-sectional techniques will depend on the required aim (merely to reduce the need for CA or to promote alternative imaging that has additional functional capacity or clinical advantages). It is also true that any expansion will be further driven by developments in the techniques themselves. How these developments are viewed by physicians will in turn depend on many factors including how such tests are ‘‘promoted’’, whether they are userfriendly to the referring doctor, patient and operator, their cost–benefit ratio and whether they are perceived as providing a real advantage compared with the current non-invasive/CA paradigm. The current paucity of publication in such areas limits definitive conclusions being drawn at this time.

Although it seems likely that CMR will develop as a challenge to nuclear and stress echocardiography (not least because of the need for MR by other disciplines), any challenge to CA imaging is more likely to come from MDCT. The numbers of MDCT required over the next 5 years can be very roughly estimated. At current projections, the annual number of coronary angiograms required in 5 years will be approximately 350 000. If PCI increases over this period from the current 60 000 to 100 000 (at about 10% increase pa) and coronary surgery remains at about 20 000, then in 5 years around 230 000 patients will be undergoing angiography but without follow-on intervention. Normal CA accounts for up to 15% of all coronary angiograms. To take account of such patients, and to include those with a suspicion of CAD but who are unsuitable for intervention this figure can be increased to 25%. Thus, to avoid CA in these patients an additional 50 000 MDCT tests may be required. On the basis of the potential to perform up to 20 procedures per day (~5000 per annum), the requirement would be for 10 extra dedicated scanners over the next 10 years.

Such estimates may be too low if further breakthroughs (lower radiation, improved resolution, functional information) occur. However, it is very unlikely that any centre could justify the installation of a dedicated cardiac CT scanner and the provision of MDCT would be best achieved through shared but dedicated cardiac time on scanners being used for current (albeit expanding) radiological indications. It is therefore essential that all new CT scanner installations have a cardiac capability (which in general adds approximately £10 000–£20 000). Clearly, many of the earlier caveats regarding MDCT are rapidly being overcome with new technological developments.

The need for CMR procedures is likely to be greater than for CT scans, as there will be a greater need to screen more patients who present with the symptoms of CAD to determine whether or not they require coronary imaging. To manage such patients with CMR and assuming that CMR could reliably exclude ischaemia, (currently under examination in appropriate studies), an extra 75 000 scans are likely to be needed which should result in 25% fewer coronary angiograms being required. This would be in addition to any expansion of need in congenital, cardiomyopathic and other non-ischaemic cardiac conditions. This extra CMR requirement could not be fully met by merely increasing access to all the 140 nationally available scanners, because of the current full utilisation of such scanners and the variability of scanner disposition, which may not be ideal for CMR. On the basis of an approximate 2000 CMR scans per scanner per year, there would be a requirement for 37 additional CMR scanners. The development of megacentres that can provide the optimal imaging, and optimal efficient use and training of staff would be an alternative, but would be against the current strategy of provision of local services, and would require efficient networks to ensure the model worked. A mixed model of local provision with more specialised services and reporting in larger centres is also a viable option particularly in view of the government’s ‘‘Connecting for Health’’ programme.

Thus, if there were an expansion of the newer investigations to the level where there was the imperative to reduce the need for CA, this could equate to a reduction in the need for CA by up to 50% and be serviced by 50 000 extra MDCT and 75 000 CMR investigations over the next 5–10 years.

Personnel

Catheter laboratories, echocardiography, nuclear cardiology and radiology departments are currently understaffed. Shortfalls in personnel in nuclear cardiology and stress echocardiography

Table 1 Current status of tests undertaken and likely/predicted expansion

Test	Current			Year 2010			Year 2020		
	Estimated no. (per million population)	Personnel required		Predicted no. tests	Personnel required		Predicted no. tests	Personnel required	
		Medical	Non-medical		Medical	Non-medical		Medical	Non-medical
Myocardial perfusion imaging	2000	60	180	3600	108	324	7200	216	2000
Stress echo	165	8	8	2000	100	100	4000	200	200
Magnetic resonance	200	10	10	400	20	20	2000	100	100
Computed tomography	50	5	5	400	20	20	2000	100	100

For information on how these data were estimated, see supplementary material in Appendix.

are only likely to be corrected as the requirement for these investigations becomes embedded in the management of those with suspected CAD. We estimate that there will be a 15% increase in either of these tests over the next 10 years (assuming that they are not competitive). Clinical networks should compare their current staffing levels with those predicted by the British Cardiovascular Society Workforce Committee, and plan training strategies accordingly.

Predicting the number of additional staff required over and above current unmet need is extremely difficult as despite publication of the estimated workforce required, unfortunately we are still unclear as to the current national workforce shortfall, although such a review is planned. Without such information, the gap cannot be easily estimated and in the interim it may be advisable for clinical networks to compare their current workforce with the BCS estimates and plan accordingly. Further it is difficult to be sure how the non-medical professions will grow. It is possible that we will need fewer consultants and more radiographic and technical staff at a senior level.

As far as CMR and MDCT are concerned, undertaking scan analyses and reporting will undoubtedly require an expansion of consultant staff. Hopefully, these will come from both cardiology and radiology, and the need served by the outlined changes in training. Careful consideration of how the cardiological and radiological groups dovetail their training to produce this new breed of imaging clinicians, is mandatory and should be proactive, with the emphasis on clinicians being involved in patient care rather than acting as clinical technicians. Such training posts need to be made attractive to juniors. On the basis of the number of hours required to analyse and report MDCT scans, it is estimated that anything up to 45 000 h/annum overall would be required. With the need for specialist skills in performance, analyses and reporting of CMR scans would require approximately 37 additional consultants. We estimate that it will require up to 3 extra ''clinical imaging'' consultants per centre over the next 5–10 years to provide for the extra service need, although as stated above it is possible that fewer consultants supported by very senior clinical physiologists or radiographers will be able to meet the additional workload.

SUMMARY AND CONCLUSIONS

Established non-invasive imaging techniques

Myocardial perfusion scintigraphy and stress echo

- Both SE and MPS are well-established clinical tools.
- While each has its own strengths and weaknesses for most purposes they are interchangeable in expert hands.
- Each provides information about inducible ischaemia, previous infarction, myocardial viability and left ventricular infarction. In particular, a normal study using either method predicts a very low risk of serious cardiac events (<1% per year) and obviates further coronary investigation in the majority of cases.
- Either technique is a good workhorse and should currently be considered as the first-line imaging investigation in patients with chest pain in whom the exercise ECG is, or is likely to be, unreliable or equivocal.

Future use

- Current underuse through resource deficiencies should be addressed and as such could reduce the need for CA by up to 50%.
- Realistically, however, this is likely to be no more than 25%.

Non-invasive imaging techniques in development

CMR

- CMR is the investigation that is most likely to see the largest expansion over the next 10 years.
- It is currently the gold standard for determining ventricular function and its quantification, and increasingly becoming so for myocardial viability.
- Perfusion imaging has attained an acceptable level to allow widespread clinical use but long-term data is still lacking for predicting clinical outcome.
- CMR allows excellent assessment of patient with cardiomyopathy and heart failure.
- CMR is valuable for assessment of coronary anomalies, and is of some value in assessment of coronary anatomy but at lower resolution than CT with more segments that are nonanalysable.
- Plaque imaging is a potentially important development but currently a long way from having clinical relevance.

The inability to scan patients with a permanent pacemaker/implantable cardioverter defibrillator remains a problem although device manufacturers are hoping to address this issue over the next 2 years

Future use

- CMR is likely to prove a major challenge to established non-invasive tests particularly driven by the multidisciplinary use of scanners.
- It is likely to reduce the need for CA by up to 25% over the next 10 years through better screening of those considered potentially in need of determining coronary anatomy.
- It is unlikely to actually replace CA when coronary anatomy images are required.

X ray MDCT

- Currently MDCT is the best non-invasive test for demonstrating coronary anatomy with real potential to improve as number of detector rows increase and other technological advances occur.
- Important current applications include imaging of grafts and aorta.
- Fairly simple to use with rapid acquisitions making it a relatively inexpensive test.
- The negative predictive value of a normal scan for CAD is high.
- It provides limited functional data—for example, LV wall thinning and systolic function—although developments are ongoing.
- Drawbacks:
  - Calcification is a significant drawback as is the high radiation dose for anatomy, potential nephrotoxic effects of contrast and need for low heart rates when assessing CA anatomy.
  - Perfusion (ie, functional) imaging is less likely to develop.
  - No chance currently of proceeding on to PCI.

Future use

- There is a definite potential for assessing coronary anatomy non-invasively and potential to reduce the need for CA in up to 15% patients.
- It may become a routine screening test in those with diagnostic uncertainty following nuclear cardiology/SE scans but should not lead to additional requirement for CA because of MDCT diagnostic uncertainty.

Concluding overview

The prediction of future demand for non-invasive coronary artery imaging is extremely difficult to estimate due to the rapid technological advances that are currently taking place, but there is no doubt that there is going to be a significant increase. Each technique has its advantages and disadvantages and no one modality is going to dominate. The newer techniques of CMR and MDCT may have advantages in terms of reproducibility and speed respectively, but they currently lack the long-term prognostic data. They do however appear to have similar if not better sensitivity and specificity than the existing techniques. There is undoubtedly a need for more consultants to be trained in cardiac imaging and this should cover all modalities. All equipment procured in future should be capable of non-invasive cardiac imaging. Professional groups need to develop new training curricula that might be open to trainees from both cardiology and radiology backgrounds.

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Supplementary Appendix containing figure A1, table A1 and supplementary data for table 1 is available at http://heart.bmj.com/supplemental

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