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REVIEW ARTICLE

Current challenges and future directions in cardiac imaging

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Abstract Imaging is one of the most important accomplishments of medicine during the last 1000 years. The contribution of modern imaging to progress in the delivery of health care is unquestioned. However, we need to refine our use of imaging, limiting its use to those occasions when it can contribute directly or indirectly to improving and lengthening the lives of patients. Technology prowess in imaging alone is not sufficient to deliver value to individuals or to society. Continued investment in imaging technology requires critical appraisal of its use in clinical decision making and patient outcomes.

At the beginning of the 21st century, the editors of the New England Journal named medical imaging as one of the 10 most important developments in all of medicine during the preceding 1000 years (Anon., 2000). Imaging of the cardiovascular system is barely a century old, beginning with the discovery of X-rays in the early 20th century. Mason Sones' pursuit of coronary arteriography in the 1960s (Sones and Shirey, 1962) led directly to the development of coronary bypass surgery and percutaneous coronary intervention and thrombolytic therapy, fundamentally impacting the practice of cardiology around the world. Echocardiography (Edler, 1966; Feigenbaum et al., 1965) and nuclear cardiology (Wagner, 1974), also introduced to clinical cardiology in the 1960s, revolutionized the evaluation of structural heart disease and myocardial ischemia. As these methods continue to be refined and popularized additional imaging methods including cardiac magnetic resonance imaging[1] and cardiovascular computed tomographic angiography (Min et al., 2010) have vastly improved our ability to image various manifestations of cardiovascular disease with ever increasing sophistication.

Cardiovascular disease is the most common cause of death worldwide, and an important focus for medical imaging. Our understanding of the fundamental pathophysiologic mechanisms underlying acute coronary syndrome and myocardial infarction continues to evolve in concert with the development of new and better means for assessing these abnormalities. Imaging has had a central role in improving our ability to recognize, characterize and successfully treat coronary artery disease. Cardiac catheterization with coronary arteriography and adjunctive techniques including intravascular ultrasound, ocular coherence tomography, and measurement of local temperature and PH within the heart have not only allowed development of the entire field of surgical and percutaneous coronary revascularization and thrombolytic therapy, but is leading to an improved understanding of the mechanisms of

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[1] CMR = Pennel review.

ischemic heart disease and development of better preventive and pharmacologic strategies.

The diagnostic and prognostic accuracy of ECG stress testing was vastly improved by the addition of concomitant nuclear or ultrasound imaging. The use of metabolically active tracers allowed better understanding of coronary artery disease at the cellular level, just as sophisticated ultrasound and magnetic resonance tools have revealed many of the mechanical, structural and hemodynamic alterations resulting from acute and chronic macro- as well as micro-vascular coronary syndromes. Imaging techniques can be used to study coronary arterial plaques. These plaques have thrombogenic potential and are manifestations of atherosclerosis, a systemic disease affecting the vessel wall which is generally believed to be the primary cause of many of the other myriad manifestations of coronary artery disease (Fayad et al., 2002; Ambrose, 2008). Non-invasive imaging holds the promise to not only identify flow limiting coronary stenosis (Meijboom et al., 2008), but to also detect calcified and non-calcified plaque, measure atherosclerotic plaque burden and its response to treatment, and to differentiate stable plaques from those which are prone to rupture (Kitagawa et al., 2009; Takumi et al., 2007). These expectations have not yet been met (Nissen, 2008).

Technologic progress in computed tomography has led to the ability to non-invasively visualize the epicardial coronary arteries with spatial and temporal resolution approaching that of invasive angiography. However, we know that high resolution angiography alone is often insufficient to differentiate flow limiting from non-flow limiting stenosis (Tonino et al., 2009; Joshi et al., 2009). Indeed, current cardiovascular nuclear and echocardiographic imaging techniques affect outcomes due to their ties with medical, percutaneous or surgical interventions. Thus, considerable attention is being focused on using CT to provide physiologic myocardial perfusion information downstream from a stenosis, much like fractional flow reserve is used in the catheterization laboratory or stress perfusion imaging in the nuclear, echocardiography or cardiovascular MR laboratories (Ambrose, 2008). We need functional as well as anatomic data to guide therapy. In a different direction, CT (Cheng et al., 2009) CMR, and other methods are being developed to better characterize the nature of atherothrombotic plaque, the cause of both flow limiting stable coronary stenosis, and, when a plaque ruptures or erodes, acute coronary occlusion and myocardial infarction.

Crucial to this work is validation of the ability of non-invasive imaging to delineate physiologically relevant structural features of atherothrombotic plaque. Histology, the *a priori* gold standard, is limited in its ability to characterize the evanescent nature of the atherothrombotic process; post-mortem examination of histologic sections represents only a limited snapshot of the overall pathologic process. Nevertheless, these ex vivo histologic observations do serve to remind us of the resolution of both 40 MHz ultrasound and 64-slice CT in failing to depict the microstructure of plaque.

Several other methods for *in vivo* interrogation of atherothrombotic plaque promise new insights into the pathophysiology of acute coronary syndromes, and could be superior not only to intravascular ultrasound and 64-detector CT, but also to conventional histologic analysis. Thermography, fluorescence imaging, nuclear imaging, magnetic resonance imaging, optical coherence tomography and near-infrared spectroscopy all have unique applications in detecting and characterizing plaque (Cheng et al., 2009; Waxman et al., 2009). In these efforts to detect and characterize plaque, it will be important to integrate morphologic and rheologic information with a patient's overall state of coagulation and inflammation. Imaging will continue to play a central role in the investigation of the atherothrombotic process and development of new treatments for patients with coronary arterial disease. Adoption of any of these techniques for clinical use in individual patients awaits clinical trials in which plaque imaging is shown to lead to better risk stratification, identification of manifest disease and application or alteration of effective therapy (Matter and Stuber, 2009).

Similar progress has also been made in applying new imaging technology to valvular, myocardial and congenital heart diseases. Ultrasound, nuclear imaging, magnetic resonance and computed tomography have all grown enormously, both in their contribution to our understanding of cardiovascular disease and in their cost to the health care system. In many regards, we have become victims of our own success. Patients and referring physicians alike have come to expect that imaging will be performed in nearly any circumstance, and many of us have been seduced by spectacular cardiovascular images to believe that imaging is an endpoint, in and of itself, rather than a means to a more meaningful end – making patients feel better, function better and live longer.

As cardiac imaging has become more complex and more widely utilized, the costs of medical health care have risen dramatically. The costs of imaging have grown faster than other areas of health care, faster than costs of non-medical services, and faster than the economy has expanded, threatening our ability as a society to pay for these wondrous imaging procedures. While a picture may still be worth a thousand words, there is now widespread recognition that unbridled expansion of imaging services does not lead to better health. We have entered an era when a beneficial outcome must be documented for nearly everything we do, so that we may make informed decisions on how to spend our limited resources on health care (Douglas et al., 2009).

We clinical imagers are now challenged not only to continue pursuing creative technical and engineering advances in our imaging procedures, but to also steer these developments toward improving patient outcomes. It is necessary but not sufficient to produce excellent quality images of the highest technical quality; reporting the results accurately and efficiently. We must also produce clinically actionable answers to clinically actionable and relevant questions in fiscally responsible and cost effective manner. We clinicians must lead the charge to use imaging discriminately, using the right procedure at the right time, for the right reason – the patients' benefit (Shaw et al., 2010; Bove, 2009; Hackbarth et al., 2008).

Imaging has obvious value in detecting and identifying disease early in its course, and in directing appropriate and effective prevention and treatment. Imaging can help measure the progression of disease, identifying ineffective treatments and helping to identify newer and better treatments. Imaging is increasingly an inseparable part of interventional cardiology and cardiovascular surgery, helping plan and monitor treatment, avoiding complications and defining "success". Echocardiographic equipment is no longer restricted to the