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Cardiovascular Magnetic Resonance Imaging—Incremental Value in a Series of 361 Patients Demonstrating Cost Savings and Clinical Benefits: An Outcome-Based Study

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ABSTRACT:

BACKGROUND: This study was designed to assess the clinical impact and cost-benefit of cardiovascular magnetic resonance imaging (CMR). In the face of current health care cost concerns, cardiac imaging modalities have come under focused review. Data related to CMR clinical impact and cost-benefit are lacking.

METHODS AND RESULTS: Retrospective review of 361 consecutive patients (pts) who underwent CMR exams was conducted. Indications for CMR were tabulated for appropriateness criteria. Components of the CMR exam were identified along with evidence of clinical impact. The cost of each CMR exam was ascertained along with cost savings attributable to the CMR exam for calculation of an incremental cost-effectiveness ratio. A total of 354 of 361 pts (98%) had diagnostic quality studies. Of the 361 pts, 350 (97%) had at least 1 published Appropriateness Criterion for CMR. A significant clinical impact attributable to CMR exam results was observed in 256 of 361 pts (71%). The CMR exam resulted in a new diagnosis in 69 of 361 (27%) pts. Cardiovascular magnetic resonance imaging results avoided invasive procedures in 38 (11%) pts and prevented additional diagnostic testing in 26 (7%) pts. Comparison of health care savings using CMR as opposed to current standards of care showed a net cost savings of $833 037, ie, per patient cost savings of $2308.

CONCLUSIONS: Cardiovascular magnetic resonance imaging provides diagnostic image quality in >98% of cases. Cardiovascular magnetic resonance imaging findings have documentable clinical impact on patient management in 71% of pts undergoing the exam, in a cost beneficial manner.

KEYWORDS: Magnetic resonance imaging, clinical impact

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Introduction

Over the past 3 decades, advances in cardiology have led to enhanced care of cardiac patients resulting in decreased mortality rates.[1] Cardiac imaging modalities have improved diagnostic acumen, allowing more specific therapies, resulting in improved outcomes.[2] However, this improvement in health care outcomes has not been achieved without a price. Medicare now consumes 14% of the gross domestic product in the United States, which is more than any other nation in the world.[3] It is projected to increase to 17.7% by 2020.[4] In the setting of the current stringent economic climate, relatively expensive imaging modalities, including cardiovascular magnetic resonance imaging (CMR), have come under close scrutiny and have become the focus of reimbursement cuts.[5] Echocardiography and nuclear cardiology are the most recent examples of changes in reimbursement policies of the Center for Medicare & Medicaid services in 2010.[6]

As a cardiac imaging modality, CMR possesses higher spatial resolution than echocardiography and nuclear cardiac technology.[7,8] Also, it offers information such as perfusion, viability, and tissue characterization from a single study, without hazards of radiation or an invasive procedure.[2,9] Despite a wealth of data on the utility of CMR in clinical medicine, it has not been widely incorporated into Clinical Cardiology Guidelines of the American College of Cardiology or American Heart Association. This phenomenon is mainly due to single center, single vender studies and lack of outcome data from large, randomized, controlled trials supporting the use of CMR to provide improved patient care. This study sought to assess whether CMR, as an independent diagnostic imaging modality, could significantly affect patient care in a cost beneficial manner.

Methods

This is a retrospective observational study. Chart review was performed on 361 consecutive patients who underwent CMR over a period of 6 months at 2 centers in Western Pennsylvania

(261 from center 1 and 100 from center 2). The first center was an academic institution, and the second was a hospital-owned outpatient diagnostic imaging center. All CMR examinations were reviewed by Society of Cardiovascular Magnetic Resonance (SCMR) level 3 physicians with a combined experience of more than 25 years of dedicated CMR experience. Between the 2 centers, there was, as expected, heterogeneity in the indications for the examination. Center 1 was dominated by patients with pulmonary hypertension, end-stage cardiomyopathy, and cardiac transplantation. Center 2 had more patients with valvular heart disease and ischemic heart disease.

All scans were performed using standard protocols established by the SCMR.[10] Scans were performed using a General Electric 1.5-T machine (GE Healthcare, Milwaukee, WI, USA) at the first center and with a Siemens Magnetom Espree 1.5 T (Siemens Medical, Malvern, PA, USA) at the second center. All 361 patients who underwent a cardiac magnetic resonance imaging (MRI) exam between March and September 2009 were included in the analysis.

The indications for CMR were reviewed, recorded, and assessed for appropriateness, using the appropriateness criteria for CMR published by the American College of Cardiology Foundation.[11] Also, all components of each CMR study were assessed and recorded. These components included assessment of cardiac structure and function using steady-state free precession (SSFP), magnetic resonance angiography (MRA), late gadolinium enhancement (LGE), phase velocity mapping (PVM), and stress/rest perfusion. We reviewed all clinical data, both inpatient and outpatient, available on each of these patients 6 to 12 months after the CMR exam was performed, to specifically determine whether the results of the CMR study independently affected patient care. If the attending physician documented a change in diagnosis, severity of diagnosis, or therapy based on the CMR scan results, we tabulated that patient as one who had a significant change in outcome based on CMR. To avoid a conflict of interest, we ensured that the reviewers were not involved in patient care. Therapeutic decision making was entirely attributed to the attending clinician's judgment. This judgment was deemed definitive and was not challenged by study personnel.

Quantification of patient outcomes was performed, 6 to 12 months after the CMR exam, using a CMR Impact Assessment Program, developed in-house for this investigation based in part on our experience with National Heart, Lung, and Blood Institute-Women's Ischemia Syndrome Evaluation (NHLBI-WISE) programs.[12] The study was approved by the respective Institutional Review Boards at each institution. Based on chart review, CMR impact was categorized into one of the following clinical outcomes: category 1—CMR data resulted in a new diagnosis, category 2—CMR data avoided the need for an invasive procedure, category 3—CMR data avoided the need for further "layered" testing, category 4—CMR data resulted in a minor change in clinical management, or category 5—CMR data did not affect any change in clinical outcome. After the CMR Impact Assessment was accomplished, we identified and quantified which components of the CMR exam were responsible for the impact element. Major clinical impact was determined when the plan of patient care was drastically changed based on CMR study results (examples include abortion of surgery, complete change of medical therapy, and a new diagnosis)

A simplified cost-benefit analysis (CBA) was computed for each patient in an effort to assess potential cost savings or loss with use of CMR.[13,14] The cost of each CMR procedure was ascertained based on Medicare reimbursement for 2010. Cost savings attributable to CMR findings was calculated by determining the expenditure that would have been incurred in the absence of CMR scan findings, again using Medicare reimbursement for 2010. In cases where additional diagnostic testing or treatments were avoided, the savings of these clinical elements were added to the net benefit from CMR. For example, if the plan of care for a patient with symptomatic advanced congestive heart failure was to proceed with cardiac resynchronization therapy (CRT) and this plan was changed based on the finding of transmural inferolateral scar on CMR, the net savings from CMR were calculated to be equal to the cost of CRT. Similarly, where a cardiac mass was discovered on another imaging modality and the plan was to proceed with open-heart biopsy of the mass, if CMR results unequivocally characterized the mass and avoided biopsy, the cost of the aborted open-heart procedure was used to define the benefit of CMR in that patient. Using these data, we calculated an incremental cost-benefit ratio, which describes the change in costs of a therapeutic or diagnostic intervention (compared with the alternative, such as doing nothing or using the best available alternative treatment). This ratio is an accepted standard for the assessment of cost-benefit in health care.[13,15,16]

Results

Of 361 patients, 350 had at least one of the American College of Cardiology and American Heart Association (ACC/AHA) Appropriateness Criteria for CMR. In all, 11 patients did not have a documented appropriateness criterion from chart review but were included in the clinical impact analysis. In total, 8 of 11 CMR studies which did not meet appropriateness criteria were ordered for left ventricular function without documentation as to why the ordering physicians chose CMR as opposed to echocardiography. In total, 3 of the 11 inappropriate CMR studies did not have adequate documentation or conflicting documentation to justify a CMR study.

A total of 353 of 361 patients (98%) who underwent CMR studies were diagnostically conclusive. Of the 8 studies that were inconclusive, 3 had severe pulmonary hypertension and significant dyspnea at rest, limiting breath-holding. The remaining 5 had significant ectopy causing electrocardiographic gating artifact or claustrophobia. Figure 1 summarizes the indications for CMR examination.

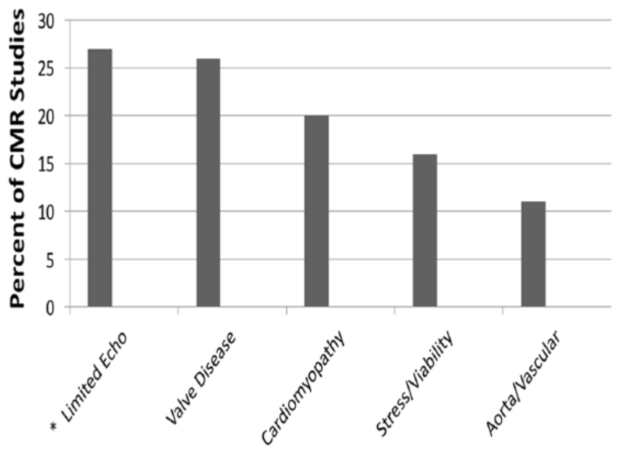

Figure 1. Indications for cardiovascular magnetic resonance imaging. “Limited echo” refers to echocardiographic examinations considered suboptimal either due to patient body morphology/anatomy or due to inherent limitation of echocardiographic technology itself (see text for examples).

Table 1. Clinical impact and appropriateness of cardiac magnetic resonance studies.

Total no. of patients	361 (100%)
Referrals meeting appropriateness criteria	350 (97%)
Clinical impact	256 (71%)
No clinical impact	105 (29%)
Major impact[a]	63 (18%)

Percentages are a subset of the total number of studies (361; 100%).
[a]Major clinical impact was defined as a drastic change to the preexisting plan of patient care (cases included a completely new diagnosis, abortion of surgery, avoidance of expensive, and potentially high side effect profile therapies, etc).

CMR safety

No deaths occurred during the performance of CMR examinations in this study. No major complications occurred. Minor complications occurred in 1% of patients (n = 4) including mild dyspnea, mild chest pain, atrial, and ventricular ectopic beats. These were observed in patients undergoing stress perfusion CMR studies. One patient undergoing MRA had mild urticaria postgadolinium administration.

Clinical impact of CMR on patient management

Among all 361 patients, we found that a clinical impact was confirmed in 256 (71%) patients (Table 1). The clinical impact included new diagnoses or change in current diagnosis (n = 69); elimination of need for an invasive procedures (n = 38) including avoidance of open-heart biopsies of benign cardiac masses, exclusion of aortic aneurysms; and avoidance of coronary artery bypass surgery/biventricular pacemaker insertion based on viability results, avoiding additional diagnostic testing (n = 26) due to conclusive and comprehensive evaluation by CMR and a definable change in clinical management (n = 123) such as exclusion of pulmonary vein stenoses in patients with recent pulmonary vein isolation procedures, change in decision about surgery in patients with valvular heart disease, and need for revascularization based on stress perfusion results.

Of the 256 patients with confirmed clinical impact of CMR, 63 (25%) patients had a major change to their plan of care, including patients with pulmonary hypertension and end-stage cardiomyopathy. Decisions about early referral to cardiac transplantation/left ventricular assist device implantation were based on LGE characteristics of the left ventricle (LV). The diagnosis of idiopathic congestive heart failure was refuted with the discovery of noncompaction and spiral cardiomyopathy in 5 patients. Five cases of “primary” pulmonary hypertension were actually found to be secondary to congenital shunts (anomalous pulmonary veins, pulmonary arteriovenous malformations, etc). Clinical management was completely changed for these patients on the basis of their CMR findings. However, PVM and shunt flow quantification conclusively excluded patients with suspected shunts on inconclusive cardiac catheterization/transesophageal echocardiograms. Other patients included in this category were those with aborted sudden cardiac death. The diagnosis of arrhythmogenic right ventricular dysplasia (ARVD) was supported using fat suppression triple inversion recovery and SSFP sequences in 1 patient and was challenged in 9 clinically suspected patients, based on imaging features, according to the ARVD 2010 Task Force Criteria. Several cases of “aortic aneurysms” referred for cardiothoracic surgery were proven to be tortuous/ectatic aortas that did not meet the criteria for surgical repair. These cases were mainly referrals from peripheral institutions with a diagnosis of thoracic aortic aneurysm. In our study, we found that the measurements by thoracic computerized tomographic angiography (CTA) were obtained by axial reconstructions only, without true orthogonal measurements. When these were orthogonally measured with a high-resolution MRA, the diagnosis of aortic aneurysm was disproven. Cases of “cardiac tumors/thrombi” were diagnosed as benign lipomatous hypertrophy of atrial septum, or ventricular lipomas, thereby avoiding open-heart procedures. However, in a case where a left atrial mass was suspected to be a thrombus, the CMR study suggested the diagnosis of angiosarcoma by characteristics on T1-weighted, T2-weighted, and LGE sequences (Figures 2 and 3). The diagnosis in this case was unfortunately confirmed at autopsy after the patient died.

A total of 105 patients had no documentable changes in clinical management based on CMR results. This subgroup included studies on atrial fibrillation patients (n = 22 studies, 11 patients) who were imaged postpulmonary vein isolation procedure as a matter of institutional protocol, to assess postablation pulmonary vein stenosis. Three out of these 11 patients did have symptoms suspicious for pulmonary vein stenosis. Although a “changed outcome” was not be attributed in such cases, the negative results did reassure the ordering clinician of the absence of pulmonary vein stenosis. This subgroup also included asymptomatic patients status after aortic surgery for

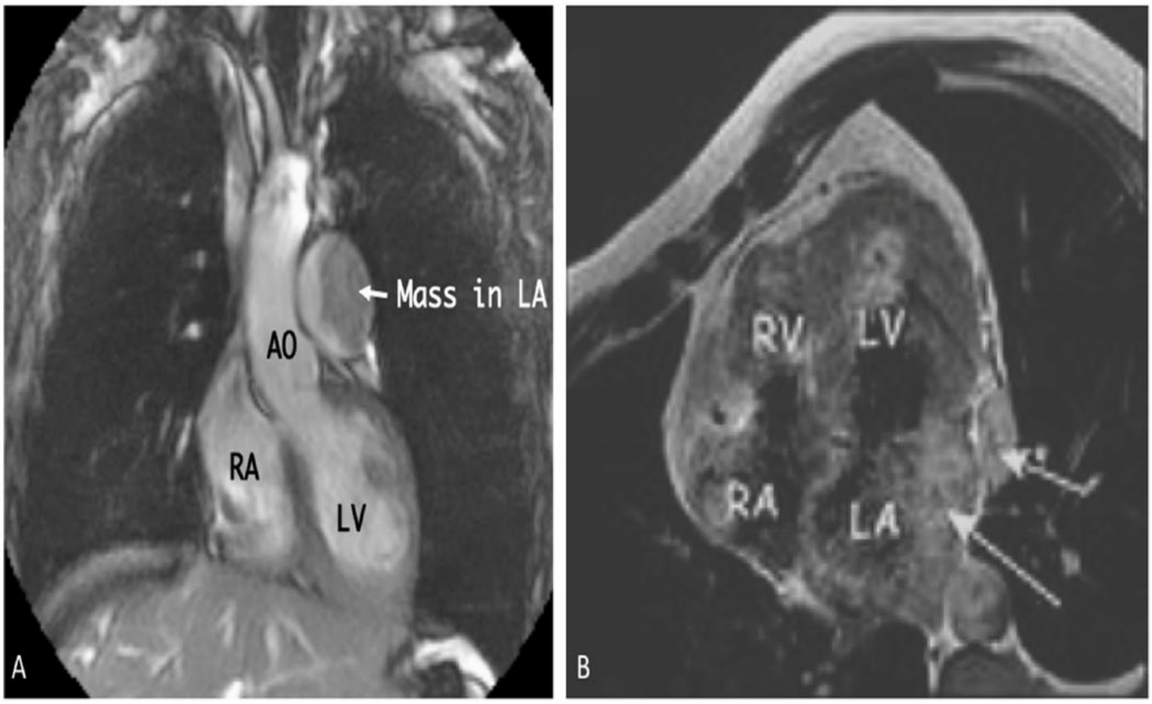

Figure 2. Cardiac mass: (Panel A) cine imaging demonstrating a mass in the left atrium, initially suspected to be a thrombus. (Panel B) Arrows point to patchy late gadolinium enhancement within the mass, suggesting a malignancy. AO indicates ascending aorta; LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

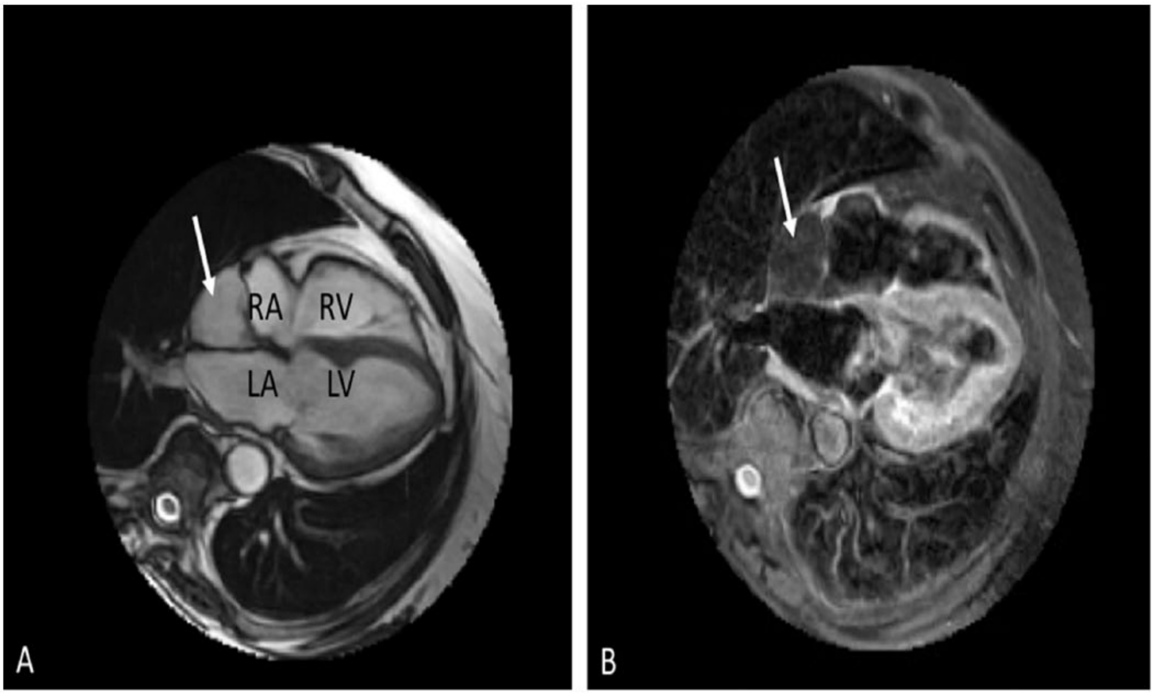

Figure 3. Suspected cardiac malignancy seen in a 4-chamber view. Arrows point to the mass in panels A and B. (Panel A) steady-state free precession cine imaging. (Panel B) Lack of high signal within the mass on T2-weighted short tau inversion recovery imaging, consistent with lipomatous hypertrophy of the interatrial septum. LA indicates left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

coarctation or dissection (n = 36). A smaller number of patients (n = 8) were asymptomatic status after surgical correction of congenital heart disease.

Cardiovascular magnetic resonance imaging assessment of structure and function via an SSFP sequence was the major contributor to patient outcomes in most cases (Figure 4). Steady-state free precession allowed for accurate assessment of left and right ventricular ejection fractions, leaflet anatomy in calcific aortic valves, and right ventricular volumes in patients with pulmonary hypertension. Among the patients with a major change in the plan of care (n = 63), LGE for assessment of myocardial fibrosis was the CMR component that most often affected clinical decision making (Figure 5). Examples from this patient cohort include cases of myocarditis, stress-induced cardiomyopathy, and dilated nonischemic cardiomyopathy. Phase velocity mapping resulted in altered clinical care in 133 of 361 patients, mainly with congenital heart disease, cardiac shunts, pulmonary hypertension, and complex valvular heart disease.

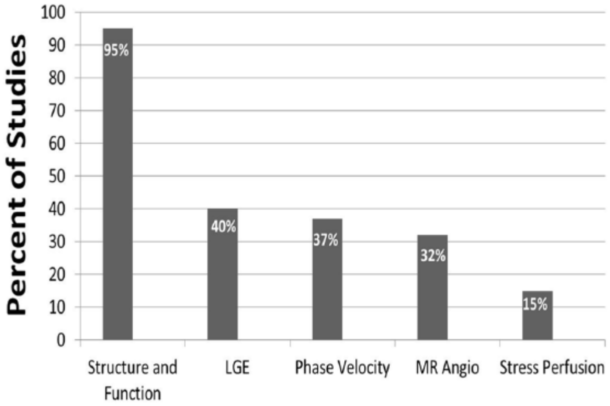

Figure 4. Components of cardiovascular magnetic resonance affecting clinical outcomes. LGE indicates late gadolinium enhancement; MR angio, magnetic resonance angiography; phase velocity, phase velocity mapping.

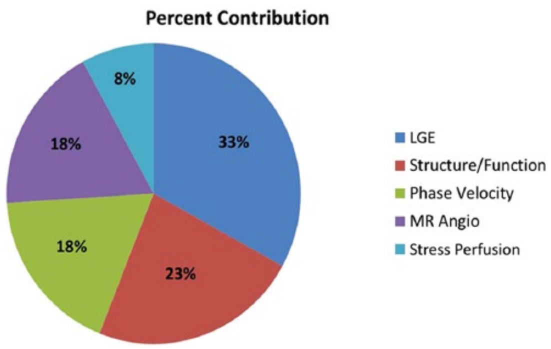

Figure 5. Percent contributions of cardiovascular magnetic resonance (CMR) components in cases with major clinical impact (n = 63 patients)[a]. LGE indicates late gadolinium enhancement; MR angio, magnetic resonance angiography; phase velocity, phase velocity mapping.
[a]Major clinical impact: defined as a drastic change to the preexisting plan of patient care (cases included a completely new diagnosis, cancellation of surgery, avoidance of expensive, and potentially high side effect profile therapies, etc).

Cost-benefit

For computation of a cost-benefit ratio,[13,15,17] Medicare data for 2010 were used to calculate costs. Table 2 and Figure 6 summarize the results of the analysis. Table 3 describes the 2010 cost/reimbursement data used for this analysis. Overall, CMR technology appeared to be cost beneficial, noting a net health care savings of $833 037, ie, per patient cost savings of $2308. The overall cost of performing cardiac MRI scans was $860 134. The computed savings and cost-benefits added up to $1 693 171. Thus, the simplified cost-benefit ratio was calculated at 0.508 (860 134/1 693 171), consistent with health care savings rather than expenditure. In total, 68% of the total cost savings ($566 465) were observed at center 1, where CMR results avoided major invasive procedures, surgeries or changed the management/therapy in patients with advanced congestive heart failure or pulmonary hypertension. The remaining 32% savings were observed at center 2 ($26 667) and were mainly driven by avoidance of invasive procedures in patients with ischemic heart disease and valvular heart disease. These results suggest that the use of CMR is a cost beneficial technology when used within the framework of the ACC/AHA Appropriateness Criteria.[11,17]

Discussion

This study evaluated the utility of cardiac MRI in a cohort of consecutive patients from both academic and nonacademic institutions over a 6-month period, so as to sample a “real-world” experience with this diagnostic modality. These data indicate that most common indication for ordering a CMR study was a limited echocardiogram. “Limited echocardiogram” in our study referred to echocardiographic examinations that were considered suboptimal, either due to patient body morphology/anatomy or due to inherent limitation of echocardiographic technology itself (reverberation artifacts). Examples of these studies included accurate assessment of left ventricular systolic function in obese patients, right ventricular morphology, aortic valve morphology in severely calcific valves, cardiac morphology in congenital heart disease, suspected complications of myocardial infarction including left ventricular pseudoaneurysms, assessment of cardiac masses, differentiating true

Table 2. Cost-benefit analysis of cardiovascular magnetic resonance studies.

CLINICAL IMPACT	NO OF PTS	Cost of CMR, $	CLINICAL BENEFIT, $	NET, $	SAVINGS/LOSS PER PATIENT, $
New diagnoses	69	138 713	1 074 000	+935 287	+13 555
Change in plan	123	86 227	63 970	−22 257	−181
Avoided invasive procedures	38	123 717	390 855	+267 138	+3256
Avoided further tests	26	117 832	164 346	+46 514	+1789
No change in Rx	105	393 645		−393 645	−3749
All patients	361	860 134	1 693 171	+833 037	+2308

Abbreviations: CMR, cardiovascular magnetic resonance imaging; pts, patients.
Cost data are based on 2010 Medicare payments for Western Pennsylvania. Analysis included 361 consecutive patients (372 scans) over a 6-month period.

cardiac masses from artifacts, etc. The growing epidemic of obesity in the United States has significantly increased the incidence of uninterpretable echocardiograms due to attenuation of ultrasound waves.[18,19] Other than bore size considerations, obesity does not limit cardiac MRI.

Clinical impact

The superior spatial resolution of cardiac MRI allows accurate assessment of cardiac anatomy without the use of ionizing radiation. As 2-dimensional (2D) echocardiography does not always visualize the right ventricular free wall well, cardiac MRI is helpful in evaluating the anatomy of the right-sided heart chambers in patients with severe pulmonary hypertension or arrhythmogenic conditions. A complete assessment of the right ventricular morphology and function is often is not feasible on transthoracic echocardiography alone, particularly, when the anatomy is distorted by dilated/congenitally deformed right ventricles. Several authors have described the utility of MRI for assessment of valvular heart disease,[20–25] and this indication was common in our patient cohort. Although echocardiography with Doppler evaluation is the initial modality of choice for valvular heart diseases, Doppler angle limitations can limit the accuracy of Doppler data.[26] Cardiovascular magnetic resonance imaging has the unique advantage of unrestricted multiplane imaging, which eliminates the issue of problematic Doppler imaging angles. Cardiovascular magnetic resonance imaging is particularly useful in quantifying volumes in patients with regurgitant valvular diseases. Accurate left ventricular volume and ejection fraction quantification are often crucial for deciding the timing of valvular surgery.

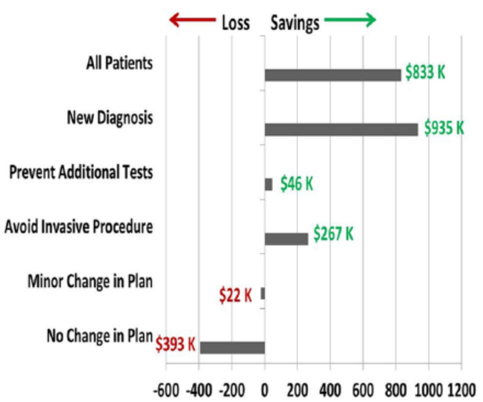

Figure 6. Cost-effectiveness of cardiac magnetic resonance imaging.

In this study, CMR was found to affect clinical outcomes in 71% of the patients. These data are similar to the much larger European Registry data published by the Euro SCMR investigators in 2009.[27] The greatest clinical impact of CMR was observed in cases where an existing diagnosis was refuted or when a completely new diagnosis was revealed by CMR findings. This was particularly notable among patients with nonischemic cardiomyopathy, who were labeled as "idiopathic cardiomyopathy" prior to their CMR study. Clinical management of these patients clearly benefitted from establishing a correct diagnosis, particularly when infiltrative cardiomyopathies such as sarcoidosis, amyloidosis, and hemochromatosis were demonstrated on CMR. The utility of CMR in this setting has been described by several other authors.[28–30] This diagnostic information helped to avoid further additional testing, prompting clinicians to consider cardiac transplantation in a more appropriate time frame and helping to reduce recurrent hospital admissions. Because of superior spatial resolution, cardiac MRI appears more efficacious in detecting noncompaction cardiomyopathy, an entity which was misdiagnosed as "idiopathic" heart failure in 4 patients. There were also patients in this study with a pre-CMR diagnosis of dilated cardiomyopathy who were found to have linear midwall scarring of the left ventricular myocardium ("midwall stripe"), a finding which has a distinctly adverse prognosis in patients with congestive heart

Table 3. Costs associated with testing, hospitalizations, and procedures.

SERVICE	*MEDICARE	PRIVATE PAYER
Cardiac magnetic resonance with structure and function	$306.53	$942.41
2-dimensional echocardiogram with Doppler	$355.78	$625.31
Cardiac magnetic resonance imaging with stress perfusion	$661.49	$1346.64
Exercise nuclear stress testing	$770.55	$747.07
Exercise stress echocardiogram	$355.78	$504.25
Congestive heart failure hospitalization	$8717	$9488
Aortocoronary bypass grafting	$24 277	$32 138
Aortic aneurysm surgery	$27 745	$34 469
Biventricular pacemaker implantation	$9546	$18 181

*Only Medicare data were used for cost analysis.

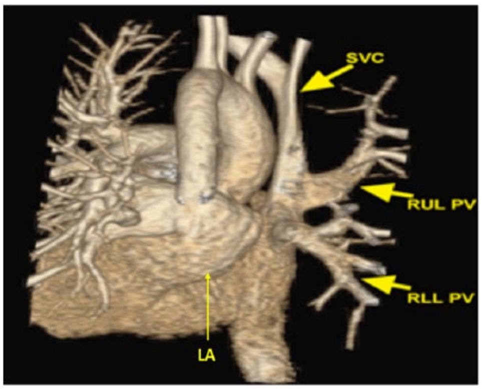

Figure 7. Anomalous right upper pulmonary vein draining into the SVC. LA indicates left atrium; RLL PV, right lower lobe pulmonary vein; RUL PV, right upper lobe pulmonary vein; SVC, superior vena cava.

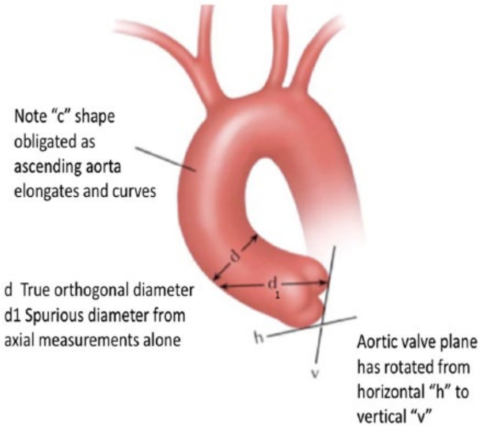

Figure 8. Considerations for orthogonal measurement of dilated/curved ascending aorta.

failure.[31] Patients with linear midwall scarring were able to move to appropriate therapy (ventricular assist devices/cardiac transplantations) sooner, avoiding recurrent clinical exacerbations and hospitalizations. In this patient cohort, ARVD was definitively diagnosed or excluded in 51 patients.

Thirty-seven patients (10%) in this study had a diagnosis of primary or secondary pulmonary hypertension prior to their CMR study. Five patients with a pre-CMR diagnosis of primary pulmonary hypertension were found to have evidence of an intracardiac or extracardiac shunt, thus enabling appropriate treatment of their pulmonary hypertension. Although this was seen in only 5 patients, the clinical impact was great in that 1 of these patients was found to have an anomalous right superior pulmonary vein draining into the superior vena cava (Figure 7), whereas another patient was found to have a coronary sinus atrial septal defect. The remaining 3 patients were found to have anomalous pulmonary veins that were undiagnosed by multiple noninvasive and invasive studies, *including* cardiac catheterization, transthoracic, and transesophageal echocardiography. Interestingly, these patients had already had an agitated saline study, but the results were either inconclusive or despite a positive study, the shunt was not localized. Establishment of a correct diagnosis by CMR allowed these patients to discontinue inappropriate vasodilator/endothelin receptor antagonist/prostaglandin therapy, which for some patients had been their main treatment for several months to years. For these patients, the economic impact of a correct diagnosis was considerable, noting that the annual estimated cost of pulmonary hypertension management with an endothelin receptor antagonist exceeds $55 000 per patient.

Impact of CMR on patient management

This study suggests that CMR, as a stand-alone cardiac imaging modality, may prevent additional diagnostic testing in specific clinical scenarios. For example, it has been well established that CMR is appropriate for myocardial viability assessment.[32,33] Fluorinated deoxy-glucose positron emission tomography (FDG-PET) is a suitable alternative, although it is also expensive, and limited in availability. If a patient is diabetic, CMR viability assessment may be more appropriate, which may have prompted clinicians to order a CMR over FDG-PET scans in this cohort of patients. In all cases, CMR results were conclusive and no further cardiac testing was required for determination of definitive clinical management. In contrast, FDG uptake in the spine/mediastinum often precludes accurate myocardial viability assessment, necessitating further testing, such as CMR, delaying and adding to the cost of a definitive clinical management decision. Similarly, attenuation and ramp artifacts that challenge the accuracy of nuclear perfusion studies in obese patients may be obviated using CMR stress perfusion imaging for patients with a body mass index above 35 kg/m^2.[34,35]

The clinical impact advantage of CMR is also supported by its ability to prevent inappropriate cardiac resynchronization procedures. Published data suggest that about one-third of patients with cardiomyopathies do not respond to CRT.[36] In this study, it was noted that some patients underwent CMR for diagnostic or prognostic indications and later became candidates for CRT. Information regarding the absence of viable lateral LV myocardium in these patients, appropriately negated consideration of CRT with considerable cost saving. This observation has been confirmed by other studies.[37–41]

This clinical impact study also included patients who were referred for CMR with a diagnosis of ascending aortic aneurysm, based on prior CTA or 2D echocardiography studies. In this patient cohort, 23% of patients with suspected ascending aortic aneurysms were proven to not to have aneurysms when the aortic diameter was measured perpendicular to flow by cardiac MRI, as recommended by the ACC/AHA Task Force.[42,43] This was particularly true of the axial aortic diameter measurements obtained by CTA, which are subject to skew (see Figure 8). Although this seems to be an easily avoided mistake, we did notice this happening fairly frequently in patients refereed from peripheral institutions where axial CT-based measurement were the sole basis of referral for aortic surgery.

With respect to cardiac mass lesions, this patient cohort had cases of suspected invasive cardiac tumors. Using T1-weighted

Table 4. Clinical indications demonstrating highest cost-effectiveness of cardiovascular magnetic resonance.

Workup of cardiac arrest cases (driven by a completely new diagnosis/unexpected finding)
Management of patients with recurrent (more than 3 hospital admissions a year) for congestive heart failure
Characterization of cardiac masses
Assessment of aortic aneurysms
Initial diagnostic workup of patients with suspected pulmonary arterial hypertension

and T2-weighted characteristics and LGE, malignancies were excluded in 5 patients, obviating the need for open-heart biopsy or surgery at considerable cost saving.

Cost-benefit of CMR

To establish cost-effectiveness by traditional criteria, a therapy or diagnostic technology should demonstrate that it enhances life, prolongs life, or does both.[44] This type of demonstration is straightforward with pharmacologic or surgical therapies using randomized controlled clinical trials to establish efficacy in terms of quality of life, outcomes, or mortality. However, diagnostic imaging modalities do not directly affect long-term patient outcomes but rather provide important information which serves as a surrogate for long-term outcomes.[14] Phelps and Mushlin[45] developed an evaluation strategy for diagnostic modalities, wherein results from clinical trials are used to calculate the incremental cost-effectiveness of the new imaging modality, relative to the existing alternative. This model served as the basis our simplified approach to assessment of cost-benefit.

Because cardiac MRI does not involve ionizing radiation, it is reasonable to predict that cardiac MRI would have a net positive benefit on cancer risk over time, compared with nuclear scintigraphic and computed CTA imaging modalities which involve ionizing radiation and have been shown to carry potential cancer risk.[46]

Conclusions

We found that CMR was able to satisfy completely all imaging requirements in more than 26% of patients (n = 94) so that no further noninvasive imaging procedure was required after the CMR exam. This observation highlights that the low rate of additional tests ordered after the CMR is not due to the fact that CMR is the very last test in an otherwise long row of imaging procedures but instead can answer multiple very important questions within a single exam. This was underscored in the European Cardiovascular Magnetic Resonance (EuroCMR) study as well.[27]

In our study, the CMR results were most useful in certain clinical scenarios. Based on our experience, we suggest that CMR be considered as the diagnostic modality of choice for these conditions. These include workup of cardiac arrest cases, idiopathic cardiomyopathies causing more than 3 hospitalizations a year for congestive heart failure, workup of challenging cardiac masses, confirming the diagnosis of pulmonary arterial hypertension (excluding/localizing cardiac shunts), and ascertaining the diagnosis for aortic aneurysms referred for surgery (see Table 4). If used as a front-line modality in such cases, CMR can contribute to significant health care savings. Replication of these results in a prospective multicenter trial would greatly help to establish the clinical and cost-effective utility of CMR.

Limitations

The retrospective nature of this study is an inherent limitation but allowed assessment of "real-world" cardiac MRI practice. The absence of a simultaneous alternate imaging arm precluded a head-to-head comparison of CMR against traditional imaging modalities across the spectrum of clinical indications described in our study. Such a study may be prohibitively expensive and logistically difficult. Also, the results were seen in a demographic patient subset from Western Pennsylvania. The costs and payments, practice patterns (particularly about utility of other diagnostic modalities such as CTA, echocardiography, and nuclear medicine) are reflective of care in this geographic area. One should be cautious when generalizing these results to clinical practices across the world.

All images were performed via 1.5-T CMR machines. No 3-T CMR studies were performed, reflecting the relatively limited penetration of 3 T in cardiology practices. Of note, a large number of patients were referred for CMR because a first-line cardiac imaging modality had failed to reveal a definite diagnosis or the patient was not following a clinical course consistent with their established diagnosis. The findings of this study were evaluated at one point in time, as opposed to longitudinally. The lack of longitudinal follow-up could potentially challenge the validity of our results.

The primary focus of our observations was to define the "Clinical Impact Factor" of CMR. Our observations are not intended to be a formal cost-effective analysis, and thus, incremental cost-effective ratio calculations were not used, and we did not necessarily follow International Society for Pharmacoeconomics and Outcomes Research series titled Good Research Practices in Cost Effective Analysis as advocated by Gazelle et al.[47] We used the suggestions of Phelps and Mushlin to generate a modified CBA which serves to provide an initial financial credibility to our clinical observations of the CMR impact. This is a proof-of-concept CBA. The lack of longitudinal follow-up essentially limits this study to be a cost study. We do realize that a simplified model may underestimate hidden cost-benefits such as prevention of radiation-induced cancers and possible complications from invasive procedures. Our study complements previous registries such as EuroCMR while providing more clinical details regarding how CMR can affect decision making at the patient level. Appropriate use guidelines may incorporate CMR into clinical use more widely if the link between CMR, improved patient decision making, and outcomes can be firmly demonstrated.

Author Contributions

VH: Data collection, manuscript writing; RWWB: Designed the study, in charge of data collection at Center 1; JRM: Senior author on manuscript, manuscript revision, cost data, figure review, data collection at Center 2.

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