Cardiac Involvement in Patients With Muscular Dystrophies: Magnetic Resonance Imaging Phenotype and Genotypic Considerations

David Verhaert, MD; Kathryn Richards, MD; Jill A. Rafael-Fortney, PhD; Subha V. Raman, MD

Muscular dystrophy (MD) connotes a heterogeneous group of inherited disorders characterized by progressive wasting and weakness of the skeletal muscles. In several forms of MD, cardiac dysfunction occurs, and cardiac disease may even be the predominant manifestation of the underlying genetic myopathy. Cardiologists may be unfamiliar with these diseases owing to their low incidence; also, significant advances in respiratory care have only recently unmasked cardiomyopathy as a significant cause of death in MD.1

Early detection of MD-associated cardiomyopathy is important, because institution of cardioprotective medical therapies may slow adverse cardiac remodeling and attenuate heart failure symptoms in these patients.2–6 Although ECG and echocardiography are typically advocated for screening,7,8 cardiovascular magnetic resonance (CMR) has shown promise in revealing early cardiac involvement when standard cardiac evaluation is unremarkable.9,10

This review will focus on 4 groups of skeletal muscle disease most commonly associated with cardiac complications (the Table): (1) dystrophin-associated diseases such as Duchenne and Becker (DMD and BMD, respectively), (2) Emery-Dreifuss MD (EDMD), (3) limb-girdle MD (LGMD), and (4) myotonic dystrophy (DM).

Dystrophin-Associated MDs

Molecular and Genetic Features
DMD and BMD are X-linked disorders affecting the synthesis of dystrophin, a large, sarcolemmal protein that is absent in DMD11 and reduced in amount or abnormal in size in BMD patients.12 Dystrophin provides the connection between a large, multimeric complex of glycoproteins in the muscle cell membrane (termed the dystrophin-glycoprotein complex) and intracellular actin filaments (Figure 1), thereby transmitting forces generated by sarcomere contraction to the extracellular matrix.13,14 Correlations between dystrophin mutations and the onset of cardiomyopathy have been noted15; some mutations result in only cardiomyopathy without skeletal myopathy.16 Other proteins not shown in Figure 1 that are partici-
by relative physical inactivity obscuring symptomatology. This most common and severe form of childhood MDs is associated with an increased R-to-S ratio in the right precordial ECG leads, deep Q waves in the lateral leads, conduction abnormalities, and arrhythmias (mainly supraventricular but also ventricular).

BMD patients, whose skeletal myopathy occurs later and progresses more slowly, experience worse cardiomyopathy

### Table. Characteristics of the Types of MD

<table>
<thead>
<tr>
<th>Dystrophy</th>
<th>Genetics</th>
<th>Incidence/Prevalence</th>
<th>Age of Onset</th>
<th>Clinical Features/Progression</th>
<th>Cardiac Complications</th>
<th>Recommended Cardiac Screening</th>
</tr>
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<tbody>
<tr>
<td>DMD</td>
<td>X-linked recessive (Xp21)</td>
<td>Incidence 1/3000 (boys)</td>
<td>3–7 years</td>
<td>Proximal skeletal muscle weakness with loss of ambulation between 7 and 13 years; Respiratory failure and death in second to third decade of life; Mild cognitive impairment</td>
<td>DCM: symptoms often masked by severity of skeletal myopathy; Ventricular arrhythmias</td>
<td>Boys: ECG + TTE every 2 years until age 10; Girls: ECG + TTE after age 16</td>
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<tr>
<td>BMD</td>
<td>X-linked recessive (Xq21)</td>
<td>Prevalence 1/30 000</td>
<td>Teenage years</td>
<td>Similar distribution of muscle wasting as in DMD, but more benign course; Death in fourth to fifth decade, usually due to cardiac complications</td>
<td>50%–70% eventually develop DCM; Ventricular arrhythmias</td>
<td>Boys: ECG + TTE every 5 years; Girls: when asymptomatic, ECG + TTE after age 16</td>
</tr>
<tr>
<td>EDMD</td>
<td>X-linked recessive (Xq28 in EDMD1, Xq26 in EDMD4); AD (EDMD2; LMNA gene at 1q21); Rarely autosomal recessive (EDMD3; also involving the LMNA gene at 1q21)</td>
<td>Combined prevalence of X-linked and autosomal EDMD estimated at 1–2/100 000</td>
<td>Bimodal distribution: often first or second decade, sometimes adult onset</td>
<td>Onset, severity, and progression of disease highly variable; Disease usually starts with contractures (elbows, Achilles tendons, posterior cervical muscles, spine); Subsequent slowly progressive weakening and wasting of humeroperoneal musculature; Eventually proximal LG musculature becomes affected</td>
<td>DCM; Atrioventricular conduction abnormalities; Atrial standstill, atrial flutter, atrial fibrillation; Sudden death, occasionally in patients with minimal skeletal myopathy</td>
<td>ECG + Holter + TTE annually in affected patients; Screening of family members indicated after age 10 (irrespective of symptoms); Consider need for pacemaker and/or defibrillator (particularly for EDMD2 patients with DCM); Consider need for anti-coagulation in case of atrial dysfunction</td>
</tr>
<tr>
<td>LGMD</td>
<td>Usually autosomal recessive (LGMD2C, 2D, 2E, and 2F; sarcoglycanopathies; LGMD2I: mutation of FKRP gene; 19q); Rarely AD (LGMD1; 1B due to mutation of the LMNA gene encoding lamin A/C)</td>
<td>Unknown; usually sporadic (autosomal recessive)</td>
<td>Variable (early childhood to adulthood)</td>
<td>Variable; AD forms generally less severe Slowly progressive weakness of shoulder and pelvic muscles; elevated serum creatine kinase</td>
<td>Cardiac involvement most common in LGMD1B (laminopathy) and LGMD 2E and 2I; DCM; right ventricular and LV fatty infiltration; conduction disorders In heterozygotes, cardiac dysfunction may be the only sign of disease</td>
<td>No formal guidelines; ECG + Holter + TTE probably indicated every 2–5 years</td>
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<tr>
<td>DM</td>
<td>AD Type 1 (DM1, Steinert’s disease): unstable expansion of CTG, the myotonic dystrophy protein kinase gene on chromosome 19q13.3; Type 2 (DM2): CCTG tetranucleotide repeat expansion in intron 1 of the zinc finger protein 9 gene on chromosome 3q21.3</td>
<td>Prevalence 1/8000 (DM1 + DM2)</td>
<td>Early childhood to adulthood</td>
<td>Rarely during infancy (congenital form)</td>
<td>DM2: proximal muscle weakness (particularly hip girdle)</td>
<td>Asymptomatic patients: annual ECG, TTE–Holter every 2 years; EP testing in case of syncope, dizziness, palpitations, documented arrhythmias or family history of sudden death or ventricular arrhythmias Consider need for pacemaker or defibrillator depending on ECG, Holter, and EP findings</td>
</tr>
<tr>
<td>DM1</td>
<td>Early adulthood</td>
<td>DM1: Skeletal muscle weakness and wasting (facial, distal forearm, intrinsic hand and ankle dorsiflexors) Myotonia (slowed relaxation after muscle contraction) Muscle pain Cataracts, baldness, infertility, mental and endocrine abnormalities DM2: proximal muscle weakness (particularly hip girdle)</td>
<td>DCM; LV hypertrophy; Conduction disturbances (atrioventricular and intraventricular) Atrial fibrillation and flutter Sudden cardiac death (most commonly in DM1)</td>
<td>Boys: ECG + TTE every 2 years until age 10, then once a year; Girls: when asymptomatic, ECG + TTE every 5 years after age 16</td>
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<tr>
<td>DM2</td>
<td>Adult onset, usually fourth decade</td>
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DCM indicates dilated cardiomyopathy; TTE, transthoracic echocardiography; and EP, electrophysiologic study. Other abbreviations are as defined in text.
than do DMD patients: up to 70% have left ventricular (LV) dysfunction on echocardiography. Perhaps because of less skeletal muscle weakness, these patients can perform more strenuous exercise with dystrophin-deficient myocardial muscle fibers and have earlier manifestations of myocardial disease.31

Most CMR data in MDs currently exist for patients with DMD and BMD. The pathology of cardiomyopathy in patients with dystrophinopathy classically produces subepicardial fibrosis of the inferolateral wall,32 remarkably similar to the pattern observed in some patients with viral myocarditis (Figures 2 and 3; movie files 1 and 2 in the online-only Data Supplement). Myocardial damage in DMD/BMD has been postulated to result from mechanical stress imposed on a metabolically and structurally abnormal myocardium, although it remains unclear how a genetic abnormality presumably affecting the heart in a diffuse manner may result in a segmental distribution.

Whether the inferolateral wall is more vulnerable owing to regional molecular changes caused by the mutation or whether this regional susceptibility results from exposure to higher mechanical stress remains to be elucidated.10 Of note, enterovirus infection has been shown to produce myocardial damage via cleavage of dystrophin33; this mechanism may help to explain the similarity in the late gadolinium enhancement (LGE) pattern between myocarditis and dystrophin-associated cardiomyopathy.

The rationale to perform CMR in BMD/DMD patients in addition to the current standard of care (monitoring by echocardiography and ECG) is based on 2 sets of observations. First, studies have shown that early initiation of standard heart failure therapy can delay the onset and progression of LV systolic dysfunction and potentially even lead to reverse remodeling in patients with X-linked dystrophinopathy2–6. Second, it has been shown that myocardial fibrosis detected by LGE imaging may be observed even

**Figure 1.** Proteins implicated in the MDs. Dystrophin is located inside the cell and is bound to actin at its N-terminus and to a large oligomeric complex of membrane glycoproteins at its C-terminus. This complex, referred to as the dystrophin-glycoprotein complex, consists of dystrophin, sarcoglycans (α, β, γ, and δ subunits), α- and β-dystroglycan, sarcospan, and syntrophins. Mutations in the dystrophin gene lead to BMD and DMD. Mutations in the sarcoglycan subunits cause LGMD. LGMD2I is a distinct form of LGMD caused by a mutation in the FKRP gene, encoding a Golgi apparatus protein. FKRP is involved in the glycosylation of α-dystroglycan, necessary for its binding to laminin-α2, and the extracellular matrix. Mutations in the genes encoding emerin and lamin A/C cause a spectrum of “nuclear envelopathies.” X-linked and AD EDMD belong to this group of diseases and are both characterized by skeletal muscle wasting, cardiac conduction defects, and cardiomyopathy. Distinct LMNA gene mutations have also been associated with AD LGMD (LGMD1B) and with isolated cardiomyopathy and conduction-system disease (lamin A/C cardiomyopathy). nNOS indicates neuronal nitric oxide synthase.

**Figure 2.** CMR findings in DMD in patients with different degrees of cardiac involvement. End-diastolic (A) and end-systolic (B) frames from a 3-chamber, long-axis cine acquisition (supplemental movie 1) show preserved LV systolic function in this 28-year-old man with DMD. LGE images (C, 3-chamber view; D, midventricular short-axis view) in the same patient show that despite preserved global LV systolic function, myocardial injury is evident as subepicardial fibrosis of the inferolateral wall (arrowheads). E, LGE in a 14-year-old boy with DMD shows more advanced cardiomyopathy with profound LV dilatation and systolic dysfunction (supplemental movie 2) and more extensive subepicardial scarring as well as septal fibrosis (arrowheads).
when findings by echocardiography are still normal\textsuperscript{9,10} (Figure 2). CMR can therefore serve as a more sensitive means to detect early cardiac involvement and help clinicians decide when cardioprotective treatment should be instituted. In addition to LGE, CMR also provides accurate and reproducible quantification of LV volumes, making this modality well suited for monitoring response to both standard therapy and novel treatment strategies.

Cardiac screening has been recommended for female DMD/BMD mutation carriers, particularly beginning after the teenage years, as these individuals are known to be at risk for developing cardiomyopathy.\textsuperscript{28} Interestingly, CMR has revealed a pattern of myocardial fibrosis in mutation carriers similar to that seen in DMD patients (Figure 4).\textsuperscript{34} Because myocardial damage in carriers has been observed even in the absence of clinically apparent muscular weakness, cardiac screening should be considered in female relatives of DMD/BMD patients.

Emery-Dreifuss MDs

Clinical and Genetic Features

The nuclear envelope is composed of a double lipid bilayer that separates the contents of the nucleus from the cytoplasm. Within the inner nuclear membrane are a variety of integral proteins. EDMD is a form of MD caused by mutations in these nuclear membrane proteins. One of these proteins, emerin (Figure 1), is almost completely absent in the X-linked form of EDMD owing to a mutation in the \textit{EMD} gene.\textsuperscript{35} The exact function of emerin is unclear; it binds to a variety of other nuclear factors involved in gene regulation, mRNA splicing, ordering of chromatin structure, and nuclear assembly.\textsuperscript{36} EDMD can also occur as an autosomal dominant (AD) or recessive disorder resulting from mutations in the \textit{LMNA} gene that encodes lamins A and C.\textsuperscript{37} Lamins A and C are nuclear intermediate-filament proteins that closely interact with emerin and other nuclear membrane proteins, thereby forming a proteinaceous meshwork (the nuclear lamina) that

Figure 3. LGE findings in BMD. The pattern of myocardial injury in patients with BMD is similar to that seen in DMD, starting at the subepicardium of the inferolateral wall, with an age-dependent increase in the extent of fibrosis and progressive decline in systolic function. The left and right upper panels (short-axis and horizontal long-axis views, respectively) show almost transmural hyperenhancement of the entire anterolateral and inferolateral walls, consistent with advanced disease. In addition, this patient also had evidence of septal mid-wall fibrosis (lower middle panel), also seen in myocarditis and other nonischemic cardiomyopathies.

Figure 4. Cardiomyopathy in a female Duchenne carrier. Coronary angiography and CMR findings in a 58-year-old female patient with Duchenne carrier status and chronic heart failure. Upper panels: Despite normal findings by coronary angiography, transmural scarring of the inferolateral wall is evident by LGE (arrowhead). Lower panels: CMR cine imaging showed severe global biventricular systolic dysfunction, with severe LV dilatation and akinesia of the inferolateral walls. Displacement of the papillary muscles due to global LV dilatation and segmental bulging of the inferolateral wall (white arrowheads) caused severe mitral regurgitation (arrow, velocity-encoded cine image, lower right panel).
underlies the inner nuclear membrane (Figure 1). This meshwork has an important role in maintaining the architecture and mechanical strength of the nucleus; it also serves as a scaffold for various other nuclear factors involved in DNA replication, chromatin organization, and transcription.\cite{38-41}

Deficiency in either emerin or lamin A/C typically results in the triad of contractures, muscle weakening, and cardiac conduction defects by mechanisms that remain elusive.

Cardiac involvement in EDMD patients is common and usually becomes evident in the third decade as muscle weakness progresses,\cite{42} although cardiac manifestations have also been reported in young adults without muscle weakness. Because cardiac dysfunction portends a high risk of sudden death,\cite{43,44} careful follow-up of these patients is mandatory. In EDMD, the normal myocardium is gradually replaced by fibrous and adipose tissue, a process that usually starts in the atria (leading to atrial arrhythmias), often involves the atrioventricular node (leading to conduction abnormalities sometimes requiring pacemaker implantation), and eventually affects the ventricles (causing progressive dilatation and systolic failure).\cite{43,44,45} Because sudden death may be the presenting symptom in this disease, cardiac screening of relatives (including female carriers with X-linked EDMD) has been recommended.\cite{7,44}

**CMR Imaging Phenotype**

In EDMD, CMR data are limited owing to the rarity of the disease but also because of the frequent need for pacemaker implantation in this population (particularly in the more advanced stages of the disease). A study by Smith et al\cite{45} in 8 patients with the AD subtype of EDMD (EDMD2; LMNA gene mutation at 1q21) showed that early-stage disease does not display apparent fibrosis, despite the presence of more subtle myocardial abnormalities, including a decrease in systolic circumferential strain in the inferior segment. This suggests a different pathogenesis of cardiac involvement in EDMD compared with DMD/BMD, wherein fibrosis typically precedes systolic dysfunction.

**Limb-Girdle MDs**

**Clinical and Genetic Features**

LGMD refers to a group of disorders with great clinical and genetic heterogeneity, all characterized by weakness affecting the proximal musculature. AD and autosomal recessive inheritance patterns have been identified. The more common autosomal recessive subtypes usually have an earlier age of onset and show more rapid disease progression compared with AD variants. The subtypes mostly associated with cardiac involvement (manifested as conduction disorders and/or myocardial disease) are those associated with a defect in the genes coding for the α-(LGMD2D), β- (LGMD2E), γ- (LGMD2C), or δ- (LGMD2F) subunits of the dystrophin-associated sarcoglycan complex in heart and skeletal muscle (Figure 1).\cite{46} Cardiomyopathy is also very common in LGMD2I, caused by a mutation in fukutin-related protein (FKRP). FKRP is an enzyme involved in the glycosylation of α-dystroglycan, a peripheral membrane component of the dystrophin-associated glycoprotein complex. Posttranslational glycosylation by FRKP allows α-dystroglycan to bind with the extracellular matrix, making it an important component in the link among cytoskeleton, sarcosomal dystrophin-associated glycoprotein complex, and extracellular matrix.

The AD subtype LGMD1B is also caused by a defect in the LMNA gene coding for lamin A/C, resulting in a phenotype similar to AD EDMD but with a different distribution of muscle involvement. The pelvic girdle weakness in LGMD1B is slowly progressive, sparing the lower muscles. In addition, contractures and cardiac disease manifestations (atrioventricular block, sudden death, atrial paralysis, atrial fibrillation/flutter, and dilated cardiomyopathy) tend to occur later compared with AD EDMD.\cite{47,48}

Different mutations involving the LMNA gene have been described, resulting in a clinically heterogeneous group of disorders (laminopathies) spanning MD, progeria, familial partial lipodystrophy, and Charcot-Marie-Tooth disease. The MDs associated with LMNA gene mutations that cause cardiac disease include the autosomal variants of EDMD, LGMD1B, and a third disorder commonly referred to as dilated cardiomyopathy with conduction-system disease. The last, though initially linked to chromosome 1p1-1q1,\cite{49} was later associated with mutations in the lamin A/C gene (1p1-p21 locus).\cite{50} Patients with this defect develop sinus node dysfunction, atrioventricular node dysfunction, ventricular arrhythmias, and adult-onset cardiomyopathy, with little clinical evidence of skeletal myopathy. The inheritance pattern is AD with high penetrance, and patients have a high risk of sudden death.\cite{50}

**Cardiac Imaging Phenotype**

In lamin A/C cardiomyopathy, we have demonstrated midmyocardial scarring of the basal interventricular septum by LGE that occurs well before the onset of ventricular dilatation and systolic dysfunction (Figure 4) and that may herald conduction-system disease.\cite{51} This midwall fibrosis is similar in distribution to that observed at autopsy and, in our experience, is often associated with diastolic dysfunction. Further studies are needed to define the prognostic significance of midwall fibrosis in this population, as it may represent a substrate for the potentially fatal ventricular arrhythmias seen in these patients as reported in other cardiomyopathies.\cite{52-54} Whereas skeletal muscle disease may not be readily apparent clinically, we have detected clear alterations involving the medial head of the gastrocnemius muscles by magnetic resonance imaging (Figure 5), similar to that described in patients with EDMD2.\cite{55} This suggests the presence of a continuum between phenotypes with predominate cardiac involvement and phenotypes with cardiac and skeletal muscle compromise.\cite{56}

Gaul et al\cite{57} recently described the CMR findings in 9 patients with LGMD2I (due to a mutation in the FKRP gene). They found CMR to be more sensitive than conventional diagnostic investigations (ECG and echocardiography) for detecting cardiac involvement, which was manifest as a decrease in ejection fraction and/or an increase in LV volumes and mass. Unfortunately, no results from late gadolinium-enhancement imaging were reported in this study. Our own experience with CMR in patients with LGMD2I suggests that at an early stage, when LV size and function are still normal, midmyocardial scarring may be
observed. As cardiomyopathy advances, extensive myocardial fibrosis is apparent (Figure 6).

A similar pattern of fibrosis was recently reported by Yilmaz et al58 in a patient with LGMD2C. Taken together, these findings suggest that different abnormalities within the dystrophin-sarcoglycan-dystroglycan complex may all lead to cardiomyocyte instability and damage, eventually resulting in a characteristic (but nonspecific) pattern of fibrosis.

**Myotonic Dystrophy**

**Clinical and Genetic Features**

Myotonic dystrophy (DM) is an AD MD that produces progressive skeletal muscle wasting and cardiac conduction abnormalities; multisystem manifestations include cataracts, testicular failure, hypogammaglobulinemia, and insulin resistance. As shown in the Table, 2 types of DM have been identified. DM1 is the most common form and is associated with abnormal expansion of a CTG-trinucleotide repeat sequence in the

\[ \text{DMPK} \]

gene that codes for MD protein kinase, a protein mainly expressed in smooth, cardiac, and skeletal muscle cells. Disease severity and age of onset in DM1 are correlated with CTG expansion length, and the number of repeats can increase from 1 generation to the next (anticipation). DM2, on the other hand, is associated with an expanded CCTG-tetranucleotide repeat in a totally unrelated gene, coding for zinc finger protein. In both cases, the gene

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**Figure 5.** CMR findings in lamin A/C cardiomyopathy. Lamin A/C cardiomyopathy has been associated with midwall fibrosis of the mid-ventricular septum (left panel, arrow) at an early stage of the disease. Note also the presence of fibrosis at the right ventricular–LV septal insertion sites (arrowheads) in this patient. Unlike patients with different types of \( \text{LMNA} \) mutations (EMDM, LGMDB1), lamin A/C cardiomyopathy does not typically produce apparent skeletal muscle weakness. Nevertheless, muscle imaging in these patients may reveal fibrosis of the gastrocnemius muscles (right panel, arrows), suggesting a continuum in the \( \text{LMNA} \) gene disorders between phenotypes with selective cardiac involvement and phenotypes with both cardiac and skeletal muscle abnormalities.

**Figure 6.** LGE findings in LGMD2I. Patient 1: LGE in an 11-year-old boy with an \( \text{FKRP} \) mutation. Despite normal LV systolic function, midwall fibrosis of the septum and inferior wall was seen, consistent with early cardiac involvement. Patient 2: LGE in a 57-year-old patient with an \( \text{FKRP} \) mutation. At an advanced stage of the disease, patients with LGMD2I may develop cardiomyopathy with severe systolic dysfunction and extensive scarring of the lateral walls (arrowheads). The septum is affected as well in this patient (arrows).
including the abnormal repeat sequences is transcribed into RNA but not translated. The mutant RNA accumulates in the nucleus69 and disturbs the function of RNA-binding proteins that normally participate in splicing of premessenger RNA into mature mRNA. This eventually results in abnormal function of different genes, including those coding for the muscle-specific chloride channel CIC-1 and insulin receptor, at least partially explaining the features of myotonia and insulin resistance in patients with DM.60

Atrioventricular and intraventricular conduction defects are common in both DM1 and DM2. Infranodal block is likely an important cause of sudden death in these patients.61,62 As in many other types of MD, cardiac arrhythmias may occur early in the disease course, that is, in the absence of severe neuromuscular impairment. Structural heart disease is also frequently observed in DM, with LV dilatation or hypertrophy observed in ≈20% of patients and LV systolic dysfunction in 14%.63 Clinical heart failure, however, is less common—2%, according to that same report.

Cardiac Imaging Phenotype

Patients with DM may present with cardiomyopathy, which usually is more benign in DM2 than in DM1. CMR may help define the LV abnormalities of the disease: dilatation, systolic dysfunction, hypertrophy, and occasionally, noncompaction.54,65 Typical LGE patterns have not been reported in DM. In our experience, mild midwall fibrosis involving the septum is occasionally present; the clinical significance of this finding in DM remains uncertain.

Beyond LGE

Myocardial Strain Analysis

The assumption that cardiac dysfunction can be prevented (or at least attenuated) in patients with MD has led to the belief that therapy should be initiated at an early stage of the disease, rather than delayed until ventricular dilatation or systolic dysfunction becomes apparent. CMR has been proposed as a sensitive screening tool for that purpose by its ability to show myocardial fibrosis, even when the left ventricle is otherwise structurally normal. Another means of revealing occult cardiac dysfunction in patients with MD may be provided by strain analysis. Ashford et al66 used CMR tagging to show that boys with DMD exhibit abnormal global and segmental circumferential strain compared with age- and sex-matched controls, despite similar LV volumes and ejection fractions. Similar findings were recently reported by Hor et al67 who showed that abnormalities in myocardial strain preceded both the age-dependent decline in ejection fraction and the appearance of myocardial fibrosis in DMD patients. This group recently showed that strain analysis better captures the serial decline in LV function compared with ejection fraction.68

The sensitivity of strain imaging analysis by CMR could potentially be used not only to reveal occult cardiac dysfunction but also to assess the efficacy of existing or novel therapeutic agents.

Some questions remain, however, regarding these tools, particularly in terms of their accuracy for measuring strain on a segmental (rather than global) level, but also with respect to the reproducibility of strain measurements among centers. Prospective and multicenter studies that randomize patients to therapeutic decision making with or without strain imaging analysis are therefore critically needed before these new techniques can become adopted into the clinical management of patients with MD.69

Fat Versus Water Imaging

Histologic studies of autopsy hearts from DMD patients suggest a component of fat infiltration, described as “predominantly epicardial” in a small case series.32 CMR may distinguish fat by cine or LGE imaging techniques that take advantage of the consistent difference in the resonance frequency of water versus fat protons.70 Studying 3 DMD dogs with these techniques, Kellman et al71 demonstrated extensive epicardial hyperenhancement on LGE imaging that was, at least in part, attributable to fat. Our experience in 1 patient with early myocardial disease by the same technique suggests that LGE in patients with dystrophin-associated cardiomyopathy may also demonstrate a component of fatty infiltration (Figure 7; movie file 3 in the online-only Data Supplement). T2-weighted CMR, which depicts myocardial water distribution, may provide additional insights into the myocardial disease of DMD.72

Suggested CMR Protocol and Clinical Implications of Findings

Suggested CMR Protocol

When designing a CMR examination for the patient with MD, the key clinical questions should be addressed: What is the degree of LV dysfunction? What evidence is there for myocardial disease? What pattern of disease is present? What is the likelihood of functional recovery? Acquisitions should...
include cine imaging in all standard long-axis and contiguous short-axis planes; real-time cine techniques may be necessary in patients who have difficulty breathholding. Fat-suppressed or fat-only cine imaging, when available, may help delineate the extent of myocardial fat infiltration. Finally, LGE acquisition forms the cornerstone of any CMR protocol in patients with cardiomyopathy, and the same is true in evaluating the MD patient. Although the optimal contrast dose and acquisition timing have not been specifically interrogated in MD cardiomyopathy LGE imaging, our experience suggests that values similar to those used for other nonischemic cardiomyopathies (save amyloidosis) perform well. If fat and water can be distinctly imaged with specialized LGE sequences, these may shed further insight into the extent of fibrosis versus fatty infiltration of the myocardium. Although the absence of hyperenhancement has established value in predicting response to, for instance, medical and resynchronization therapies in other cardiomyopathy populations, the predictive value in MD-associated myocardial disease remains to be established. Given the evidence that subclinical abnormalities in regional strain may precede overt contractile dysfunction, strain analysis may be included at centers where robust postprocessing affords reproducible results.

**Clinical Implications of Findings**

Increased recognition of subclinical myocardial changes with advanced imaging raises challenging management questions. Evidence-based guidelines for patients with cardiomyopathy advocate initiation of drugs like angiotensin converting enzyme inhibitors and β-blockers in stage B cardiomyopathy, defined in the adult guidelines as “impaired left ventricular (LV) function, hypertrophy, or geometric chamber distortion.”73 Pediatric guidelines also advocate angiotensin converting enzyme inhibitor therapy for subclinical LV dysfunction;74 notably, neither document addresses the management of myocardial fibrosis that may be present in the absence of structural and functional changes. Our approach is to initiate angiotensin converting enzyme inhibitor and occasionally aldosterone antagonist therapy, given the proven antifibrotic effect of both in other cardiomyopathy populations.75 If CMR demonstrates myocardial fibrosis in the MD patient and particularly in the lamin A/C mutation-positive patient. Whereas I prospective, randomized trial in children with DMD supports a possible long-term benefit with angiotensin converting enzyme inhibitors even when the initial LV ejection fraction by echocardiography is normal,76 it is unknown whether any of these patients had subclinical fibrosis in the absence of CMR data. A strategy of fibrosis-guided initiation of cardioprotective drug therapy requires prospective, randomized trial data before it can be widely advocated.

Electrophysiologic testing should be considered in MD-associated cardiomyopathies known to affect the conduction system, such as DM and lamin A/C. Timing of such may be informed by symptoms suspicious for conduction-system disease or conduction abnormalities by ECG.77 We have observed longer PR intervals in lamin A/C patients with septal fibrosis by CMR relative to those of mutation-positive patients without evident fibrosis51; longitudinal studies are suggested to test the predictive value of hyperenhancement for pacemaker requirement in appropriate DM and lamin A/C patients.

**Cardiac Disease in MD: Genotype Versus Phenotype**

One of the major problems for clinicians dealing with the cardiovascular complications of MD is that clear correlations between genotype and phenotype have been difficult to achieve. It remains unclear why distinct mutations may result in a clinically indistinguishable phenotype, whereas strikingly different phenotypes may result in carriers of identical gene mutations or even among affected siblings. In this respect, MD-associated cardiomyopathies are no different from other heritable cardiomyopathies (hypertrophic cardiomyopathy, for instance). Although there is little doubt that genotype plays a central role in initiating the cardiomyopathic process, the ultimate cardiovascular phenotype is likely also determined by other multiple interacting factors, including genetic background effects, biomechanical stress pathways (with loss of functional myocardium creating additional stress on the remaining viable heart muscle), and modifying effects of calcium cycling and signaling.78,79

A better understanding of clinical variability in MD-associated myocardial disease will therefore require identification of modifying genes and improved knowledge of gene-protein function and protein interactions. Importantly, it will also benefit from continued advances in cardiac phenotyping; lack of sensitivity in the armamentarium of diagnostic tests has previously impaired detection of early cardiac involvement in many of these patients. The greater sensitivity and reproducibility of CMR to demonstrate early abnormalities or subtle changes in serial assessment offer the promise of better defining the natural history and offer significant value in developing novel therapeutic approaches for these disorders. It is hoped that this review’s demonstration of the limitations of the state of the art in imaging phenotype prompts synergistic efforts among geneticists, molecular biologists, and CMR specialists to eventually generate new insights into the pathogenesis and expression of cardiac disease in MD, which is critically needed to help reduce the burden of heart disease in this patient population.

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