

HEREDITARY MUSCLE DISEASES AND THE HEART: THE CARDIOLOGIST'S PERSPECTIVE

**L. Giuliani, *A. Di Toro, *M. Urtis, *A. Smirnova, *M. Concardi,
°V. Favalli, *A. Serio, *M. Grasso, *E. Arbustini*

***Centre for Inherited Cardiovascular Diseases. IRCCS Foundation
University Hospital Policlinico San Matteo, Pavia, Italy.
°Ingenomics srls, Polo Tecnologico, Pavia, Italy.**

Abstract

Cardiomyopathies, cardiac conduction defects and arrhythmias, either isolated or combined, are the clinical manifestations of cardiac involvement in hereditary NeuroMuscular Diseases (NMD). The onset may occur in pediatric or adult age in patients with clinically manifested NMD or can be the first clinical manifestations of the cardio-muscular disease. In the latter condition, cardiologists play a key-role in the diagnosis, monitoring, and planning of the multidisciplinary care needed for the management of these patients. The current classifications of hereditary NMD are very complex and based on either phenotype, cause or pathologic features. This complexity may be potentially impractical for cardiologists. We propose grouping hereditary NMD involving the heart based on their most typical recurring cardiac phenotypes. Paradigmatic examples are Dilated Cardiomyopathy in Dystrophinopathies, LGMDs, Emerinopathies; Hypertrophic phenotype in Friedreich Ataxia, mitochondrial diseases and glycogen storage diseases; Restrictive phenotype with conduction defects in Myofibrillar myopathies. Moreover, conduction defects and arrhythmias may represent Steinert muscle dystrophy cardiac phenomarkers, where sudden cardiac death can occur as its first manifestation. CKemia is a common, low-cost, marker that should be regularly tested in patients with either cardiomyopathies or rhythm disorders.

Cardiac manifestations in hereditary muscle diseases include cardiomyopathies, defects of cardiac conduction with or without primary myocardial muscle involvement, and arrhythmias^{1,2}. Symptoms and signs of these diseases may exhibit in pediatric as well as in adult age³ and in many cases only a multidisciplinary clinical approach can ensure correct diagnosis and manage-

ment^{4,5}. Cardiologists might be the first to recognize an apparently-lone cardiac involvement as an important clinical marker of an hereditary muscle disease or be the first in line in a multidisciplinary team when cardiac involvement represents the major clinical manifestation affecting evolution and prognosis of the disease⁶.

The actual classifications of hereditary muscle disorders are based on phenotype, etiology and pathology and may result complex and potentially impractical for a cardiologic clinical approach. For this reason, we are proposing the grouping of most common cardiac manifestations observed in hereditary muscle diseases on the basis of the cardiac phenotypes. A new way of describing the complexity of cardiac phenotype and genotype together with extracardiac clinical manifestations, as represented by MOGES nosology for cardiomyopathies⁷, is the possible solution for nosology assignment and deep phenotype description of these patients in a way to collect data useful in accelerating targeted treatment development.

Dilated and hypokinetic phenotypes (DCM)

The most common heritable muscle diseases affecting the heart and leading to dilated and hypokinetic cardiac phenotype include dystrophinopathies, Limb Girdle Muscular Dystrophies (LGMD), and Emery Dreifuss Muscular Dystrophies (EDMD).

Dystrophinopathies

Mutations in the DMD gene encoding for dystrophin cause dystrophinopathies, a group of rare X-Linked Recessive (XLR) muscle diseases. Dystrophin is a large sarcolemmal protein that is essential for structural and functional integrity of the myocyte membranes. Patients affected by dystrophin defects manifest DCM as unique and often fatal cardiac phenotype. Muscle and cardiac phenotypes are clinically heterogeneous and classified according to the severity of the dystrophy [from the severe Duchenne Muscle Dystrophy (DMD) to the milder Becker Muscular Dystrophy (BMD)] or the exclusive involvement of the heart, when skeletal muscle is clinically spared (i.e. in XLR-DCM).

- *DMD* (1:4000-1:6000 live male birth)⁸ is a severe muscle dystrophy clinically and genetically diagnosed in pediatric age. In most of the cases (>70%), the genetic defects are large rearrangements in DMD gene. The pathologic hallmark is the total absence of dystrophin in the skeletal myocyte sarcolemma⁹. Regular cardiology care is needed since initial diagnosis in all DMD patients and annual echocardiograms represent the minimum follow-up^{4,5,8}. The prevalence of DCM is age-dependent and in nearly all young-adult patients cardiac involvement is demonstrated¹⁰⁻¹³. ECG changes like right axis deviation, Q wave in the left precordial leads, and conduction defects may exhibit an early onset¹⁰. DCM is diagnosed through transthoracic echocardiogram and when feasible, CMR may add information on adipose and fibrous replacement of LV (Left Ventricle) wall structure and LV trabecular anatomy¹¹. Patients have to be treated for cardiac manifestations according to Heart Failure (HF) guidelines and disease-specific recommendations^{4,5} with ACE-I and ARBs as cornerstone therapy. Multiple contribu-

tors to cardio-respiratory failure determine end-stage evolution of the disease¹³ precluding indication to heart transplantation (HTx). In recent years life expectancy has increased from the late twenties¹² to early forties¹⁴ thanks to steroid treatment, spinal stabilization surgery, nocturnal ventilation and physiotherapy.

- *In patients with BMD* [1:18000 live male birth¹⁵] DCM fully manifests in the second to fourth decade of life but it can be recognized even earlier when BMD is clinically suspected¹⁶. Skeletal muscle involvement is milder than in DMD and variable, depending on the severity of the loss of protein expression¹⁷. Patients usually remain ambulatory until advanced adult age^{8,9,15}. DCM may be the first clinically overt manifestation of the disease¹⁸ but hyperCKemia is common and by itself may represent a reason for neurological consultation. The most common cause of end-stage disease is HF^{4,5,19}. Patients with BMD-DCM have to be treated according to HF guidelines and HTx may be indicated. Post-transplant outcome is similar to that of (non-BMD) idiopathic DCM^{4,5,19};
- *XLR-DCM* can be the unique overt manifestation in patients with dystrophin defects. The prevalence ranges from 3 to 7% in consecutive male patients with familial, non-paternally inherited DCM^{20,21}. Patients have no history or symptoms of muscular dystrophy but almost always present hyperCKemia. Clinical management is based on HF guidelines; transplantation is the elective treatment for patients with end-stage HF and has the same outcome as in BMD-DCM²².

Limb Girdle Muscle Dystrophy

The LGMD phenotype includes genetically heterogeneous group of more than 30 disorders in which skeletal, respiratory, gastrointestinal and nervous systems may be variably involved. They are characterized by weakness and wasting of pelvic and shoulder girdle muscles. Recently a novel gene-based nosology²³ has classified LGMDs using the clinical descriptor (LGMD) followed by a number that distinguishes autosomal dominant (AD, type 1, LGMD1) and autosomal recessive (AR, type 2, LGMD2) diseases. Alphabetic letters indicating the mutated protein/gene complement the description²³. Currently eight AD LGMDs (LGMD1) and more than 25 AR LGMDs are known.

The prevalence of LGMDs is estimated to be ranging from 1:14,500 to 2.27:100,000^{24,25}. Cardiac and respiratory impairment is common. The most represented cardiac phenotype in LGMD is DCM²⁶ having a prevalence that varies between the different subgroups of patients; in sarcoglycanopathies (α -, β -, δ -, γ -) more than 30% of patients develop DCM²⁷. The risk of Sudden Death (SD) is also variable, being particularly high in LGMD1B (laminothy) where is also associated with DCM and conduction defects²⁸. Disease-specific biomarkers exist but hyperCKemia represents a common finding in all LGMDs. Functional studies of cardiac (echocardiography and CMR) and skeletal muscle (electromyography, muscle ultrasound and magnetic resonance imaging) are useful to characterize the involvement of the heart and skeletal muscles^{29,30}. Patients usually need a scheduled monitoring in multidisciplinary settings and the actual therapeutic options include steroids with variable effectiveness³⁰. Since actionable targeted therapies currently do not exist, DCM,

arrhythmias and conduction defects have to be treated according to contemporary guidelines^{4,5,19,26}.

Emery-Dreifuss Muscle Dystrophy (EDMD)

Contractures of elbows, ankles and cervical spine associated with slowly progressive muscle weakness are the major traits in EDMD³¹. The cardiac phenotype is characterized by LV dilation and dysfunction often preceded by conduction disease that requires PM implantation. HyperCKemia is common. The disease is genetically heterogeneous and is caused by mutations in genes that code for nuclear envelope protein. Half of the patients diagnosed with EDMD are carriers of mutations in genes that code for emerin, lamin A/C, nesprin-1 and nesprin-2³¹. Depending upon the disease gene, the pattern of inheritance is either X-Linked or autosomal, both dominant (common) or recessive (rare).

In XLR emerinopathies patients are usually referred to cardiologists for arrhythmia consultation and consideration of possible PaceMaker (PM) placement; AV conduction defects and arrhythmias, mostly of atrial origin, may appear before LV systolic dysfunction^{32,33}. In AD EDMD caused by mutations in LMNA gene³³ the risk of ventricular arrhythmias is high. DCM, arrhythmias and conduction disease should be treated according to HF guidelines. However, the disease-causing gene and the type of mutation should be taken into account in the stratification of arrhythmogenic risk².

Hypertrophic Phenotypes

HCM represents the cardiac phenotype in a large group of clinically and genetically heterogeneous hereditary muscle disorders caused by impaired synthesis and utilization of energy substrates with proliferation of abnormal organelles [i.e. Friedreich ataxia (FRDA) and mitochondrial myopathies] or by intracellular accumulation of energy substrates (i.e. glycogen storage diseases).

Friedreich Ataxia (FRDA)

Friedreich ataxia is a rare (1:50.000) AR neuromuscular disease characterized by HCM as cardiac phenotype. In most of the cases it is caused by homozygous GAA triplet expansions in the first intron of the FXN gene³⁴ that encodes for frataxin, a mitochondrial protein involved in iron homeostasis. The GAA triplet expansion (60-1.500 vs. <12 in normal individuals)^{34,35} leads to transcriptional gene silencing and loss of frataxin expression³⁶ impairing and dysregulating mitochondrial iron trafficking. The clinical onset is usually in the first or second decade of life^{35,36} and presentation is characterized by cerebellar ataxia, dysarthria, HCM, diabetes, neurosensory hearing loss, and visual impairment. The HCM is usually symmetrical and non-obstructive with diastolic dysfunction and progression to systolic dysfunction^{37,38}. Cardiac involvement is demonstrated in more than 90% of patients with about 40% suffering from supraventricular tachycardia³⁹. Therapy is based on the use of antioxidants and iron chelators but their efficacy is still debated⁴⁰. In end-stage cardiomyopathy HTx may be a potential option but it has to be considered feasible when neurologic dysfunction is mild or absent⁴¹.

Mitochondrial myopathies and cardiomyopathies

Deficiencies in the mitochondrial oxidative phosphorylation (OXPHOS) system are at the basis of mitochondrial diseases. The estimated prevalence is 1:4000⁴² and both heart (mitochondrial cardiomyopathies) and skeletal muscle (mitochondrial myopathy) are involved. The clinical traits however can include hearing loss, ocular disorders, cryptogenic stroke, gastrointestinal diseases, renal failure and diabetes. They are caused by defects in mitochondrial DNA (mtDNA) or in nuclear genes, with matrilinear or Mendelian inheritance, respectively^{42,43}.

mtDNA defects most commonly lead to concentric, non-obstructive LV hypertrophy characterized by potential evolution to LV dilation and dysfunction^{44,45}. ECG may show short PR interval and pre-excitation, a sign that may constitute a useful marker for clinical hypothesis⁴⁶. The severity of clinical manifestations depends on the degree of somatic heteroplasmy⁴³. Mutations in mtDNA genes coding transfer RNAs are the most common cause of MELAS, one of the more malignant mitochondrial disorders⁴⁷. Death in MtDNA-related diseases mostly occurs for recurrent stroke-like episodes, HF and renal failure⁴⁸.

Mitochondrial nuclear genes encode for over 1.500 mitochondrial proteins and the number of novel diseases caused by nDNA defects is progressively increasing⁴⁸. They are inherited mostly with AR pattern, with clinical onset in pediatric/juvenile age. The current classification of nuclear mitochondrial myopathies is based on phenotype and genetic cause^{42,43}. The most common cardiac phenotype is HCM, followed by DCM, RCM and arrhythmogenic cardiomyopathy⁴⁸.

Glycogen Storage Disorders (GSD)

Both heart and skeletal muscle are involved in GSD. Each glycogenesis is a rare disease but when considered collectively, they are relatively common. Screening studies and the extensive application of next generation sequencing have modified knowledge on GSDs prevalence favoring the discovery of late-onset phenotypes that were previously undiagnosed⁴⁹. Most frequent GSDs forms involving heart muscle are Pompe disease and McArdle disease (about 1:40.000 people)^{50,51}.

Pompe disease (GSD type II) is an AR disease caused by mutations in GAA gene leading to deficiency of alpha 1,4 glucosidase activity^{51,52}. The enzyme deficiency leads to glycogen accumulation in heart, skeletal muscle and liver. Myocytes and myocardial walls are thickened by progressive lysosomal glycogen gathering (diastolic dysfunction) and are irreversibly damaged. This leads to systolic dysfunction and HF⁵². In infantile forms, characterized by enlarged tongue, severe skeletal muscle hypotonia (floppy babies) and normal liver size, HCM is the main cause of death. The ECG shows large QRS complexes and short PR intervals⁵². The disease is rapidly fatal in absence of the specific Enzyme Replacement Treatment (ERT). Heart is less commonly involved in juvenile forms, which are characterized by delayed motor milestones and gradually-worsening myopathy, especially in the limb girdle and truncal muscles. Death occurs for respiratory failure before adulthood in absence of ERT^{51,52}. In adult-onset or Late-Onset Pompe Disease (LOPD), the most common form of the disease, mild and non-specific cardiac abnormalities are

detectable by CMR only in a small proportion of patients⁵³. The diagnosis can be achieved non-invasively through the dosage of enzyme activity and genetic testing even if skeletal muscle or endomyocardial biopsy can be useful⁵³.

Mutations in the LAMP2 gene, encoding the lysosomal-associated membrane protein 2, cause a rare multi-systemic disorder, the *XLD Danon Disease* (or GSD II type 2b). The phenotype is early-onset in male patients and characterized by cognitive impairment, severe biventricular HCM with evolution to LV thinning with systolic dysfunction and skeletal muscle disease with hyperCKemia. HCM is later-onset but severe even in female patients. Common ECG findings are tall QRS voltages, short PR and pre-excitation. In end-stage hearts extensive fibrosis is demonstrated by CMR. No specific treatment for Danon disease exist and patients are cared for as per phenotype⁵⁴ with HTx as therapeutic option in end-stage disease. Post-transplant outcome is similar to other cardiomyopathies⁵⁴.

The AR McArdle Disease (GSD type V) is caused by homozygous or double heterozygous mutations in PYGM that reduce or abolish myophosphorylase enzyme activity in the muscle. The enzyme initiates glycogen breakdown in the skeletal muscle fibers⁵⁵. The disease clinically manifests in late childhood or in early teens with cramps, myalgias and skeletal muscle weakness worsened by physical activity and relieved by rest. Episodes of rhabdomyolysis and prolonged pain may be elicited by strenuous exercise⁵⁵. Exercise-associated symptoms are characterized by a partial relieve of the muscles pain which presents after the first minutes of activity (“second wind” phenomenon). This is due to the mobilization of other forms of energy (fatty acids). Exercise-related symptoms, baseline hyperCKemia, myoglobinuria (>50%) help in suspecting the diagnosis which can be confirmed with the dosage of myophosphorylase and with genetic testing. In a minority of cases cardiomyopathy may be present as a mild HCM with possible evolution through LV dilatation.

Fatty acid oxidation disorders

Fatty acid oxidation disorders may variably involve both heart and skeletal muscle. They are classified depending on whether the enzymatic defect involves the plasma membrane function or transport or the long- medium-, and short-chain fatty acid β -oxidation. In the severe early-onset cardiac and multiorgan failure form of VLCADD (Deficiency of very long-chain acyl-CoA dehydrogenase) diagnosis is confirmed on the basis of abnormal acylcarnitine biochemical analysis and/or biallelic mutations in the ACADVL gene⁵⁶. HCM or HCM with DCM-like evolution characterize the cardiac phenotype. Low-fat diet supplemented by medium-chain triglycerides and triheptanoin and early supportive care can improve both cardiomyopathy and myopathy.

Restrictive phenotypes

Diastolic dysfunction, presence of normal or reduced diastolic volumes of one or both ventricles, normal or reduced systolic volumes, normal ventricular wall thickness and enlarged atrial chambers characterize restrictive physiology⁵⁷. The latter recurs most of all in patients with Myofibrillar Myopathies (MFM).

Myofibrillar myopathies with RCM

This group of myopathies is characterized pathologically by the abnormal accumulation of intrasarcoplasmic proteins with disorganization of the myofibrillar network at the level of the Z-disks. In about one third of patients they usually manifest at the cardiac level with a restrictive pattern and conduction defects in association with hyperCKemia⁵⁸. Slowly progressive weakness of both the proximal and distal skeletal muscles (80%), sensory defects, skeletal muscle stiffness, cramps and aching complete the clinical presentation.

AVB and intramyocyte accumulation of osmiophilic granulophilamentous and desmin-immunoreactive material is the clinico-pathologic phenotype of the highly malignant, restrictive cardiodesminopathy. The clinical exordium is in young age and rapidly-evolving to end-stage HF. These patients usually require HTx at a relatively young age⁵⁹. Even in the absence of clinically overt myopathy the skeletal muscle is always structurally affected⁵⁹⁻⁶¹. When the skeletal muscle involvement is minimal, HTx have to be considered and has the same outcome of non-DES patients.

BAG3-opathies with MFM are also characterized by early RCM phenotype with typical intrasarcoplasmic inclusion bodies⁶². In end-stage myocardial disease HTx is the only treatment option, although it has to be considered in the context of the severity of systemic involvement.

Left Ventricular NonCompaction

LVNC describes a left ventricular wall anatomy with prominent trabeculae, a thin compacted layer, and deep inter-trabecular recesses⁶³. The definition does not imply functional effects, which are manifest only when LVNC is associated with dilated, hypertrophic or restrictive cardiomyopathy. LVNC has been described as part of the cardiac phenotype in many different heritable muscle diseases as well as in congenital heart defects, genetic syndromes, and cardiomyopathies^{64,65}. Even if its possible prognostic role is still debated in the general population⁶⁶, in DMD/BMD, the presence of LVNC has been significantly associated with a faster deterioration in LV function and higher mortality⁶⁷.

LVNC is part of the dilated, hypokinetic cardiomyopathy that occurs in more than 90% of XLR Barth syndrome (BTHS) patients together with early non-progressive, hypotonic skeletal myopathy involving proximal muscles with developmental motor delay⁶⁸. Oral aphtae, dysmorphic facial traits and selective learning difficulties may also be part of the phenotype. The disease gene (TAZ) encodes Tafazzin, a protein that is located on the inner mitochondrial membrane. Tafazzin is essential for high energy-consuming tissue. The severity of the cardiac phenotype is variable with HTx as a possible treatment option⁶⁹.

Rhythm disorders and myopathies

Conduction diseases and arrhythmias are common in skeletal muscle diseases even in absence of primary myocardial muscle involvement with cardiomyopathic phenotypes. Myotonic dystrophies and skeletal muscle channelo-

pathies may have life-threatening ventricular arrhythmias and SD as their first clinical manifestations.

Myotonic Dystrophies (DM)

Type 1 (DM1) and type 2 (DM2) AD myotonic dystrophies are clinically characterized by myotonia, progressive skeletal muscle weakness, conduction defects and CNS involvement. The DM1 patients are referred to cardiologists mostly for AVB and need for PM implantation. Genetic testing is usually available as it has been feasible for decades with nearly 100% diagnostic yield. SD risk has not to be under-evaluated because about 30% of these patients die suddenly ⁷⁰.

The unstable CTG repeat expansion in DMPK gene is the cause of DM1; the extent of the expansion is associated with the severity of the muscular phenotype ⁷¹. DM1 has been recently classified in five groups according to the most recent criteria of the International Myotonic Dystrophy Consortium ⁷². The most common and well-recognized cardiac traits of the disease are conduction defects ⁷³; cardiomyopathy is uncommon. Conversely the risk of SD is high and ventricular arrhythmias or complete heart block can occur in the early stages of disease ⁷⁴. The risk of cardiac events has been demonstrated not to be correlated with the extent of CTG expansions. Patients with small and large triplet expansions have a similar increase in the risk of cardiac events and the follow-up should not differ in the two groups ⁷⁵.

A CCTG-repeat expansion in intron-1 of the CNBP/ZNF9 gene represents the molecular basis of DM2 (or proximal myotonic myopathy, PROMM). Skeletal muscle pain and weakness, myotonia (from 60% ⁷⁶ to 85% ⁷⁷), hypogonadism (male patients), cardiac rhythm disorders, diabetes and early cataracts characterize the phenotype. 20% to 36% of patients show cardiac conduction defects ⁷⁸. In 10 to 20% of cases atrial fibrillation, LV systolic dysfunction and HF have been demonstrated ⁷⁹. A minority of patients may manifest DCM but it may be characterized by a severe phenotype ⁸⁰. SD have been reported in rare cases in DM2 ⁸¹.

Heritable skeletal muscle channelopathies

Skeletal muscle channelopathies are very rare genetic neuromuscular disorders having a prevalence in the general population of 1:100.000. They are of cardiac interest because they are a possible cause of malignant ventricular arrhythmias and SD. They include the non-dystrophic myotonias ⁸² and the primary periodic paralysis ⁸³.

Conclusion

The heart is frequently involved in Inherited Muscle Disorders. Cardiomyopathies (i.e. dilated, hypertrophic or restrictive, with potential overlap) together with rhythm disorders can be the first or predominant manifestations (fig 1). They can present as an apparently-lone cardiac involvement or be part of a complex “cardio-skeletal-muscular” disease. Serum CKemia and lactic acidemia represents “red flags” providing preliminary clues for exploring skeletal muscle disease in patients with cardiomyopathies or rhythm disorders.

HERITABLE MUSCLE DISEASES AND HEART

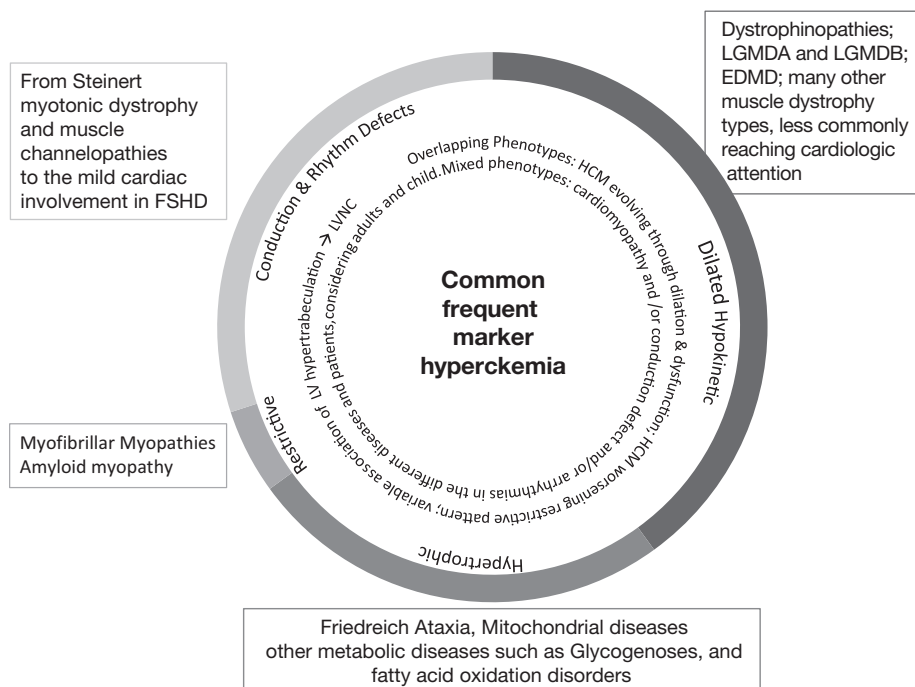


Fig. 1. Hereditary muscle diseases listed according to their most common clinical cardiac phenotypes.

Cardiovascular care is necessary in a large proportion of patients with skeletal muscle disorders and cardiac involvement. Cardiologist may be key figures in complex diagnostic pathways or in clinical emergencies.

REFERENCES

- 1) *Finsterer J, Stöllberger C, Wahbi K.* Cardiomyopathy in neurological disorders. *Cardiovascular Pathology* 2013; 22:389-400
- 2) *Groh WJ.* Arrhythmias in the muscular dystrophies. *Heart Rhythm* 2012; 9:1890-95
- 3) *McNally EM, Pytel P.* Muscle diseases: the muscular dystrophies. *Annu Rev Pathol Mech Dis* 2007; 2:87-109
- 4) *Tawil R, Kissel JT, Heatwole C, Pandya S, Gronseth G, Benatar M.* Evidence-based guideline summary: Evaluation, diagnosis, and management of facioscapulohumeral muscular dystrophy Report of the Guideline Development, Dissemination, and Implementation Subcommittee of the American Academy of Neurology and the Practice Issues Review Panel of the American Association of Neuromuscular & Electrodiagnostic Medicine. *Neurology* 2015; 85:357-364
- 5) *Feingold B, Mahle WT, Auerbach S et al.* Management of Cardiac Involvement Associated With Neuromuscular Diseases: A Scientific Statement From the American Heart Association. *Circulation* 2017; 136:e200-e231

- 6) *Sommerville RB, Vincenti MG, Winborn K et al.* Diagnosis and management of adult hereditary cardio-neuromuscular disorders: a model for the multidisciplinary care of complex genetic disorders. *Trends in cardiovascular medicine* 2017; 27:51-58
- 7) *Arbustini E, Narula N, Tavazzi L et al.* The MOGE (S) classification of cardiomyopathy for clinicians. *J Am Coll Cardiol* 2014; 64:304-318
- 8) *Bushby K, Finkel R, Birnkrant DJ et al.* Diagnosis and management of Duchenne muscular dystrophy, part 1: diagnosis, and pharmacological and psychosocial management. *The Lancet Neurology* 2010; 9:77-93
- 9) *Muntoni F, Torelli S, Ferlini A.* Dystrophin and mutations: one gene, several proteins, multiple phenotypes. *The Lancet Neurology* 2003; 2:731-740
- 10) *Thrush PT, Allen HD, Viollet L, Mendell JR.* Re-examination of the electrocardiogram in boys with Duchenne muscular dystrophy and correlation with its dilated cardiomyopathy. *Am J Cardiol* 2009; 103:262-265
- 11) *Silva MC, Magalhães TA, Meira ZMA et al.* Myocardial fibrosis progression in Duchenne and Becker muscular dystrophy: a randomized clinical trial. *Jama cardiology* 2017; 2:190-199
- 12) *Nigro G, Comi L, Politano L, Bain R.* The incidence and evolution of cardiomyopathy in Duchenne muscular dystrophy. *Int J Cardiol* 1990; 26:271-277
- 13) *Connuck D, Sleeper L, Colan S et al.* Pediatric Cardiomyopathy Registry Study Group. Characteristics and outcomes of cardiomyopathy in children with Duchenne or Becker muscular dystrophy: a comparative study from the Pediatric Cardiomyopathy Registry. *Am Heart J* 2008; 155:998-1005
- 14) *Ryder S, Leadley R, Armstrong N et al.* The burden, epidemiology, costs and treatment for Duchenne muscular dystrophy: an evidence review. *Orphanet journal of rare diseases* 2017; 12:79
- 15) *Bushby K, Thambyayah M, Gardner-Medwin D.* Prevalence and incidence of Becker muscular dystrophy. *The Lancet* 1991; 337:1022-24
- 16) *Jefferies JL, Eidem BW, Belmont JW et al.* Genetic predictors and remodeling of dilated cardiomyopathy in muscular dystrophy. *Circulation* 2005; 112:2799-2804
- 17) *Saito M, Kawai H, Akaike M, Adachi K, Nishida Y, Saito S.* Cardiac dysfunction with Becker muscular dystrophy. *Am Heart J* 1996; 132:642-647
- 18) *Hoogerwaard E, de Voogt WG, Wilde AA et al.* Evolution of cardiac abnormalities in Becker muscular dystrophy over a 13-year period. *Journal of neurology* 1997; 244:657-663
- 19) *Yancy CW, Jessup M, Bozkurt B et al.* 2013 ACCF/AHA guideline for the management of heart failure: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines. *J Am Coll Cardiol* 2013; 62:e147-e239
- 20) *Arbustini E, Diegoli M, Morbini P et al.* Prevalence and characteristics of dystrophin defects in adult male patients with dilated cardiomyopathy. *J Am Coll Cardiol* 2000; 35:1760-68
- 21) *Nakamura A.* X-linked dilated cardiomyopathy: a cardiospecific phenotype of dystrophinopathy. *Pharmaceuticals* 2015; 8:303-320
- 22) *Papa AA, D'Ambrosio P, Petillo R, Palladino A, Politano L.* Heart transplantation in patients with dystrophinopathic cardiomyopathy: Review of the literature and personal series. *Intractable & rare diseases research* 2017; 6:95-101
- 23) *Nigro V, Savarese M.* Genetic basis of limb-girdle muscular dystrophies: the 2014 update. *Acta Myologica* 2014; 33:1
- 24) *Norwood FL, Harling C, Chinnery PF, Eagle M, Bushby K, Straub V.* Prevalence of genetic muscle disease in Northern England: in-depth analysis of a muscle clinic population. *Brain* 2009; 132:3175-86
- 25) *Van der Kooi A, Barth P, Busch H et al.* The clinical spectrum of limb girdle muscular dystrophy A survey in the Netherlands. *Brain* 1996; 119:1471-80
- 26) *Narayanaswami P, Weiss M, Selcen D et al.* Evidence-based guideline summary:

- Diagnosis and treatment of limb-girdle and distal dystrophies Report of the Guideline Development Subcommittee of the American Academy of Neurology and the Practice Issues Review Panel of the American Association of Neuromuscular & Electrodiagnostic Medicine. *Neurology* 2014; 83:1453-63
- 27) *Kirschner J, Lochmüller H.* Sarcoglycanopathies. *Handbook of clinical neurology*: Elsevier 2011; 41-46
 - 28) *van Rijsingen IA, Arbustini E, Elliott PM et al.* Risk factors for malignant ventricular arrhythmias in lamin a/c mutation carriers: a European cohort study. *J Am Coll Cardiol* 2012; 59:493-500
 - 29) *Wattjes MP, Kley RA, Fischer D.* Neuromuscular imaging in inherited muscle diseases. *European radiology* 2010; 20:2447-60
 - 30) *Bushby K.* Diagnosis and management of the limb girdle muscular dystrophies. *Practical neurology* 2009; 9:314-323
 - 31) *Bonne G, Leturcq F, Ben Yaou R.* Emery-Dreifuss muscular dystrophy. In: Adam MP, Ardinger HH, Pagon RA, et al. editors. *GeneReviews*. University of Washington, Seattle; 1993-2018. Available at: <http://www.ncbi.nlm.nih.gov/books/NBK1436>. Accessed September 29, 2004
 - 32) *Stoyanov N, Winterfeld J, Varma N, Gollob MH.* Atrial arrhythmias in the young: early onset atrial arrhythmias preceding a diagnosis of a primary muscular dystrophy. *Europace* 2014; 16:1814-20
 - 33) *Finsterer J, Stöllberger C, Sehnal E, Rehder H, Laccone F.* Dilated, arrhythmogenic cardiomyopathy in Emery-Dreifuss muscular dystrophy due to the emerin splice-site mutation c. 449+ 1G> A. *Cardiology* 2015; 130:48-51
 - 34) *Schulz JB, Boesch S, Bürk K et al.* Diagnosis and treatment of Friedreich ataxia: a European perspective. *Nature Reviews Neurology* 2009; 5:222
 - 35) *Payne RM.* The heart in Friedreich's ataxia: basic findings and clinical implications. *Progress in pediatric cardiology* 2011; 31:103-109
 - 36) *Pandolfo M.* Friedreich ataxia. *Archives of neurology* 2008; 65:1296-1303
 - 37) *Reetz K, Dogan I, Costa AS et al.* Biological and clinical characteristics of the European Friedreich's Ataxia Consortium for Translational Studies (EFACTS) cohort: a cross-sectional analysis of baseline data. *The Lancet Neurology* 2015; 14:174-182
 - 38) *Weidemann F, Rummey C, Bijmans B et al.* The heart in Friedreich ataxia: definition of cardiomyopathy, disease severity, and correlation with neurological symptoms. *Circulation* 2012;CIRCULATIONAHA.111.059477
 - 39) *Weidemann F, Liu D, Hu K et al.* The cardiomyopathy in Friedreich's ataxia. New biomarker for staging cardiac involvement. *Int J Cardiol* 2015; 194:50-57
 - 40) *Elinx-Benizri S, Glik A, Merkel D et al.* Clinical experience with deferiprone treatment for Friedreich ataxia. *Journal of child neurology* 2016; 31:1036-40
 - 41) *McCormick A, Shinnick J, Schadt K et al.* Cardiac transplantation in Friedreich Ataxia: Extended follow-up. *Journal of the neurological sciences* 2017; 375:471-473
 - 42) *Gorman GS, Schaefer AM, Ng Y et al.* Prevalence of nuclear and mitochondrial DNA mutations related to adult mitochondrial disease. *Annals of neurology* 2015; 77:753-759
 - 43) *Molnar MJ, Kovacs GG.* Mitochondrial diseases. *Handbook of clinical neurology*: Elsevier 2017; 147-155
 - 44) *Bates MG, Bourke JP, Giordano C, d'Amati G, Turnbull DM, Taylor RW.* Cardiac involvement in mitochondrial DNA disease: clinical spectrum, diagnosis, and management. *Eur Heart J* 2012; 33:3023-33
 - 45) *Hsu Y-HR, Yogasundaram H, Parajuli N, Valtuille L, Sergi C, Oudit GY.* MELAS syndrome and cardiomyopathy: linking mitochondrial function to heart failure pathogenesis. *Heart failure reviews* 2016; 21:103-116
 - 46) *Rapezzi C, Arbustini E, Caforio AL et al.* Diagnostic work-up in cardiomyopathies: bridging the gap between clinical phenotypes and final diagnosis. A posi-

- tion statement from the ESC Working Group on Myocardial and Pericardial Diseases. *Eur Heart J* 2012; 34:1448-58
- 47) *DiMauro S, Hirano M. MELAS*. In: Adam MP, Ardinger HH, Pagon RA, et al., editors. *GeneReviews*. Seattle: University of Washington, 2001: 1993-2018. Available at: <http://www.ncbi.nlm.nih.gov/books/NBK1233/>
 - 48) *Chinnery PF. Mitochondrial disorders overview*. In: Adam MP, Ardinger HH, Pagon RA, et al., editors. *GeneReviews*. Seattle: University of Washington, 1993-2018. Available at: <http://www.ncbi.nlm.nih.gov/books/NBK1224/>
 - 49) *Hobson-Webb LD, Kishnani PS*. How common is misdiagnosis in late-onset Pompe disease? *Muscle & nerve* 2012; 45:301-302
 - 50) *De Castro M, Johnston J, Biesecker L*. Determining the prevalence of McArdle disease from gene frequency by analysis of next-generation sequencing data. *Genetics in medicine* 2015; 17:1002
 - 51) *Lukacs Z, Cobos PN, Wenninger S et al*. Prevalence of Pompe disease in 3,076 patients with hyperCKemia and limb-girdle muscular weakness. *Neurology* 2016; 87:295-298
 - 52) *Chen MA, Weinstein DA*. Glycogen storage diseases: Diagnosis, treatment and outcome. *Translational Science of Rare Diseases* 2016; 1:45-72
 - 53) *Boentert M, Florian A, Dräger B, Young P, Yilmaz A*. Pattern and prognostic value of cardiac involvement in patients with late-onset Pompe disease: a comprehensive cardiovascular magnetic resonance approach. *Journal of Cardiovascular Magnetic Resonance* 2017; 18:91
 - 54) *D'souza RS, Levandowski C, Slavov D et al*. Danon disease: clinical features, evaluation, and management. *Circulation: Heart Failure* 2014; 7:843-849
 - 55) *Martín MA, Lucía A, Arenas J, et al*. Glycogen storage disease type V. 2014. In: Adam MP, Ardinger HH, Pagon RA, et al., editors. *GeneReviews*. Seattle: University of Washington, 1993-2018. Available at, <http://www.ncbi.nlm.nih.gov/books/NBK1344/>
 - 56) *Miller MJ, Burrage LC, Gibson JB et al*. Recurrent ACADVL molecular findings in individuals with a positive newborn screen for very long chain acyl-coA dehydrogenase (VLCAD) deficiency in the United States. *Molecular genetics and metabolism* 2015; 116:139-145
 - 57) *Arbustini E, Serio A, Favalli V, Dec GW, Palladini G, J. N*. Restrictive Heart Diseases. In: Fuster V, Harrington RA, J N, editors. *Hurst's the Hearth 14th Edition*. New York: Mc Graw Hill 2017:1482-1508
 - 58) *Adam M, Ardinger H, Pagon R, et al*. Myofibrillar myopathy. In: Adam MP, Ardinger HH, Pagon RA, et al., editors. *GeneReviews*. Seattle: University of Washington, 1993-2018. Available at: <https://www.ncbi.nlm.nih.gov/books/NBK1499/>
 - 59) *Arbustini E, Morbini P, Grasso M et al*. Restrictive cardiomyopathy, atrioventricular block and mild to subclinical myopathy in patients with desmin-immunoreactive material deposits. *J Am Coll Cardiol* 1998; 31:645-653
 - 60) *Arbustini E, Pasotti M, Pilotto A et al*. Desmin accumulation restrictive cardiomyopathy and atrioventricular block associated with desmin gene defects. *European journal of heart failure* 2006; 8:477-483
 - 61) *Ojrzynska N, Bilińska ZT, Franaszczyk M, Płoski R, Grzybowski J*. Restrictive cardiomyopathy due to novel desmin gene mutation. *Kardiologia Polska (Polish Heart Journal)* 2017; 75:723-723
 - 62) *Semmler A-L, Sacconi S, Bach JE et al*. Unusual multisystemic involvement and a novel BAG3 mutation revealed by NGS screening in a large cohort of myofibrillar myopathies. *Orphanet journal of rare diseases* 2014; 9:121
 - 63) *Jenni R, Oechslin EN, van der Loo B*. Isolated ventricular non-compaction of the myocardium in adults. *Heart* 2007; 93:11-15
 - 64) *Oechslin E, Jenni R*. Left ventricular non-compaction revisited: a distinct phenotype with genetic heterogeneity? *Eur Heart J* 2011; 32:1446-56

- 65) *Arbustini E, Favalli V, Narula N, Serio A, Grasso M.* Left ventricular noncompaction: a distinct genetic cardiomyopathy? *J Am Coll Cardiol* 2016; 68:949-966
- 66) *Zemrak F, Ahlman MA, Captur G et al.* The relationship of left ventricular trabeculation to ventricular function and structure over a 9.5-year follow-up: the MESA study. *J Am Coll Cardiol* 2014; 64:1971-80
- 67) *Kimura K, Takenaka K, Ebihara A et al.* Prognostic impact of left ventricular non-compaction in patients with Duchenne/Becker muscular dystrophy-prospective multicenter cohort study. *Int J Cardiol* 2013; 168:1900-04
- 68) *Ferreira C, Thompson R, Vernon H.* Barth syndrome. In: Adam MP, Ardinger HH, Pagon RA, et al., editors. *GeneReviews*. Seattle: University of Washington, 1993-2018. Available at: <http://www.ncbi.nlm.nih.gov/books/NBK247162/>
- 69) *Mangat J, Lunnon-Wood T, Rees P, Elliott M, Burch M.* Successful cardiac transplantation in Barth syndrome—single-centre experience of four patients. *Pediatric transplantation* 2007; 11:327-331
- 70) *Groh WJ, Groh MR, Saha C et al.* Electrocardiographic abnormalities and sudden death in myotonic dystrophy type 1. *New Eng J Med* 2008; 358:2688-97
- 71) *Hammans S.* Myotonic dystrophy. *Brain* 2002; 125:1225-6
- 72) *De Antonio M, Dogan C, Hamroun D et al.* Unravelling the myotonic dystrophy type 1 clinical spectrum: a systematic registry-based study with implications for disease classification. *Revue neurologique* 2016; 172:572-580
- 73) *Sovari AA, Bodine CK, Farokhi F.* Cardiovascular manifestations of myotonic dystrophy-1. *Cardiology in review* 2007; 15:191-194
- 74) *Christensen AH, Bundgaard H, Schwartz M, Hansen SH, Svendsen JH.* Cardiac myotonic dystrophy mimicking arrhythmogenic right ventricular cardiomyopathy in a young sudden cardiac death victim. *Circulation: Arrhythmia and Electrophysiology* 2008; 1:317-320
- 75) *Denicourt M, Pham MT, Mathieu J, Breton R.* DM1 Patients with Small CTG Expansions are also at Risk of Severe Conduction Abnormalities. *Journal of neuromuscular diseases* 2015; 2:99-105
- 76) *Meola G, Sansone V, Rotondo G et al.* PROMM in Italy: clinical and biomolecular findings. *ACTA MYOLOGICA* 1998; 2:21-26
- 77) *Ricker K, Koch MC, Lehmann-Horn F et al.* Proximal myotonic myopathy: clinical features of a multisystem disorder similar to myotonic dystrophy. *Archives of neurology* 1995; 52:25-31
- 78) *Day J, Ricker K, Jacobsen J et al.* Myotonic dystrophy type 2 molecular, diagnostic and clinical spectrum. *Neurology* 2003; 60:657-664
- 79) *Wahbi K, Meune C, Bécane HM et al.* Left ventricular dysfunction and cardiac arrhythmias are frequent in type 2 myotonic dystrophy: a case control study. *Neuromuscular Disorders* 2009; 19:468-472
- 80) *Lee TM, Maurer MS, Karbassi I, Braastad C, Batish SD, Chung WK.* Severe dilated cardiomyopathy in a patient with myotonic dystrophy type 2 and homozygous repeat expansion in ZNF9. *Congestive Heart Failure* 2012; 18:183-186
- 81) *Schoser B, Ricker K, Schneider-Gold C et al.* Sudden cardiac death in myotonic dystrophy type 2. *Neurology* 2004; 63:2402-04
- 82) *Matthews E, Fialho D, Tan S et al.* The non-dystrophic myotonias: molecular pathogenesis, diagnosis and treatment. *Brain* 2009; 133:9-22
- 83) *Venance S, Cannon S, Fialho D et al.* The primary periodic paralyses: diagnosis, pathogenesis and treatment. *Brain* 2005; 129:8-17