Intrinsic Myogenic Potential of Skeletal Muscle-Derived Pericytes from Patients with Myotonic Dystrophy Type 1

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Pericytes are multipotent, vessel-associated progenitors that exhibit high proliferative capacity, can cross the blood-muscle barrier, and have the ability to home to muscle tissue and contribute to myogenesis. Consequently, pericyte-based therapies hold great promise for muscular dystrophies. A complex multi-system disorder exhibiting muscular dystrophy for which pericytes might be a valuable cell source is myotonic dystrophy type 1 (DM1). DM1 is caused by an unstable (CTG)n repeat in the DMPK gene and characterized by skeletal muscle weakness, muscle wasting, and myotonia. We have successfully isolated alkaline phosphatase-positive pericytes from skeletal muscle of DM1 patients and a transgenic mouse model. Intranuclear (CUG)n RNA foci, a pathogenic DM1 hallmark, were identified in human and mouse pericytes. Notably, pericytes from DM1 patients maintained similar growth parameters and innate myogenic characteristics in vitro compared to cells from unaffected controls. Our in vitro results thus demonstrate the potential of pericytes to ameliorate muscle features in DM1 in a therapeutic setting.

INTRODUCTION

In a search for myogenic cells from non-somite origin, De Angelis and colleagues were the first to show that vessel-associated cells isolated from the wall of the embryonic dorsal aorta, generally called mesangioblasts, hold myogenic potential. Follow-up research revealed that their postnatal analogs surrounding vessels in postnatal tissues, pericytes, also have the capacity to contribute to myogenesis. The close association of pericytes with the vasculature positions the cells at the forefront of endogenous tissue repair responses. Consequently, pericytes seem to be indispensable for growth and regeneration of muscle fibers during postnatal life.

Isolation of pericytes can provide researchers with a promising pool of undifferentiated cells capable of differentiating into other tissue types when experimentally relocated. Encouraging results in the field of Duchenne muscular dystrophy (DMD), limb-girdle muscular dystrophy (LGMD), facioscapulohumeral muscular dystrophy (FSHD) made us wonder whether functional pericytes are also present in postnatal tissues of patients with the variable and most prevalent neuromuscular disease, myotonic dystrophy type 1 (DM1). If so, would these pericytes present DM1 hallmarks and still hold myogenic potential? In fact, it has been reported that pericyte abundance is negatively correlated with increasing age due to an age-related decrease in the microvasculature system of the skeletal muscle. Because DM1 is considered to be a progeroid syndrome with progressive age-dependent dysfunction of many organ systems, an increased demand of progenitor cells might exhaust the pericyte cell pool. Additionally, pericytes isolated from elderly subjects, and consequently DM1 patients, could be impaired in proliferation and myogenic differentiation ability.

DM1 is a multisystemic repeat expansion disorder with pathogenic effects brought about by an expanded (CTG•CAG)n repeat in the DMPK/DM1-AS gene pair. Because this repeat tends to show somatic and intergenerational instability, DM1 is one of the most variable genetic diseases. An increase in repeat length, from 50 up to a few thousand triplets, correlates with more severe symptoms and an earlier age of onset. Expression of expanded DMPK RNA causes sequestration of RNA binding proteins (RBPs), such as members of the muscle blind-like family (MBNL) of proteins. Formation of these ribonuclear complexes, visualized as so-called foci in microscopy, is thought to initiate a cascade of downstream effects resulting in muscle necrosis, apoptosis, and a decrease in muscle mass.

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in widespread dysregulated RNA processing, including alternative splicing and polyadenylation. Additionally, repeat-associated non-AUG (RAN) translation of repeat transcripts may contribute to disease via the production of toxic homopolymeric proteins. Taken together, the expanded repeat results in a complex set of features in patients. For skeletal muscle this relates to progressive muscle weakness, muscle wasting, and myotonia. Currently, clinical management of DM1 patients is limited to symptomatic treatment.

The myogenic cell type that is first harmed in DM1 by repeat-expanded RNA during development, and therefore must be repaired in cell-based therapeutic strategies, has not been identified. The onset of DMPK expression is already seen in somites in developing embryos, even before commitment to specific muscle cell fate and onset of myogenesis. To investigate the potential of pericytes for therapeutic purposes, we attempted to isolate pericytes from patients with variable repeat lengths and DM1 mice. These pericytes were cultured in vitro and used for characterization of gene expression, cell growth, and myogenic fusion capacity. Spontaneous differentiation of human pericytes, triggered by serum reduction, indeed resulted in fused and elongated myosin heavy chain (MHC) positive multi-nucleated myotubes, without obvious differences between cells from patients and unaffected controls. Our results indicate that pericytes from skeletal muscle of DM1 patients and DMSXL mice may pave the road for cell therapy approaches.

RESULTS

Explant Cultures of Skeletal Muscle from DMSXL Mice and DM1 Patients

Culture of tissue fragments in vitro, hereafter called explants, can give rise to the outgrowth of a mixed population of cells. Due to the inability of other cell types to rapidly proliferate under the specific conditions used here, we expected a progressive increase in the proportion of pericytes. The isolation and characterization of mouse pericytes is depicted in Figure 1, while Figure 2 provides the results of the human muscle biopsies. Skeletal muscle was chosen as the source for our explant cultures since muscle-derived pericytes show a preference for differentiation into the myogenic lineage. For the isolation of mouse pericytes, we collected skeletal muscle tissue of the hind limbs from DMSXL mice. These mice express a human DM1 allele including a CTG1300 repeat. Regulatory sequences from the human locus drive a near-to-natural expression of these transgenes in all DM1-related tissues (skeletal muscle, heart, CNS), making it a valuable and useful model to study DM1 pathomechanisms.

For the isolation of human pericytes, we included six DM1 patients and two unaffected individuals as controls. The participants showed

Figure 1. Isolation of Pericytes from DMSXL Mice and WT Controls

(A) Outgrowth of cells (left top corner) from a skeletal muscle explant (right bottom corner) of a DMSXL mouse, 7 days after muscle isolation. Scale bar, 300 μm. (B) ALP-activity staining on sorted pericytes. Scale bar, 100 μm. (C) Representative flow cytometry analysis of a negative control for surface expression of ALP. Colors represent a density plot. Gates were set according to the negative control. (D) Representative flow cytometry analysis of sample. The ALP + results are between 0.1% and 0.4% of the total unsorted population. Input is live cells without debris or doublets (Figure S1B). (E) Relationship between the weight of muscle dissected from the hind limbs and whole-mouse body weight. Each data point represents data from one mouse (n = 3–5 per genotype). (F) The number of ALP + pericytes sorted from skeletal muscle biopsies after explant cultures. Each data point represents data from one mouse (n = 3–5 per genotype).
a broad diversity in age and sex (Table 1). The DM1 patients had variable (CTG)n repeat lengths and scores on the Muscular Impairment Rating Scale (MIRS), a simple and reliable five-point rating scale for muscular impairment in DM1.31 Muscle biopsies from the quadriceps were cultured following the same approach as for mouse tissue. Initially, the human explant cultures showed increased presence of red blood cells. Repeated removal of these small nonadherent cells via selected washing and replating of the explants was necessary to promote efficient outgrowth of adherent cells (Figure 2A).

**Purification and Validation of Mouse and Human DM1 Pericytes**

Pericytes can be identified by the presence of alkaline phosphatase (ALP).3,6,32 In contrast to other pericyte markers such as neuron-glial antigen 2 (NG2) and platelet-derived growth factor receptor beta (PDGFRβ), ALP is not expressed in skeletal muscle fibers, nor in other myogenic progenitors, but it is restricted to the microvasculature of striated muscle in postnatal life and is therefore an appropriate selection marker. Expression of this phosphatase by pericytes enabled us to distinguish them from PAX7⁺ or MYOD⁺ satellite cells, which might also be present in the explant cultures. Moreover, pericytes lack endothelial markers such as CD31.3 To obtain ALP⁺ cells from the mixed population of outgrown mouse cells, we sorted these cells via fluorescent-activated cell sorting (FACS) on the presence of ALP and absence of CD31 on day 7 (Figures 1C and 1D; Figures S1A and S1B). Enzymatic ALP staining in all cells after sorting confirmed our selection protocol (Figure 1B). Due to the presence of blood cells in the human cultures, it took 7 days longer for an outgrowth ring of cells to appear. Cell sorting of five cell lines (control-derived lines C1 and C2, and patient-derived lines P1, P3, P6) showed that via replating under pericyte-favorable conditions, we had already established a selection for ALP⁺ and CD31⁻ cells during cell culture (Figures 2C and 2D; Figures S1C and S1D). Consequently, the last three patient-derived lines (P2, P4, P5) were not sorted but were validated via enzymatic ALP stain (Figure 2B). We thus were able to collect pure ALP⁺ cultures from all participants (Table 1).

After sorting of mouse and human ALP⁺ cells, we further confirmed the cell type via immunocytochemistry. A combination of pericyte markers alpha smooth muscle actin (α-SMA), NG2, and PDGFRβ, combined with absence of MHC, clearly demonstrated both identity and purity of our pericyte isolates from both mouse and human muscle (Figure 3).

Homozygous (HOM) DMSXL mice show high neonatal mortality, muscle defects, and growth retardation, whereas heterozygous (HET) mice show milder muscle symptoms and no increase in neonatal death.29 As expected from these phenotypes, we found a strong positive correlation ($R^2 = 0.70$) between body weight of the mice and the amount of skeletal muscle isolated from the hind limbs (Figure 1E). Unexpectedly, however, no correlation existed between
the total weight of the muscle biopsy used for the explant cultures and the number of pericytes obtained after sorting ($R^2 = 0.03$; Figure 1F), and comparable numbers of pericytes could be isolated from HOM, HET, and wild-type (WT) mice. Importantly, we cannot exclude that the abundance of pericytes in skeletal muscle tissue in vivo varies between the genotypes.

Human pericytes maintained their diploid karyotype after at least nine passages (Figure 2E) and showed a typical triangular refractile morphology for at least 20 population doublings, with a doubling time of approximately 40 h (Figure 2F). Notably, the proliferation rate of all pericyte cultures was comparable and independent of donor, MIRS, sex, and participants’ age (note that no growth curve was measured for P6, as this biopsy was used to optimize the isolation protocol).

To examine the progenitor cell state at higher passages, we re-sorted mouse pericyte cultures at passage 19. The entire population of cells still expressed Alp (Figures S2A and S2B), so no differentiation toward myoblasts or contamination of additional cell types was encountered. For human pericytes, we performed MHC staining at passage 20 to verify that they did not differentiate toward MHC+ myotubes. MHC staining was negative and all cells still expressed DMPK transcripts in the form of fluorescent in situ hybridization (FISH)-detectable RNP complexes in the nucleus, generally termed foci, after hybridization with a CAG repeat probe. The number of foci varied strongly between cells, but, on average, 1–2 foci per nucleus were present in pericytes from HET mice versus 5–10 foci in cells from HOM mice (Figure 3). Few foci were detected in some WT mouse cells, which has been reported before for myoblasts and may represent background staining recorded by the automated image analysis. Especially noticeable was the high variation in foci count per cell in pericytes from HOM animals, ranging between 0 and >25 per nucleus.

We also examined the occurrence of FISH foci in human pericytes. Pericytes from P1, P2, P3, and P5 showed an average of 1–2 foci per nucleus. No foci could be detected in pericytes from P4 and P6, presumably due to the smaller repeat lengths, which reduces the number of fluorescent probes that can bind to one transcript. As expected, no foci were detected in control pericytes (Figure 6; Figure S3). To verify MBNL1 protein accumulation in the (CUG)n RNA foci, we combined FISH with immunofluorescent detection of MBNL1. Nuclei in DM1 patient pericytes, but not controls, consistently showed focal accumulation of MBNL1 protein, which colocalized with (CUG)n RNA FISH foci (Figure 6). The number of MBNL1 foci counted per nucleus was slightly lower than the number of FISH foci, which is probably due to automated image analysis and thresholding.

**Characterization of Disease Biomarkers in DM1 Pericytes**

The DM1 mutation is an autosomal-dominant, unstable (CTG)n repeat in the 3′ untranslated region of DMPK. The repeat mutation ends up as a long (CUG)n stretch in pathogenic, expanded transcripts, which initiate a broad range of detrimental downstream effects. We investigated the expression of endogenous *Dmpk* and transgenic *DMPK* transcripts in pericytes from the DMSX1 line. *Dmpk* expression in proliferating pericytes was similar between cells isolated from WT, HET, and HOM mice, as well as DM500 myoblasts (Figure 4A). DM500 myoblasts are an immortalized cell lineage that was isolated earlier from the same transgenic mouse line, when the (CTG)n repeat still contained only ~500 triplets. No significant differences were found in *DMPK* (CTG)1300 transcript levels between HET and HOM pericytes, carrying one and two transgene copies, respectively. As expected, no *DMPK* expression was detected in WT pericytes (Figure 4B). *DMPK* expression in human pericytes was remarkably similar between patients and controls, and also comparable to that in human myoblasts (Figure 4C).

According to the RNA dominance theory, expression of *DMPK* RNA with abnormal repeat length may affect proper muscle development and have consequences for regenerative muscle capacity in adulthood. Both the timing and the level of expression of pathogenic repeats will influence the type and the extent of down-stream toxicity caused by for example RNP binding or RAN translation products. Pericytes isolated from HET and HOM DMSXL mice displayed expanded *DMPK* transcripts in the form of fluorescent in situ hybridization (FISH)-detectable RNP complexes in the nucleus, generally termed foci, after hybridization with a CAG repeat probe. The number of foci varied strongly between cells, but, on average, 1–2 foci per nucleus were present in pericytes from HET mice versus 5–10 foci in cells from HOM mice (Figure 5). Few foci were detected in some WT mouse cells, which has been reported before for myoblasts and may represent background staining recorded by the automated image analysis. Especially noticeable was the high variation in foci count per cell in pericytes from HOM animals, ranging between 0 and >25 per nucleus.

**DM1 Patient Pericytes Maintain Intrinsic Myogenic Potential**

To examine whether DM1 pericytes still contained intrinsic myogenic potential, we focused on the purified human cells, since isolated mouse pericytes need co-culture with a myogenic inducer cell line for myotube formation in vitro. Human pericytes were grown to confluency and then shifted to low-serum conditions to initiate myogenic commitment and fusion to myotubes (Table S1). *MHC* expression was used as a differentiation marker. Notably, we were able to obtain MHC+ fused and elongated myotubes from all control and patient pericyte populations. Up to 1.5-mm-long myotubes containing multiple nuclei were seen after keeping pericytes for 8 days under differentiation conditions (Figures 7A and 7B). Although strong variations between different isolates were observed, the differences in myogenic fusion efficiency could not be linked to disease state, sex, age of participant, or passage number of pericytes. Besides variations in fusion potential between individual cell cultures and...
separate experiments, diverse myotube morphologies were generally observed in all cultures. Roundish or elongated MHC+ mononuclear cells were visible (Figures 7C and 7D), and occasionally even mononucleated MHC+ cells with sarcomeric striations were seen (Figure 7E).

To quantify myogenic differentiation, we defined myotubes as MHC+ cells containing at least two nuclei (Figures 7F and 7G), and we determined the myogenic fusion index (MFI; 100 × the ratio of the number of nuclei inside MHC+ myotubes to the number of total nuclei), the number of nuclei per myotube, and the myotube width and length (Figures 7H–7K). The MFI was variable between cultures (average, 5.3% ± 4.4%), and also the number of nuclei per tube (3.6 ± 2.6) differed between donors. The myotube width and length were similar for all cultures (22.6 ± 8.5 μm and 422 ± 179 μm, respectively). However, under the conditions tested in this study, none of the four parameters showed a significant difference between control and patient pericyte populations, and therefore we conclude that DM1 pericytes still maintain normal, intrinsic myogenic capacity, independent of the disease state.

DISCUSSION

In this study, we generated explant cultures of skeletal muscle from DMSXL mice, DM1 patients, and unaffected controls. From these cultures, through a combination of FACS and immunocytochemistry, we purified and identified vessel-associated pericytes, a myogenic progenitor cell type that holds promise for cell-therapeutic purposes in muscular disorders. Mouse model and patient pericytes displayed typical DM1 disease characteristics, such as DMPK expression and nuclear repeat RNA foci, but still demonstrated great proliferative ability. We were able to show that, despite the presence of these disease biomarkers, human DM1 pericytes displayed normal myogenic capacity in vitro, which facilitates their therapeutic application.

In adult skeletal muscle, only vessels contain ALP+ cells.3,37 Since pericytes are ALP+ and endothelial cells are ALP−, we could isolate ALP+ cells with myogenic potential, while excluding myoblasts and satellite cells from our cultures.3,6 FACS sorting was validated via immunocytochemistry, by which we found around 1% ALP+ mouse cells in our primary cell isolates. Because we followed a strict sorting protocol, the actual percentage of sorted mouse ALP+ cells was lower. Similar numbers of ALP+ cells were isolated out of different amounts of skeletal muscle from WT, HET, and HOM DMSXL mice. Presumably, since pericytes are wrapped around blood vessels, the amount of skeletal muscle has no effect on the number of pericytes present in the tissue, but the number of blood vessels does. Because it has been reported that the vasculature between slow and fast fiber types differs in rats, with slow oxidative muscle possessing a more enriched capillary structure than the fast glycolytic muscle38, it would be interesting to investigate pericyte abundance within these tissues. We expect that our cell populations constitute a mix of pericytes originating from fast and slow muscle tissue in the gastrocnemius-plantaris-soleus biopsy. When translating to humans, the observation that comparable numbers of pericytes could be sorted from HOM mice and their WT littermates is promising for an autologous therapy for DM1 patients.

Six DM1 patients and two unaffected controls were included for isolation of human pericytes. No differences in the number of pericytes or in the proliferation capacity between sorted cells from DM1 patients and controls were found. The human pericytes were isolated from a
needle biopsy from the quadriiceps muscle, a relatively spared proximal muscle in DM1 that usually is involved only in later, more severe stages of the disease. We are unaware whether distal muscles marked by typical DM1-associated dystrophy show pericyte-related differences in abundance or proliferation capacity. Previous research showed a significant, 2-fold increase in the number of satellite cells in the distal tibialis anticus muscle compared to the proximal vastus lateralis muscle of the same DM1 patients. The satellite cells isolated from the distal muscles, however, had a reduced proliferative capacity due to the abnormal activation of the p16 stress pathway, related to premature senescence.

A comprehensive verification of cell identity, based on a combination of phenotypic markers, validated that we isolated and expanded authentic pericytes from both mouse and human muscle. Pericyte markers may be dynamic in their expression and can be upregulated or downregulated in conjunction with developmental states, pericyte maturity, pathological reactions, and in vitro culturing. We found α-Sma/α-SMA, Ng2/NG2, and Pdgfrβ/PDGFRβ to be consistently expressed, while the myogenic marker Mhc/MHC was absent.

The prenatal onset of congenital DM1 implies a pathogenic effect of expanded DMPK alleles early during embryonic development. Jansen et al. noticed that Dmpk expression could be detected as early as embryonic day 10.5, before commitment to specific muscle cell fate and onset of myogenesis. Expression of normal and expanded Dmpk/DMPK transcripts is generally low and occurs at an absolute number of only a few to a few dozen transcripts per cell. We found no obvious differences in expression of Dmpk/DMPK between pericytes from DMSXL genotypes nor in DMPK expression between pericytes from different patients with DM1 or unaffected controls. We did not separately quantify expanded DMPK transcripts from normal transcripts, but previous research has shown that both types of alleles contribute generally equally to DMPK RNA levels in human myoblast cultures and skeletal muscle from DM1 patients. Moreover, no evidence for a marked effect of repeat length on DMPK RNA expression level has been reported.

It is not surprising that pericytes isolated from both HET and HOM DMSXL mice showed pathogenic transcripts as FISH-detectable foci in the nucleus. Similarly, pericytes from DM1 patients with a repeat above 200 triplets showed on average one to two foci per nucleus. Noticeable is the high variation in foci count in pericytes from HOM animals, ranging from 0 to up to >25 per nucleus, but these numbers match our observations regarding DMPK expression and foci number in myoblasts from this transgenic mouse line. We have provided evidence that every RNP complex that forms a FISH-visible aggregate is nucleated by one or only few expanded (CUG)n transcripts. Due to inaccessibility of the transcripts to the probe or loss of RNA molecules from the fixed cells during washing, the actual number of RNP complexes in the nucleus may even be a bit higher. Due to technical differences between (CUG)n RNA FISH and immunofluorescence detection of MBNL1 protein, the quantification of MBNL1 foci resulted in lower foci number per nucleus. In all cases, however, (CUG)n RNA FISH foci colocalized with high concentrations of MBNL1 protein.

No major variations in myogenic capacity between pericytes from DM1 patients and unaffected controls were found. We were able to generate multinucleated MHC+ myotubes from all human pericyte populations. Sometimes cultures showed mononuclear MHC+ cells and myosacs, while others showed mainly textbook multinucleated and striated myotubes. We attribute these differences between cultures and experiments to subtle, not well-understood differences in culture conditions at the start of myogenic differentiation. For the quantification of MFI and myotube length and width, the presence

![Figure 4. Dmpk/DMPK Expression in Mouse and Human Pericytes](image)

qRT-PCR quantification of Dmpk and DMPK expression. Endogenous Dmpk (A) and transgenic DMPK (B) expression in pericytes from WT, HET, and HOM DMSXL mice. DMPK expression was significantly higher in HOM and HET pericytes compared to WT pericytes. Immortalized DM500 mouse myoblasts (MB) were included as reference (n = 2).***p < 0.0001. (C) DMPK expression in pericytes from unaffected controls and DM1 patients. Immortalized human DM1 myoblasts (MB) were included as reference (n = 1). Error bars indicate SEM.
of mononucleated MHC+ cells and myosacs could have a great influence on the outcome. For the length and width quantifications, all mononuclear cells were excluded. Thin MHC+ mononucleated cells, which may be regarded as incompletely differentiated and immature muscle fiber growth, affected MFI values.

Onset of disease and myopathy in DM1 are highly diverse, but clearly positively correlated with repeat length. We therefore expected the myogenic potential to decrease with an increased number of CTG triplets in DMPK. In fact, pericytes isolated from FSHD patients showed normal morphology and proliferation, but impaired differentiation correlated with overall disease severity. Even though many variables differ between individuals in our diverse cohort, DM1 disease status, age, and sex did not influence isolation, proliferation, or differentiation abilities of pericytes. The observed variation in MFI might be partly explained by the genetic background of the individuals, but it is also regularly observed in the formation of myotubes from myoblasts.

To obtain an even higher, and possibly more continuous, differentiation efficiency, pericytes can be exposed to a "myogenic environment," e.g., co-culture with murine myoblasts or direct re-programming by overexpression of selected transcription factors such as MYOD. With MYOD induction, cells are pushed toward myogenic lineage and therefore exhibit an increased myogenic ability. However, this behavior does not necessarily correspond to normal fate during unperturbed development and regeneration. Results from the present study show the innate myogenic ability of primary pericytes from DM1 patients.

The promise of pericytes for cellular therapy in muscular dystrophies is mainly due to the widespread distribution of these cells through the capillary network, a distinct advantage over previous cell-based approaches. For example, pericytes that express a missing protein (dystrophin in DMD) or lack the RNA gain-of-function mutation (repeat expansion in DM1) may be systemically administered. Autologous pericytes can infiltrate multiple target tissues from the circulation in response to cytokines released by dystrophic muscle. In the dystrophic target tissue, the healthy pericytes can replenish the progenitor pool and from then on efficiently differentiate toward the myogenic lineage and contribute to muscle regeneration by formation of healthy postmitotic myofibers. We were able to culture pericytes for up to 20 passages. Using in vitro expansion, we will be able to obtain $8.8 \times 10^{16}$ cells from approximately $8 \times 10^{4}$ culture-initiating cells, a promising number for future therapeutic applications when compared on a per kilogram comparison with previously used animal models.

So far, research on the presence and potential of pericytes in DM1 was missing. Several successful attempts to treat other muscular dystrophies with vessel-associated pericytes in mice models have been performed. A translational study in a dog model of DMD myopathy showed "a remarkable clinical amelioration and preservation of active motility." The first exploratory clinical trial for DMD investigated the safety of intra-arterial transplantation of HLA-matched donor...
Based on the results presented herein, we will now work toward autologous and possibly genetically edited pericytes that can systemically be applied, renew the progenitor cell pool, and fuse with existing myotubes to form regenerating fibers, thereby preventing or relieving muscle symptoms in patients with DM1.

**MATERIALS AND METHODS**

**Ethics Statement**
Animal experiments were approved by the Animal Ethics Committee of Radboud University (permit no. RU-DEC 2016-0049). The human biopsy procedure including the cell culture protocol was approved by the local Committee on Research Involving Human Subjects (CMO 2016-0049). Informed consent to participate in our study was obtained from all participants. No adverse events following the biopsy procedure were reported.

**DMSXL Mice**
DMSXL mice (C57BL/6 background) used in this study carry a 45-kb genomic fragment encompassing the DM1 locus of a patient, including a (CTG)1300 repeat.28,29,56 Mouse number 4, 5, 11, and 12 were females; all others were males. Transgenic status was assessed by PCR on ear punch DNA. The DMSXL phenotype includes reduced muscle strength, lower motor performances, and respiratory impairment, which is essentially only apparent in HOM mice. On the molecular level, weak splicing abnormalities and RNA foci are present in skeletal muscle from HOM mice.30,57

**Human Participants**
DM1 patients and unaffected controls visited Radboudumc (Nijmegen, the Netherlands) where a skeletal muscle biopsy was taken from the quadriceps femoris (vastus lateralis) using a Bergström needle.58 Specifications of the eight participants can be found in Table 1. MIRS was the latest score of clinical evaluation.31 (CTG)n repeat length was determined in blood DNA at diagnosis of the disease.

**Cell Culture Media**
Aliquots of 80 mL fetal calf serum (FCS, Sigma-Aldrich) were heat-inactivated in a water bath at 56°C for 40 min. Horse serum (HS, Sigma-Aldrich) was aliquoted into 10 mL and heat-inactivated at 56°C for 30 min. Proliferation medium for mouse pericytes (DMEM20) was made by combining DMEM (AQmedia, Sigma-Aldrich) with 20% heat-inactivated FCS, 50 IU/mL penicillin, 0.05 mg/mL streptomycin (Sigma-Aldrich), 10 mM nonessential amino acids (Sigma-Aldrich), 1 mM sodium pyruvate, and 50 mM β-mercaptoethanol (Gibco) over a 0.22-μm filter. Proliferation medium for human pericytes (DMEM5) has a similar composition but without sodium pyruvate, only 5% heat-inactivated FCS, and an additional 5 ng/mL human basic fibroblast growth factor (Sigma-Aldrich). Differentiation medium contained DMEM with 2% heat-inactivated horse serum, 50 IU/mL penicillin, 0.05 mg/mL streptomycin, and 1 mM sodium pyruvate. Coating of cell culture surfaces was performed with collagen from calf skin (Sigma-Aldrich) at 1 mg/mL dissolved in 20% glacial acetic acid. Then, 1 mg/mL collagen (20% glacial acid) was applied to the surface and left for at least 15 min at room temperature. The solution was removed and the collagen-coated wells and/or flasks were transferred to a dedicated 30°C oven to dry the surface for 24 h. The next day, the surface was washed twice with 1× PBS and once with a medium containing phenol red to ensure no glacial acid was left behind.
Human and Mouse Explant Cultures
DMSXL mice were euthanized via CO₂ and weighed. Skeletal muscles of both hind limbs (GPS complex [gastrocnemius-plantaris-soleus complex]) of 4- to 5-week-old mice were dissected, weighed, and collected in DMEM20 with as little manipulations as possible to increase the yield of cells. Tissue from human participants was collected in 1/2 PBS on ice. For both mouse and human skeletal muscle biopsies, the following procedures were performed in a laminar flow hood. Muscle tissue was transferred into a 10-cm dish containing the appropriate medium. Any residues of fat or tendon were carefully removed while the tissue was dissected into ~2-mm³ fragments with a sterile round-shaped scalpel. For human material, around half of the muscle biopsy already consisted of small fragments due to the collection procedure. To avoid contamination with blood as much as possible, tissue fragments were washed repeatedly with 1/2 PBS. Around 12 muscle fragments were then placed per well in a collagen coated six-well plate. To ensure maximal yield, the muscle fragments were distributed over the surface of the well. 200 µL of prewarmed DMEM5 (human explant) or DMEM20 (mouse explant) was placed on top of all fragments in one well, and an additional 400 µL was

Figure 7. Myogenic Potential of DM1 Patient and Control Pericytes
Human pericytes were cultured under low-serum conditions and stained for differentiation marker MHC (green) and DNA (blue). Overview of a relatively efficient (A) and inefficient (B) differentiation culture. Scale bar in (A) and (B), 500 µm. (C–G) Typical cell morphologies and features that were observed in the cultures: roundish (C) and elongated (D) mononuclear cells; mononuclear cells with typical striated sarcomeric features (E); long multinucleated myotube (F); multinucleated myosac (G). Scale bar in (C)–(G), 100 µm. Differentiation cultures of each pericyte isolation were separately analyzed for MFI (H), number of nuclei per myotube (I), myotube width (J), and myotube length (K). Each data point represents the average MFI per culture (n = 4) (H), the number of nuclei per one myotube (n = 2–35) (I), width of one myotube (n = 2–38) (J), and the length (n = 3–37) (K). Bars indicate median with interquartile range.
滴加至六孔板。MQ（MilliQ超纯水）被添加到芽的顶部以保持一个湿润的环境，并且要保持液体从干燥的顶部到芽的底部分离。芽被置于37°C下18-24小时，在5% CO2/5% O2的孵育箱中。第二天，1.5mL预加热的DMEM20或DMEM5培养基将被添加到侧边以防止芽的脱落。芽的培养物在2-3天内被分离。剩下的细胞因芽的芽点被分离，接着被细胞分选。细胞通常被圆润、小，并且附着在芽的表面。分选后4-5天对于小鼠芽的，脉络的生长是可见的，并且在分选300μL预加热的DMEM20或DMEM5培养基的后，细胞的生长将被检测到。脉络的生长从芽的生长中分离出来。6-7天后对于小鼠芽的，1cm的脉络生长在所有细胞在所有细胞中被检测到，且在表面至少几乎每一个细胞被生长在培养基中。细胞被通过胰烟酸分选以FACS。

FACS

移液管和收获的细胞被收集并过一个70-μm的细胞分离器以将细胞从芽中分离。细胞被收集且之后被在200μL的培养基中稀释，在室温下，HBSS Ca2⁺ Mg2⁺（Sigma-Aldrich）被补充有2%的热灭活的FCS和10mM Hepes（Sigma-Aldrich）。标记物的标记物被使用pH值为4.5的Cytofix/Cytoperm（BD Biosciences）来固定细胞。标记物的细胞在4°C的冰箱中过夜。在计数前，细胞被洗涤3次。为脉络的标记，对细胞的细胞分选被做。脉络从芽的芽点，被称为脉络的细胞。细胞最初被观察到是圆润和小，并且附着于芽的表面。之后4-5天对于小鼠芽的，脉络的生长是可见的，并且一个额外的500μL预加热的DMEM20或DMEM5培养基被添加到侧边。脉络的生长从芽的生长中分离出来。之后的6-7天对于小鼠芽的，1cm的脉络生长在所有细胞在所有细胞中被检测到，且在表面至少几乎每一个细胞被生长在培养基中。细胞被通过胰烟酸分选以FACS。

Characterization of Pericytes

细胞被置于玻璃盖玻片上并用豚鼠皮肤天然胶原蛋白被覆盖。覆盖的细胞被洗涤与1×PBS，20,000-15,000细胞/cm²被洗涤。之后，细胞被洗涤与1×PBS在室温下。标记物的标记物的细胞被固定并被在2%的paraformaldehyde (PFA)在0.1M磷酸缓冲液（pH7.4）中15分钟。对免疫检测，将NG2（ab129051, Abcam），α-SMA（ab7817, Abcam）和MHC（MF20 DSHB，University of Iowa）的细胞被固定以4%PFA。在5% CO2/5% O2的二氧化碳中。为脉络的标记，脉络的细胞和细胞发生器被收集和放在细胞分选器中。隔天后，细胞被洗涤三次。为脉络的标记，对细胞的细胞分选被做。脉络从芽的芽点，被称为脉络的细胞。细胞最初被观察到是圆润和小，并且附着于芽的表面。之后4-5天对于小鼠芽的，脉络的生长是可见的，并且一个额外的500μL预加热的DMEM20或DMEM5培养基被添加到侧边。脉络的生长从芽的生长中分离出来。之后的6-7天对于小鼠芽的，1cm的脉络生长在所有细胞在所有细胞中被检测到，且在表面至少几乎每一个细胞被生长在培养基中。细胞被通过胰烟酸分选以FACS。

Analysis of Myotube Characteristics and Image Analysis

在培养基中去除了90%的肌肉碎片。我的天线性通过MHC标记，30,000脉络被培养在有1mg/mL的胶原蛋白在20%的乳酸酸的8- wells ibidi细胞培养中。为评估肌肉的去分化能力，30,000个脉络被用在含1% Triton X-100 [Sigma-Aldrich]，4%正常山羊血清[NGS, Sigma-Aldrich]和0.1% BSA [Sigma-Aldrich]的1×PBS中60分钟。标记物的标记物的细胞被固定并被在2%的paraformaldehyde (PFA)在0.1M磷酸缓冲液（pH7.4）中15分钟。在培养基中，细胞被洗涤1×PBS和标记物被4μg/mL的anti-mouse Alexa Fluor 568或anti-rabbit Alexa Fluor 488（Thermo Fisher）和100ng/mL 4,6-diamidino-2-phenylindole (DAPI)（Sigma-Aldrich）在阻断缓冲液中60分钟。细胞被洗涤以1×PBS和被放在在滑上。标记物的标记物的细胞被通过一个Leica DM6000B显微镜用一个x63倍镜被获得。

FiJi软件[Image] v1.52d)被使用分析肌肉的形成。我的天线性通过MHC标记，30,000个脉络被培养在含1mg/mL的胶原蛋白在20%的乳酸酸的8-wells ibidi细胞培养中。我的天线性通过MHC标记，30,000个脉络被培养在含1% Triton X-100 [Sigma-Aldrich]，4%正常山羊血清[NGS, Sigma-Aldrich]和0.1% BSA [Sigma-Aldrich]的1×PBS中60分钟。标记物的标记物的细胞被固定并被在2%的paraformaldehyde (PFA)在0.1M磷酸缓冲液（pH7.4）中15分钟。在培养基中，细胞被洗涤1×PBS和标记物被4μg/mL的anti-mouse Alexa Fluor 568或anti-rabbit Alexa Fluor 488（Thermo Fisher）和100ng/mL 4,6-diamidino-2-phenylindole (DAPI)（Sigma-Aldrich）在阻断缓冲液中60分钟。细胞被洗涤以1×PBS和被放在在滑上。标记物的标记物的细胞被通过一个Leica DM6000B显微镜用一个x63倍镜被获得。
qRT-PCR
In human samples, DMPK expression levels were determined at passage 8. To quantify expression levels in cells from WT, HET, and HOM DMSXL mice, qRT-PCR was performed in three biological replicates (three mice per genotype) and two technical replicates. Cell pellets of passage 5–7 were collected and stored in 350 μL of RA1 lysis buffer (Macherey-Nagel NucleoSpin RNA, lot no. 75858). RNA isolation for all samples was performed using the NucleoSpin RNA isolation kit (Macherey-Nagel) according to the manufacturer’s protocol. Next, cDNA synthesis with random hexamers from the iScript cDNA synthesis kit (Bio-Rad Laboratories) was performed using 2 μg of RNA as a template in a reaction volume of 40 μL. For qRT-PCR, cDNA was diluted 40×. The cDNA sample was mixed in a final volume of 25 μL containing GoTaq qPCR Master Mix, distilled H2O, and 0.4 pmol of each primer. Samples were analyzed using the 7900HT Fast Real-Time PCR System (Thermo Fisher). RT minus and no-template control were included as negative controls. A DMS500 myoblast RNA sample17 was included as a positive control for analysis of DMPK expression, while DM11 cells50 were included as a reference for DMPK expression. Gene-of-interest levels were normalized to Gapdh and Hprt1 levels for mouse pericytes. TBP and HPRT1 were included as reference genes for human pericytes.

PCR primers used were as follows: Gapdh e2–e3, 5'-GAGCCTGTTGAAATATCGC-3' and 5'-TTTTGGTCAAAATGACG-3'; Hprt1 e6–e7, 5'-GACATCGTTAAAAACTGC-3' and 5'-CTGTTATCCACACTTTCGAG-3'; Dmpk e2–e3, 5'-TTTTGTGAAGGTGATTCA-3' and 5'-CTGTGCCGCAGTGATCCATTA-3'; DMPK e15-3', 5'-TGCTCCTCTCTCACTGCACTA-3' and 5'-GAGCAAGCTGAGCTCA-3'; TBP e3, 5'-CTGCTTCTCACTGCACTA-3' and 5'-CTGTCAGCAAGCTCA-3'; TBP e2, 5'-CTGCTTCTCACTGCACTA-3' and 5'-CTGTCAGCAAGCTCA-3'; TBP e3, 5'-CTGCTTCTCACTGCACTA-3' and 5'-CTGTCAGCAAGCTCA-3'; TBP e2, 5'-CTGCTTCTCACTGCACTA-3' and 5'-CTGTCAGCAAGCTCA-3'.

RNA FISH and Image Analysis
Mouse and human pericytes were grown on coverslips, which were prepared as described above. The cells were fixed in 350 μL of 4% PFA for 10 min RT. Samples were then incubated overnight at 4°C in the same buffer containing 1:10 diluted anti-MBN1 antibody, MB1a (4A8; DSHB, University of Iowa). The next day, samples were washed three times for 5 min with 1× PBS and incubated with 4 mg/mL goat anti-mouse Alexa Fluor 488 (Thermo Fisher) and 100 ng/mL DAPI in blocking buffer for 1 h at room temperature in the dark. Finally, coverslips were washed with PBS, Milli-Q, and 70% and 100% ethanol and mounted with Mowiol 4-88 (Sigma-Aldrich). Images from the Zeiss LSM880 with Airyscan were analyzed using Fiji software. Nuclear masks were created using Isodata auto-threshold followed by a watershed and particle analysis (“size=1000-Infinity pixel” for the FISH only and “size=500-Infinity pixel” for the FISH-MBN1 analysis). Within the nuclear selection, the “spot counter” in Fiji was applied using a noise tolerance of 50 for FISH only and a noise tolerance of 120 for the FISH-MBN1 analysis. Using the nuclear masks, the positive pixels representing the foci in each nucleus were counted. For MBNL1 co-localization, a region of interest (ROI) was established around each FISH focus. The signal outside was cleared, and only the ROI with a FISH focus and MBNL1 signal were quantified using the macros “find maxima single point” and “spot counter.”

SUPPLEMENTAL INFORMATION
Supplemental Information can be found online at 10.1016/j.omtm.2019.09.002.

AUTHOR CONTRIBUTIONS

CONFLICTS OF INTEREST
The authors declare no competing interests.
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