

# Myotonic Dystrophy Protein Kinase is Involved in the Modulation of the $\text{Ca}^{2+}$ Homeostasis in Skeletal Muscle Cells

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## Abstract

Myotonic dystrophy (DM), the most prevalent muscular disorder in adults, is caused by  $(\text{CTG})_n$ -repeat expansion in a gene encoding a protein kinase (DM protein kinase; DMPK) and involves changes in cytoarchitecture and ion homeostasis. To obtain clues to the normal biological role of DMPK in cellular ion homeostasis, we have compared the resting  $[\text{Ca}^{2+}]_i$ , the amplitude and shape of depolarization-induced  $\text{Ca}^{2+}$  transients, and the content of ATP-driven ion pumps in cultured skeletal muscle cells of wild-type and DMPK $[-/-]$  knockout mice.

In vitro-differentiated DMPK $[-/-]$  myotubes exhibit a higher resting  $[\text{Ca}^{2+}]_i$  than do wild-type myotubes because of an altered open probability of voltage-dependent L-type  $\text{Ca}^{2+}$  and  $\text{Na}^+$  channels. The mutant myotubes exhibit smaller and slower  $\text{Ca}^{2+}$  responses upon triggering by acetylcholine or high external  $\text{K}^+$ . In addition, we observed that these  $\text{Ca}^{2+}$  transients partially result from an influx of extracellular  $\text{Ca}^{2+}$  through the L-type  $\text{Ca}^{2+}$  channel. Neither the content nor the activity of  $\text{Na}^+/\text{K}^+$  ATPase and sarcoplasmic reticulum  $\text{Ca}^{2+}$ -ATPase are affected by DMPK absence.

In conclusion, our data suggest that DMPK is involved in modulating the initial events of excitation-contraction coupling in skeletal muscle. (*J. Clin. Invest.* 1997; 100:1440–1447.) Key words: excitation-contraction coupling • ion channels • ion pumps • knockout mouse • cultured myotubes

## Introduction

Myotonic dystrophy (DM)<sup>1</sup> follows an autosomal dominant inheritance, and is characterized by a wide variety of symptoms, including increased excitability and delayed relaxation of muscle, muscle weakness and wasting, ocular cataract, sensorineu-

ral deafness, cardiac conduction defects, hypersomnia, testicular atrophy causing male sterility, and endocrine dysfunction (1). Clinical manifestation of this rather frequent disorder is caused by expansion of an unstable CTG-repeat in the 3'-untranslated region of a gene encoding the myotonic dystrophy protein kinase (DMPK), with the age of onset and the severity of the disease being correlated to the extent of expansion (2–4).

Contradictory results have been obtained with regard to the effects of abnormally long CTG repeats on DMPK mRNA and protein levels in patient tissues (5–8). In addition, the study of transgenic mouse models with altered DMPK levels (9, 10) has not provided the answer on the question whether over- or underexpression of this protein is involved in disease etiology. Homozygous DMPK $[-/-]$  mice exhibit only minor changes in neck muscle fibres at older age, whereas animals carrying multiple copies of the DMPK transgene show hypertrophic cardiomyopathy and enhanced neonatal mortality as the only features.

Typically, muscle fibers and/or cultured skeletal muscle cells of DM patients exhibit a decreased resting membrane potential (11–13) and increased basal cytosolic  $\text{Na}^+$  and  $\text{Ca}^{2+}$  concentrations (14–16). These features may be attributed to anomalies in the functioning of voltage-operated  $\text{Na}^+$  channels (17, 18) and  $\text{Ca}^{2+}$  channels (15, 16) and/or to a reduced content of  $\text{Na}^+/\text{K}^+$ -ATPase and sarcoplasmic reticulum (SR)  $\text{Ca}^{2+}$ -ATPase (19, 20). In addition, the persistence of an apamin-receptor, i.e.  $\text{Ca}^{2+}$ -activated  $\text{K}^+$  channel, has been demonstrated (21).

Many of these ion channels and ion pumps are key players in the excitation-contraction (E-C) coupling mechanism of skeletal muscle in vivo, a cascade of events in which, sequentially, acetylcholine receptors (AChR) of the neuromuscular junction, sarcolemmal tetrodotoxin-sensitive voltage-operated  $\text{Na}^+$  channels (TTXR), T-tubular dihydropyridine receptors (DHPR), and finally ryanodine receptors (RyR), i.e.  $\text{Ca}^{2+}$  release channels in the terminal cisternae of the SR, are involved (22). E-C coupling of vertebrate skeletal muscle is thought to occur by a mechanical coupling, in which intramembrane charge movements and associated conformational changes of the voltage-sensing DHPR activate the RyR without entry of external  $\text{Ca}^{2+}$  through DHPR (23–25). Before relaxation, the disturbed ion concentrations are restored to resting levels by ATP-driven ion pumps, i.e.,  $\text{Na}^+/\text{K}^+$ -ATPase and SR  $\text{Ca}^{2+}$ -ATPase.

This whole process is subject to complex regulation in which local luminal and cytosolic  $\text{Ca}^{2+}$  and ATP levels are in-

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1. Abbreviations used in this paper: ACh(R), acetylcholine (receptor); DHPR, dihydropyridine receptor; DM, myotonic dystrophy; DMPK, myotonic dystrophy protein kinase; E-C, excitation-contraction; RyR, ryanodine receptor; SR, sarcoplasmic reticulum; TTX(R), tetrodotoxin (receptor);  $\tau_d$ , half-decay time;  $\tau_i$ , half-increase time; 3-O-MFPase, 3-O-methylfluorescein phosphatase.

volved. It is also influenced by protein phosphorylation and ion channel-modulating proteins like FK506, triadin, or calsequestrin. Since dysregulation of ion fluxes is a likely determining factor in the abnormal cellular functions in DM, and since DMPK-mediated protein phosphorylation could play a role, we examined if and how DMPK deficiency affects the depolarization behavior and  $\text{Ca}^{2+}$  homeostasis in cultured skeletal muscle cells in the absence or presence of specific inhibitors of the voltage-operated ion channels or the SR  $\text{Ca}^{2+}$  release channel. We also determined the activity and content of SR  $\text{Ca}^{2+}$ -ATPase and  $\text{Na}^+/\text{K}^+$ -ATPase in cultured muscle cells and skeletal muscle of wild-type and DMPK $[-/-]$  mice. Although the morphological and physiological effects of DMPK absence at the animal level are surprisingly mild, we demonstrate here, that DMPK deficiency has conspicuous consequences at the cellular level. Our finding of abnormally operating TTXRs and DHPRs gives evidence for a relation between DMPK activity and ion homeostasis in skeletal muscle.

## Methods

**Materials.** The acetoxymethyl ester of Fura-2 (Fura-2/AM) was purchased from Molecular Probes Europe (Leiden, The Netherlands); acetylcholine chloride (ACh), tetrodotoxin (TTX), ryanodine and ionomycin were from Sigma (St. Louis, MO, USA); and nifedipine from Bayer (Leverkusen, Germany). Sources of other materials were described previously (20, 26).

**DMPK-deficient mice.** Homozygous DMPK-deficient (DMPK $[-/-]$ ) mice were generated by targeted mutagenesis and genotyped by PCR analysis as described (9). DMPK $[-/-]$  animals from the F3 generation (on a mixed C57BL/6  $\times$  129/OLA 50-50% background) were used. Wild-type animals from the C57BL/6 inbred strain, and from a colony with a C57BL/6  $\times$  129/OLA mixed background were taken as controls.

**Cytosolic  $\text{Ca}^{2+}$  concentration measurement in cultured skeletal muscle cells.** Hind leg muscles of 3–10-d-old wild-type and DMPK $[-/-]$  mice were dissociated, and the isolated satellite cells were allowed to proliferate for 2 d, and were then cultured under differentiation-promoting conditions for 4 d on collagen-coated glass coverslips ( $\phi$  25 mm) in serum-containing media, as described for human muscle cells (26). The free cytosolic  $\text{Ca}^{2+}$  concentration ( $[\text{Ca}^{2+}]_i$ ) and the effects of depolarization induced by the addition of 20  $\mu\text{M}$  ACh or 125 mM KCl on  $[\text{Ca}^{2+}]_i$  were measured in single cells with Fura-2 using conventional fluorescence video microscopy (26). For calibration,  $\text{Ca}^{2+}$ -saturated or  $\text{Ca}^{2+}$ -free dye was set by 2  $\mu\text{M}$  ionomycin in the presence of 1.8 mM  $\text{Ca}^{2+}$  (pH 7.5) or 20 mM EGTA (pH 8.0), respectively. Under these conditions the myotubes remain attached to the coverslip. Although the calibration parameters of wild-type and DMPK $[-/-]$  skeletal muscle cells did not differ significantly, we used these parameters strictly separated for calculation of  $[\text{Ca}^{2+}]_i$  to rule out cell-type-dependent artefacts (27). The half-increase ( $\tau_i$ ) and half-decay time ( $\tau_d$ ) of the depolarization-triggered  $\text{Ca}^{2+}$  responses were analyzed as described (26, 28).

**SR  $\text{Ca}^{2+}$ -ATPase and  $\text{Na}^+/\text{K}^+$ -ATPase.** The activity and concentration of SR  $\text{Ca}^{2+}$ -ATPase were examined in homogenates of cultured muscle cells (differentiated for 4 d) and hind leg skeletal muscle of adult mice by measuring  $\text{Ca}^{2+}$ -dependent ATP hydrolysis and steady-state phosphorylation, respectively (20). The activity of  $\text{Na}^+/\text{K}^+$ -ATPase was assayed as the  $\text{K}^+$ -dependent, ouabain-sensitive 3-*O*-methylfluorescein phosphatase (3-*O*-MFPase) activity and the content of  $\text{Na}^+/\text{K}^+$ -ATPase was derived from the binding capacity of [ $^3\text{H}$ ]ouabain (20).

**Other procedures.** Creatine kinase (CK) activity of cultured muscle cells (differentiated for 4 d) was determined with the CK *N*-acetylcysteine-activated monotest (26). For determining the percentage CK muscle-specific isoenzyme MM (CK-MM), this isoenzyme was

separated from the other CK isoenzymes by gel electrophoresis (29). The protein content was assayed according to Lowry et al. (30) with BSA as a standard.

**Statistics.** Data represent means  $\pm$  SD. Statistical analysis was performed by means of the unpaired Student's *t* test, and significance was set at  $P < 0.05$ .

## Results

**General characteristics of cultured wild-type and DMPK $[-/-]$  skeletal muscle cells.** Upon differentiation, in vitro skeletal muscle cells derived from wild-type and DMPK-deficient mice exhibit a similar morphological appearance. Typically, the diameter of these cells is  $\sim 10$ – $20 \mu\text{m}$ , whereas their length varies between 500 and 700  $\mu\text{m}$ . Also, the total CK activity of wild-type ( $1.93 \pm 0.59$  U/mg protein;  $n = 11$ ) and mutant cells ( $1.84 \pm 0.84$  U/mg protein;  $n = 5$ ) and the percentage of CK-MM, a measure for the overall maturation grade, are the same for both cell types (wild-type:  $33.8 \pm 10.1$ ;  $n = 11$ , and DMPK $[-/-]$ :  $37.1 \pm 5.8$ ;  $n = 5$ ). Spontaneous contractions of wild-type and DMPK $[-/-]$  myotubes are occasionally observed in culture, and occurred frequently upon agonist-induced depolarization in both cell types.

**$\text{Ca}^{2+}$  homeostasis of wild-type skeletal muscle cells.** The resting  $[\text{Ca}^{2+}]_i$  of differentiated wild-type mouse skeletal muscle cells in culture is 120 nM (Table I). Depolarization of the sarcolemma of these cells either by 20  $\mu\text{M}$  ACh or by 125 mM KCl, induces  $\text{Ca}^{2+}$  transients with an amplitude ( $[\text{Ca}^{2+}]_{i,\text{max}}$ ) of  $\sim 0.8 \mu\text{M}$  (Fig. 1) and a  $\tau_i$  and  $\tau_d$  of  $\sim 3$  and 5 s, respectively. The provoked  $\text{Ca}^{2+}$  responses are completely prevented by inhibition of the SR  $\text{Ca}^{2+}$  release channel (RyR) using 10  $\mu\text{M}$  ryanodine (Fig. 2, B and C). Thus,  $\text{Ca}^{2+}$  release from the SR is entirely responsible for the increase of the  $[\text{Ca}^{2+}]_i$ , indicating that the wild-type myotubes possess a skeletal muscle type of E-C coupling mechanism (28, 31). As anticipated, also nifedipine (5  $\mu\text{M}$ ), a blocker of DHPR, impedes the depolarization-induced  $\text{Ca}^{2+}$  transients (Fig. 3, B and C). Inhibition of TTXR by 5  $\mu\text{M}$  tetrodotoxin only partially suppresses depolarization by ACh (Fig. 4 B). This inhibition is incomplete due to the coexistence of TTX-sensitive and TTX-resistant volt-

**Table I.  $\text{Ca}^{2+}$  Transients Induced by ACh or KCl in Cultured Skeletal Muscle Cells From Wild-type and DMPK $[-/-]$  Mice**

Stimulus	Parameter	Wild-type	DMPK $[-/-]$
None	$[\text{Ca}^{2+}]_{i,\text{basal}}$	$122 \pm 17$ (170)	$185 \pm 24^*$ (63)
20 $\mu\text{M}$ ACh	$[\text{Ca}^{2+}]_{i,\text{max}}$	$775 \pm 131$	$511 \pm 124^*$
	$\tau_i$	$3.0 \pm 0.6$	$6.6 \pm 1.9^*$
	$\tau_d$	$4.6 \pm 0.8$ (84)	$8.4 \pm 2.1^*$ (38)
125 mM KCl	$[\text{Ca}^{2+}]_{i,\text{max}}$	$881 \pm 164$	$552 \pm 130^*$
	$\tau_i$	$3.2 \pm 0.7$	$6.1 \pm 1.7^*$
	$\tau_d$	$4.8 \pm 0.7$ (86)	$7.9 \pm 2.8^*$ (25)

Values are means  $\pm$  SD of the number of muscle cells examined (listed between parentheses) from at least four individual cultures. The values of  $[\text{Ca}^{2+}]_i$  are expressed in nM, and the half-increase ( $\tau_i$ ) or half-decay time ( $\tau_d$ ) in s. Parameters of DMPK $[-/-]$  and wild-type cells differ with  $^*P < 0.01$ .

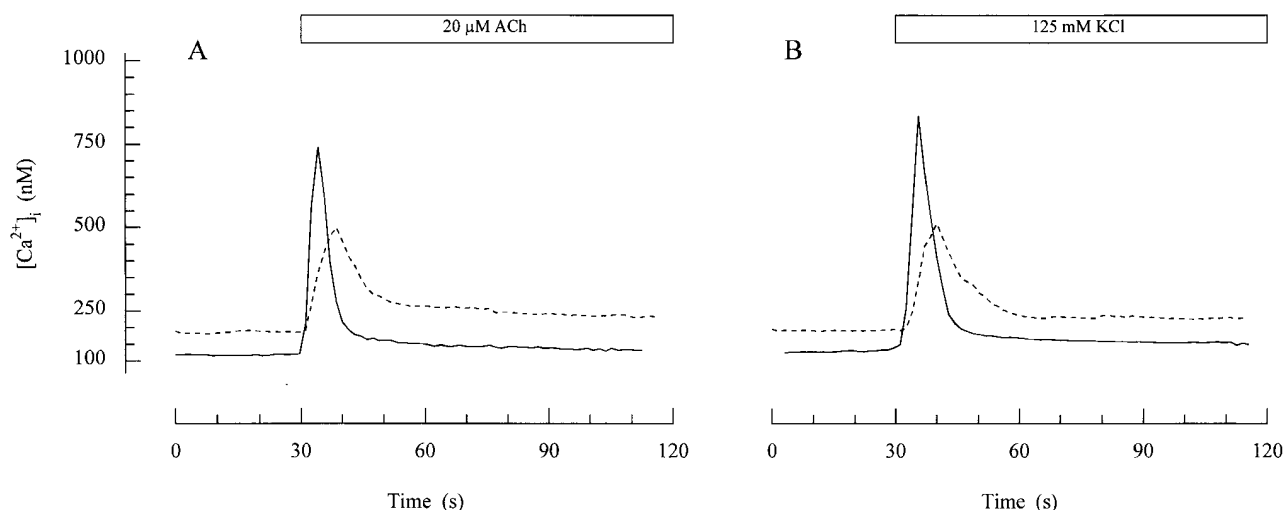


Figure 1. Depolarization-induced  $\text{Ca}^{2+}$  transients in cultured skeletal muscle cells derived from wild-type (solid line) and DMPK $[-/-]$  mice (dashed line). Depolarization was generated by 20  $\mu\text{M}$  ACh (A) or 125 mM KCl (B) as marked by the bars. Traces show the average  $[\text{Ca}^{2+}]_i$  after superimposing all appropriate experiments as listed in Table I.

age-operated  $\text{Na}^+$  channels in cultured skeletal muscle cells (28, 32). The  $\text{K}^+$ -triggered  $\text{Ca}^{2+}$  transients are not affected by tetrodotoxin (Fig. 4 C), as expected. It is important to note that neither of the three inhibitors have any effect on the resting  $[\text{Ca}^{2+}]_i$  (Figs. 2 A, 3 A, and 4 A).

Depolarization of the cultured muscle cells in the absence of extracellular  $\text{Ca}^{2+}$  could not be performed, since the omission of external  $\text{Ca}^{2+}$  before depolarization provokes a  $\text{Ca}^{2+}$  transient (data not shown). As a result, the SR becomes at least partially depleted for  $\text{Ca}^{2+}$ , which in turn can affect the kinetics of the SR  $\text{Ca}^{2+}$  release channel (33). In addition, the DHPR may become inactivatable due to a loss in occupancy of its priming site (23, 25).

**$\text{Ca}^{2+}$  homeostasis of DMPK $[-/-]$  skeletal muscle cells.** Surprisingly, the resting  $[\text{Ca}^{2+}]_i$  (185 nM) of DMPK $[-/-]$  skeletal muscle cells in culture is significantly higher than in wild-type cells (Table I, Fig. 1). Ryanodine does not affect this elevated level (Fig. 2 A), but nifedipine and tetrodotoxin normalize the increased resting  $[\text{Ca}^{2+}]_i$  completely or partially, re-

spectively (Figs. 3 A and 4 A). This means that DHPRs and TTXRs are constitutively open in resting mutant skeletal muscle cells, unlike in wild-type cells. Strikingly, the amplitudes of the  $\text{Ca}^{2+}$  responses provoked by depolarization with ACh or KCl are reduced by about 40%, whereas  $\tau_i$  and  $\tau_d$  are increased 2- and 1.6-fold, respectively (Fig. 1). We observed that ryanodine reduces the depolarization-induced  $\text{Ca}^{2+}$  responses in DMPK $[-/-]$  cells by only 90% (Fig. 2, B and C), whereas complete blocking is achieved with nifedipine (Fig. 3, B and C). This observation indicates that the  $\text{Ca}^{2+}$  transients in these cells partially result from an influx of extracellular  $\text{Ca}^{2+}$  through the DHPRs. Tetrodotoxin incompletely inhibits ACh-evoked  $\text{Ca}^{2+}$  transients like in wild-type cells (Fig. 4 B). After inhibition of TTXR by tetrodotoxin, when the basal  $[\text{Ca}^{2+}]_i$  in DMPK $[-/-]$  cells has become lowered, the KCl-generated  $\text{Ca}^{2+}$  responses are both higher and faster than in the absence of tetrodotoxin. The average amplitude of the  $\text{Ca}^{2+}$  transients raises  $\sim 140\%$  and  $\tau_i$  and  $\tau_d$  are reduced 1.5- and 1.6-fold, respectively, and become similar to the values in wild-type cells

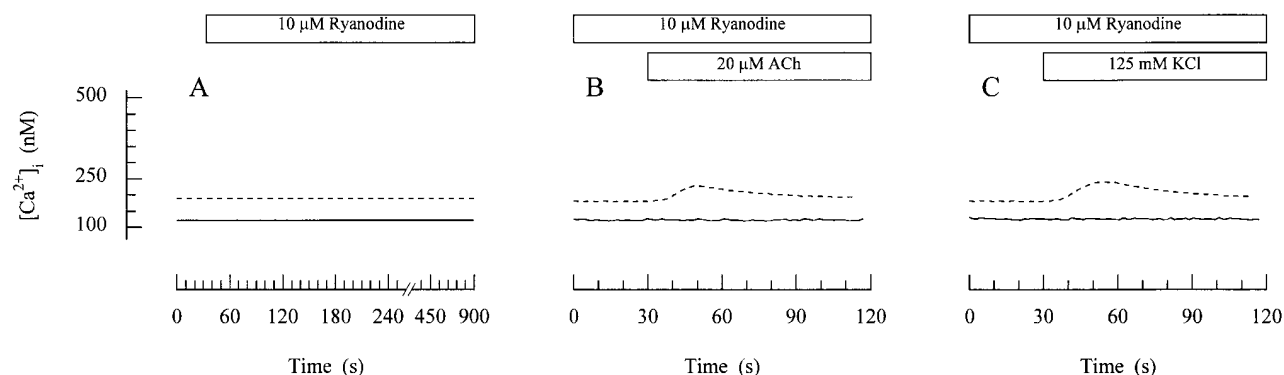
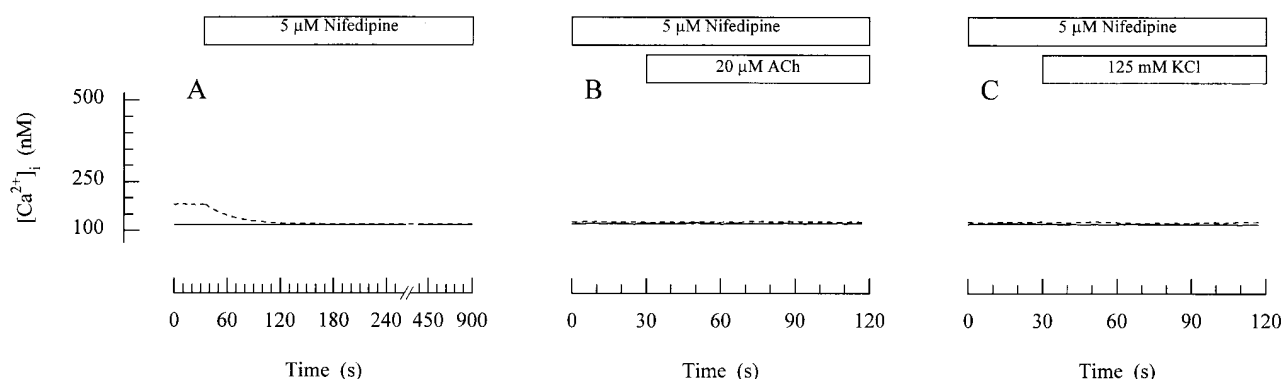


Figure 2. Effects of ryanodine on resting  $[\text{Ca}^{2+}]_i$  (A) and depolarization-provoked  $\text{Ca}^{2+}$  responses (B and C) in cultured wild-type and DMPK $[-/-]$  muscle cells. Muscle cells were incubated with 10  $\mu\text{M}$  ryanodine for 30 min before depolarization (B and C). Traces show the mean  $[\text{Ca}^{2+}]_i$  after superimposing all relevant experiments as given in Table II. Ryanodine does not normalize the higher resting  $[\text{Ca}^{2+}]_i$  of DMPK $[-/-]$  cells (A), and only partially inhibits depolarization-induced  $\text{Ca}^{2+}$  transients (B and C).



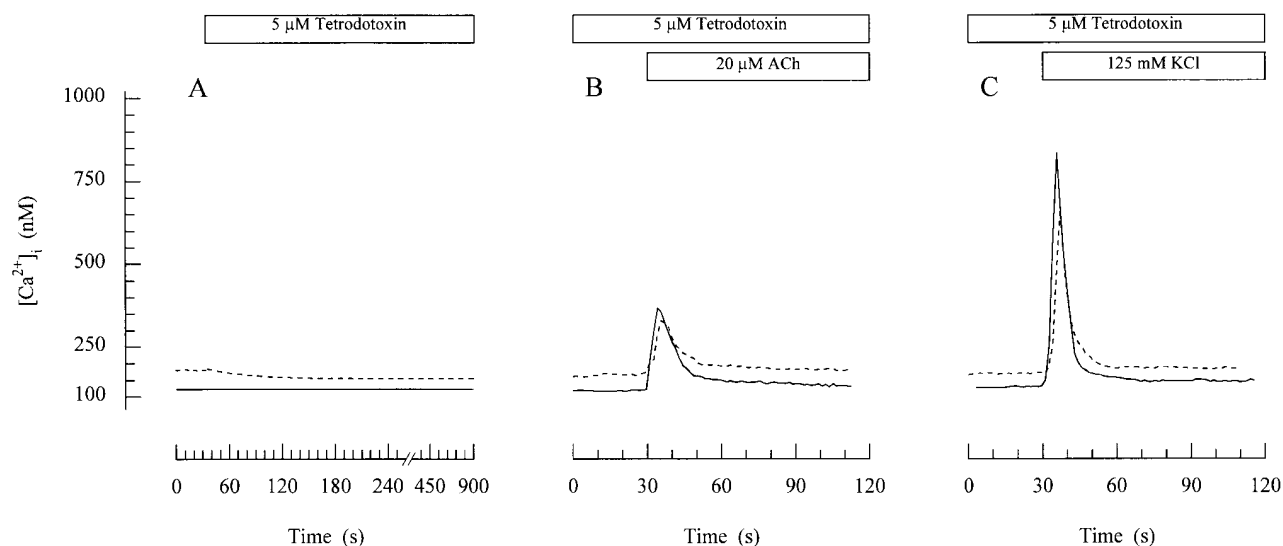
**Figure 3.** Effects of nifedipine on resting  $[Ca^{2+}]_i$  (A) and depolarization-generated  $Ca^{2+}$  transients (B and C) in cultured wild-type and DMPK $^{-/-}$  muscle cells. Muscle cells were incubated with 5  $\mu$ M nifedipine for 30 min before depolarization (B and C). For other details, see legend to Fig. 2. Nifedipine completely normalizes the higher resting  $[Ca^{2+}]_i$  of DMPK $^{-/-}$  cells (A).

(compare Figs. 1 B and 4 C). Since these latter observations suggest a  $[Ca^{2+}]_i$ -regulated fine-tuning of depolarization-induced  $Ca^{2+}$  responses, we investigated whether there was any relation between  $[Ca^{2+}]_i$  and any of the parameters that describe the shape and the magnitude of the  $Ca^{2+}$  transients in both cell types. The calculations clearly demonstrate that the resting  $[Ca^{2+}]_i$  inversely correlates with  $[Ca^{2+}]_{i,max}$  (Fig. 5 A), and exhibits a high correlation with  $\tau_i$  (Fig. 5 B). In addition, an inverse correlation exists between  $[Ca^{2+}]_{i,max}$  and  $\tau_d$  (Fig. 5 C).

The statistical evaluations of the depolarization-induced  $Ca^{2+}$  transients of both wild-type and mutant skeletal muscle cells in the absence or presence of ion channel-specific inhibitors are listed in Tables I and II, respectively, and sustain the described phenomena.

**SR  $Ca^{2+}$ -ATPase and  $Na^+/K^+$ -ATPase.** The here observed  $Ca^{2+}$  homeostasis of cultured DMPK $^{-/-}$  mouse muscle cells

has the same characteristics as in cultured skeletal muscle cells derived from DM patients (15, 16). Since muscle and cultured muscle cells of patients have been shown to exhibit a lowered activity of both SR  $Ca^{2+}$ -ATPase and  $Na^+/K^+$ -ATPase due to a reduction of their content (20), we also examined these ATP-driven ion pumps in our wild-type and mutant mice. As for human (20), the activity and the concentration of SR  $Ca^{2+}$ -ATPase as well as the  $K^+$ -dependent, ouabain-sensitive 3-O-MFPase activity and the ouabain-binding capacity, i.e., the number of  $Na^+/K^+$ -ATPase molecules, are lower in cultured mouse muscle cells than in mouse whole hind limb muscle, but the molecular activities do not differ (Table III). Furthermore, pairwise comparison between the two types of cultured muscle cells or skeletal muscle of wild-type and DMPK $^{-/-}$  mice do not reveal any difference in the activity or content of SR  $Ca^{2+}$ -ATPase and  $Na^+/K^+$ -ATPase (Table III).



**Figure 4.** Effects of tetrodotoxin on resting  $[Ca^{2+}]_i$  (A) and depolarization-elicited  $Ca^{2+}$  responses (B and C) in cultured wild-type and DMPK $^{-/-}$  muscle cells. Muscle cells were preincubated with 5  $\mu$ M tetrodotoxin for 30 min before depolarization (B and C). For other details, see legend to Fig. 2. Tetrodotoxin partially normalizes the higher resting  $[Ca^{2+}]_i$  of DMPK $^{-/-}$  cells (A).

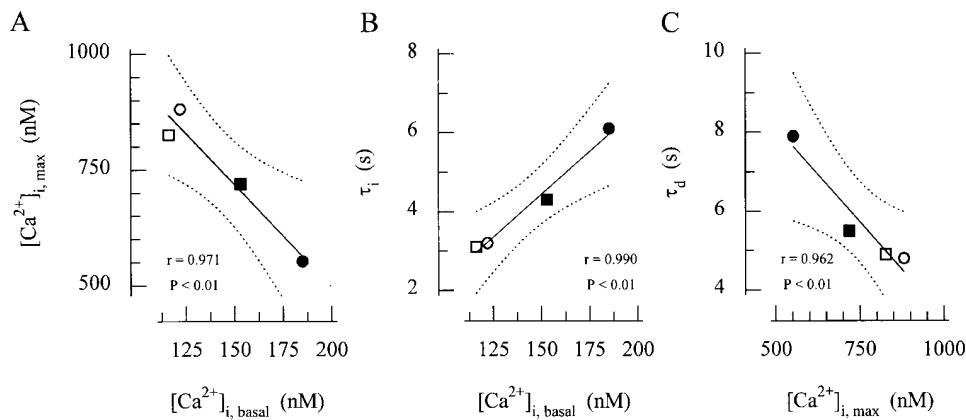


Figure 5.  $[Ca^{2+}]_i$ -regulated fine-tuning of  $Ca^{2+}$  responses in cultured wild-type (open symbols) and DMPK $^{-/-}$  skeletal muscle cells (solid symbols). The relation is shown for the mean values of  $[Ca^{2+}]_{i,rest}$  and  $[Ca^{2+}]_{i,max}$  (A) or  $\tau_i$  (B), and for  $[Ca^{2+}]_{i,max}$  and  $\tau_d$  (C). Data originate from  $Ca^{2+}$  transients induced by 125 mM KCl in the absence (○, ●) and presence of tetrodotoxin (□, ■). The solid lines represent the regression curves, and the dotted lines mark the 99% confidence intervals.

## Discussion

The focus of interest in DM research has slowly drifted from the behavior of the unstable (CTG)<sub>n</sub> repeat to the actual function(s) of individual genes in the mutant chromosome 19q area. Three candidate genes for the DM locus have now been characterized: DMR-N9, DMPK, and DMAHP (34, 35). As the expanding repeat in DM actually interrupts the gene for DMPK, most efforts in explaining disease etiology have been directed towards the involvement of the product(s) of this single gene. The results presented in this paper provide novel evidence that there is a specific relationship between DMPK ac-

tivity and  $Ca^{2+}$  homeostasis in skeletal muscle cells. Although results from DMPK-cDNA transfection studies in BC<sub>3</sub>H1 cells pointed to a function of DMPK in the myogenic pathway (36), we conclude from study of the close-to-natural context presented here, that the sole absence of DMPK does not appear to interfere with the growth and differentiation profiles of muscle-derived satellite cells in vitro. Neither the morphological appearance, nor the maturation grade, or the ability to contract, differed between wild-type and mutant cells. Moreover, our observations are in accordance with the absence of any gross morphological and structural modifications in vivo in mice that lack or overexpress the DMPK gene (9, 10).

*The behavior of  $Ca^{2+}$  homeostasis in cultured muscle cells depends on DMPK activity.* Estimates for resting  $[Ca^{2+}]_i$  values of mouse skeletal muscle cells in culture clearly depend on the cell origin, the  $Ca^{2+}$  indicator used for assaying, and the calibration procedure applied. All we can say is that our value for the resting  $[Ca^{2+}]_i$  in cultured muscle cells of wild-type mice, based on the in vivo calibration of Fura-2, falls well within the range of values published for cultured mouse myotubes (37) and myofibers in vivo (38). Since inhibition of the SR  $Ca^{2+}$  release channel by ryanodine effectively blocks depolarization-induced  $Ca^{2+}$  efflux in cultured wild-type cells (Fig. 2, B and C), these cells, like those of rats and humans, must possess a skeletal muscle type of E-C coupling mechanism, rather than a cardiac muscle type, in which  $Ca^{2+}$  release is provoked by an influx of external  $Ca^{2+}$  (28, 31). Moreover, it suggests that the contribution of a  $Ca^{2+}$  influx through the ion-unselective AChR (39), the dihydropyridine-insensitive fast-activated voltage-operated T-type  $Ca^{2+}$  channel (40), and/or the slow-activated voltage-dependent L-type  $Ca^{2+}$  channel, i.e., DHPR (41), during depolarization is negligibly small, and/or is ineffective to induce  $Ca^{2+}$  release from the SR. This does not rule out that  $Ca^{2+}$  entry via the DHPR may play a role in long-lasting depolarizations in wild-type cells, but usually this process is slower than the charge movement in DHPR and the associated activation of the RyR (41).

The situation in mutant myotubes is clearly different in that absence of DMPK augments the resting  $[Ca^{2+}]_i$ , and has dampening effects on the release and sequestration of  $Ca^{2+}$  upon depolarization. Application of inhibitors showed that the phenomenon of higher resting  $[Ca^{2+}]_i$  and the altered excitability are somehow linked to the mode of action of voltage-dependent  $Ca^{2+}$  and  $Na^{+}$  channels. It is unlikely that a recently described  $Ca^{2+}$ -specific leak channel is involved, as the situation

Table II. Effects of E-C Coupling Inhibitors on ACh- and KCl-induced  $Ca^{2+}$  Transients in Cultured Skeletal Muscle Cells From Wild-type and DMPK $^{-/-}$  Mice

Inhibitor	Stimulus	Parameter	Wild-type	DMPK $^{-/-}$
Ryanodine (10 $\mu$ M)	ACh	$[Ca^{2+}]_{i,basal}$	119 $\pm$ 21	182 $\pm$ 38*
		$[Ca^{2+}]_{i,max}$	119 $\pm$ 21 (40)	251 $\pm$ 31* (21)
	KCl	$[Ca^{2+}]_{i,basal}$	120 $\pm$ 24	179 $\pm$ 39*
		$[Ca^{2+}]_{i,max}$	120 $\pm$ 24 (28)	248 $\pm$ 31* (17)
Nifedipine (5 $\mu$ M)	ACh	$[Ca^{2+}]_{i,basal}$	120 $\pm$ 23	127 $\pm$ 33
		$[Ca^{2+}]_{i,max}$	120 $\pm$ 23 (42)	127 $\pm$ 33 (19)
	KCl	$[Ca^{2+}]_{i,basal}$	121 $\pm$ 20	125 $\pm$ 29
		$[Ca^{2+}]_{i,max}$	121 $\pm$ 20 (52)	125 $\pm$ 29 (32)
Tetrodotoxin (5 $\mu$ M)	ACh	$[Ca^{2+}]_{i,basal}$	120 $\pm$ 23	155 $\pm$ 36*
		$[Ca^{2+}]_{i,max}$	378 $\pm$ 56 (29)	351 $\pm$ 67 (23)
	KCl	$[Ca^{2+}]_{i,basal}$	116 $\pm$ 25	153 $\pm$ 40*
		$[Ca^{2+}]_{i,max}$	826 $\pm$ 196 (48)	719 $\pm$ 234 <sup>‡</sup> (45)

Values expressed in nM, are means $\pm$ SD of the number of muscle cells (listed between parentheses) from at least three individual cultures. Concentrations of ACh and KCl are 20  $\mu$ M and 125 mM, respectively. Parameters of DMPK $^{-/-}$  and wild-type cells differ with \* $P$  < 0.01 and <sup>‡</sup> $P$  < 0.05. In the presence of tetrodotoxin  $\tau_i$  of the KCl-evoked  $Ca^{2+}$  responses in wild-type and mutant cells are 3.1 $\pm$ 0.9 s and 4.2 $\pm$ 1.3 s ( $P$  < 0.01), whereas  $\tau_d$  are 4.9 $\pm$ 1.1 s and 5.5 $\pm$ 1.5 s ( $P$  < 0.05), respectively.

Table III. SR  $\text{Ca}^{2+}$ -ATPase and  $\text{Na}^+/\text{K}^+$ -ATPase in Muscle and Cultured Muscle Cells of Wild-type and DMPK[−/−] Mice

Parameters	Muscle		Cultured muscle cells	
	Wild-type	DMPK[−/−]	Wild-type	DMPK[−/−]
SR $\text{Ca}^{2+}$ -ATPase activity (mU/mg protein)	76.2±7.4 (5)	75.9±4.5 (3)	13.1±2.3 (8)	13.3±1.8 (4)
SR $\text{Ca}^{2+}$ -ATPase content (pmol/mg protein)	94.9±8.0 (5)	94.7±5.8 (3)	16.4±2.8 (8)	16.5±2.0 (4)
Molecular activity ( $\text{min}^{-1}$ )	802±14 (5)	801±9 (3)	800±8 (8)	803±13 (4)
$\text{Na}^+/\text{K}^+$ -ATPase activity (mU/mg protein)	0.57±0.06 (5)	0.56±0.08 (3)	0.93±0.09 (7)	0.95±0.13 (4)
$\text{Na}^+/\text{K}^+$ -ATPase content (pmol/mg protein)	6.3±0.6 (5)	6.2±0.2 (3)	10.1±0.7 (5)	10.4±1.6 (4)
Molecular activity ( $\text{min}^{-1}$ )	91±7 (5)	89±11 (3)	92±8 (5)	91±8 (4)

Values are means±SD of the number of muscles or muscle cell cultures (given between parentheses). The activity and content of SR  $\text{Ca}^{2+}$ -ATPase were determined by  $\text{Ca}^{2+}$ -dependent ATP hydrolysis and steady-state phosphorylation, respectively. The  $\text{K}^+$ -dependent, ouabain-sensitive hydrolysis of 3-*O*-MFP and the binding capacity of ouabain were used as a measure for the activity and content of  $\text{Na}^+/\text{K}^+$ -ATPase, respectively.

is completely normalized by nifedipine, which fails to inhibit this leak channel (42). Our mutant myotubes lack a protein kinase that is closely related to the subfamilies of cAMP-dependent protein kinases and protein kinases C (2, 43). Hence, it is most likely that the phosphorylation status of the  $\text{Ca}^{2+}$  and/or  $\text{Na}^+$  channels or any other protein that mediates the clustering of ion channels in the sarcolemma is modified in DMPK[−/−] myotubes. In turn, this may change the gating properties of these channels and/or influence the distribution and regulation of voltage-dependent SR  $\text{Ca}^{2+}$  release events (44). Importantly, phosphorylation of both the  $\alpha_1$  and  $\beta$  subunits of the DHPR is known to occur. Phosphorylation of the  $\alpha_1$  subunit leads to an increase of the  $\text{Ca}^{2+}$  current (45), and we would expect absence of phosphorylation to reduce this current, a feature that is inconsistent with the observed high  $[\text{Ca}^{2+}]_i$  in resting DMPK[−/−] cells. Perhaps more relevant is that recombinant-DMPK can use the  $\beta$ -subunit as a substrate in vitro (46), although the precise effects of phosphorylation of this subunit, which regulates the  $\alpha_1$ -subunit activity (47), are unknown. Similarly interesting is that phosphorylation of the  $\alpha$  subunit of the TTX-sensitive  $\text{Na}^+$  channel in cultured mouse and rat muscle cells by protein kinase C and in transfected oocytes by DMPK leads to a reduction of the  $\text{Na}^+$  current (48, 49). A persistent influx of  $\text{Na}^+$  as a consequence of DMPK absence may lead to mild long-lasting depolarization of the sarcolemma, and results in a more frequent opening of the L-type  $\text{Ca}^{2+}$  channel. We cannot, however, exclude the possibility that DMPK-mediated phosphorylation primarily influences the gating by affecting the sarcolemmal and T-tubular architecture, or is involved in the (in)activation of voltage-gated ion channels that set the resting membrane potential, like  $\text{K}^+$  and  $\text{Cl}^-$  channels. Delayed rectifier (50), inward rectifier (51), as well as  $\text{Ca}^{2+}$ -activated  $\text{K}^+$  channels (52) can be phosphorylated by cAMP-dependent protein kinase and/or protein kinase C in heart, smooth muscles, and neurons. Activation of protein kinase C reduces  $\text{Cl}^-$ -conductance and leads to myotonia (53). It is difficult to discriminate as ion channel regulation by phosphorylation is extremely complex (51, 54). Thus, although our findings do not provide direct clues for any of these channels being a direct target for DMPK, they illustrate a unique property of DMPK, namely that it exerts a modulating function on the initial events of the E-C coupling in skeletal muscle. The localization of DMPK isoforms at sites of dense channel clus-

tering (55–57) is consistent with the fact that these processes occur at or close to the sarcolemma.

**Relevance for disease etiology?** Since  $[\text{Ca}^{2+}]_i$  is a crucial regulator of many physiological processes, elevated  $[\text{Ca}^{2+}]_i$  could potentially have profound consequences in vivo. Can we extrapolate our in vitro findings and relate abnormal  $\text{Ca}^{2+}$  homeostasis to disease manifestation in DM patients? We realize that our knockout mouse and cell models do not provide a direct answer to this question, as the effects of CTG expansion on DMPK expression still have not been clearly resolved. The mouse myotubes, however, do provide the ideal test system to study the normal biological significance of DMPK against a well-defined, constant genetic background. Earlier we discussed the apparent lack of an overt phenotype in our animal model (9) in terms of possible adaptation, compensation, or threshold effects, which in mice, with a relatively low muscle workload due to small body weight, often obscure the manifestation of myopathic features (58). Here we study the system in isolation, outside the context of the entire tissue, and it is perhaps more relevant that the elevated resting  $[\text{Ca}^{2+}]_i$ , and the effects on release and sequestration of  $\text{Ca}^{2+}$  coupled to abnormal regulation of TTX-sensitive  $\text{Na}^+$  channels and voltage-operated L-type  $\text{Ca}^{2+}$  channels match the data obtained with myotubes derived from DM patients (15–18). There are also differences in that abnormal SR  $\text{Ca}^{2+}$ -ATPase and  $\text{Na}^+/\text{K}^+$ -ATPase levels were not found in mouse DMPK[−/−] cells (Table III, 20). It is possible that  $\text{Ca}^{2+}$ -dependent gene expression critical for these changes may have a differential threshold sensitivity in man and mouse, and almost certainly there are differential effects due to the completely distinct mutation type in the human and mouse situation. For example, for DM patients it is conceivable that large expansions of the  $(\text{CTG})_n$  repeat affect other genes in the immediate vicinity, like the downstream-located DMAHP gene which specifies a transcription factor implemented in ion-channel expression regulation (35, 59).

Thus, although the cell model is clearly too simplistic, our finding of similar disturbances in  $\text{Ca}^{2+}$  homeostasis in muscle cells of both DM patients and DMPK[−/−] mice lends indirect support to the contention that the DM mutation results in a reduction or redistribution of DMPK mRNA and protein isoforms, in line with the molecular explanations provided by others (8, 60, 61). In conclusion, our study provides new insight in the relation between DMPK activity and  $\text{Ca}^{2+}$  responsive-

ness in skeletal muscle. The suggestion that DMPK modulates the movement of gating charge and/or the activity of voltage-gated ion channels opens up new possibilities for studies into the molecular etiology of DM.

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