Bradykinin restores left ventricular function, sarcomeric protein phosphorylation, and e/nNOS levels in dogs with Duchenne muscular dystrophy cardiomyopathy

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Aims Cardiomyopathy is a lethal result of Duchenne muscular dystrophy (DMD), but its characteristics remain elusive. The golden retriever muscular dystrophy (GRMD) dogs produce DMD pathology and mirror DMD patient’s symptoms, including cardiomyopathy. We previously showed that bradykinin slows the development of pacing-induced heart failure. Therefore, the goals of this research were to characterize dystrophin-deficiency cardiomyopathy and to examine cardiac effects of bradykinin in GRMD dogs.

Methods and results At baseline, adult GRMD dogs had reduced fractional shortening (28 ± 2 vs. 38 ± 2% in control dogs, *P*, 0.001) and left ventricular (LV) subendocardial dysfunction leading to impaired endo-epicardial gradient of radial systolic velocity (1.3 ± 0.1 vs. 3.8 ± 0.2 cm/s in control dogs, *P*, 0.001) measured by echocardiography. These changes were normalized by bradykinin infusion (1 μg/min, 4 weeks). In isolated permeabilized LV subendocardial cells of GRMD dogs, tension–calcium relationships were shifted downward and force-generating capacity and transmural gradient of myofilament length-dependent activation were impaired compared with control dogs. Concomitantly, phosphorylation of sarcomeric regulatory proteins and levels of endothelial and neuronal nitric oxide synthase (e/nNOS) in LV myocardium were significantly altered in GRMD dogs. All these abnormalities were normalized in bradykinin-treated GRMD dogs.

Conclusions Cardiomyopathy in GRMD dogs is characterized by profound LV subendocardial dysfunction, abnormal sarcomeric protein phosphorylation, and impaired e/nNOS, which can be normalized by bradykinin treatment. These data provide new insights into the pathophysiological mechanisms accounting for DMD cardiomyopathy and open new therapeutic perspectives.

Keywords Duchenne muscular dystrophy cardiomyopathy • Myofilament Ca2+ sensitivity • Protein phosphorylation • Nitric oxide synthase • Bradykinin

1. Introduction Duchenne muscular dystrophy (DMD) affects 1 in 3500 male births and is the most prevalent X-linked genetic disorder. Cardiac involvement evolves towards cardiomyopathy with dilatation of the chambers and depression of left ventricular (LV) function. It is responsible for death in approximately 40% of patients aged between 10 and 30 years.1–3 However, the characteristics of the dystrophin-deficiency...
Cardiomyopathy remain to be explored. Since the late 1980s, the golden retriever muscular dystrophy (GRMD) dogs have been used as the most relevant model of DMD in preclinical investigations, including drug treatment,7 gene transfers,8 and cell therapy.9 Similar to DMD patients, GRMD dogs also develop lethal cardiomyopathy.6,8 The mdx mouse model is classically used for pathophysiological and therapeutic investigations. Nonetheless, compared with DMD patients and dogs, mdx mice present mild muscle pathology due to the upregulation of the dystrophin homolog utrophin,9 whereas this mechanism does not exist in GRMD dogs8 and utrophin expression increases with the age and correlates with disease severity in DMD patients.10 In addition, regional myocardial function is almost impossible to assess in mdx mice due to the small heart size and high heart rate. Because GRMD dogs present severe skeletal muscle pathology and clinical symptoms similar to DMD,4–8 this study was designed to characterize DMD cardiomyopathy in GRMD dogs with a special focus on regional contractile properties both in vivo and in vitro.

Previous studies showed that in dogs with pacing-induced cardiomyopathy, endogenous bradykinin exerted cardioprotective effects11 and was involved in the beneficial effects of angiotensin-converting enzyme inhibitors.12 Moreover, in the same model, a bradykinin analogue improved LV endocardial flow reserve13 and we showed that the progression of heart failure was prevented by early bradykinin administration.14 However, the curative effect of bradykinin has never been evaluated in any model of established heart failure. Thus, the present study attempted to address this question in GRMD dogs with apparent cardiomyopathy.

2. Methods

2.1 Animal model and experimental protocol

The animal care and the experimental protocol were in accordance with the Directive 2010/63/EU of the European Parliament and approved by the Animal Ethic Committee of Institut National de la Sante et de la Recherche Médicale.

In a preliminary echocardiographic study, fractional shortening in three normal golden retriever dogs (12-month-old), four GRMD dogs (9–12-month-old), and four younger GRMD dogs (<9 months) was 37.0–42.3, 22.7–33.9, and 36.0–40.0%, respectively. Accordingly, the criteria for the enrolment of GRMD dogs in the study were: age ≥ 9 months and fractional shortening ≥ 25 and ≤ 35%.

Fourteen GRMD dogs (CEDS, Mèzilles, France) were instrumented with catheters in the left atrium and in the thoracic descending aorta during a left thoracotomy under general anaesthesia induced with propofol (6.5 mg/kg, i.v.) and maintained with isoflurane (1–3% vol in 100% O2). The adequacy of anaesthesia was monitored by examination of animal reaction to pain stimulation. Preemptive and postoperative analgesia was ensured with morphine (0.1 mg/kg, i.v.) and fentanyl (50 μg/h). After 2–3 weeks of recovery (Figure 1a), echocardiographic measurements were performed. Thereafter, pyrogen-free 0.9% saline (166 μL/min) or bradykinin (NewMPS, France; dissolved in pyrogen-free 0.9% saline solution, 1 μg/min, 166 μL/min) was infused through the left atrial catheter for 4 weeks using a portable pump. The dose of bradykinin was chosen according to our previous studies, showing that it slows the progression of heart failure without affecting arterial pressure.14,15 Unchanged arterial pressure during bradykinin treatment was confirmed in the present study (Supplementary data). After sacrifice (pentobarbital, 100 mg/kg), cardiac tissues were collected for the myocyte study and frozen with liquid nitrogen and stored at −80°C for the protein analysis.

Among the 14 GRMD dogs, 3 died of acute respiratory failure following food inhalation, bronchopneumonia, or gastric ulcers during postoperative recovery period, and 1 died of pulmonary haemorrhage during saline infusion. Finally, 10 GRMD and 8 age-matched normal golden retriever dogs of same genetic background were randomized.

Detailed echocardiography, myocyte experiments, and western blot analysis are described in Supplementary Data. Briefly, conventional echocardiography and 2D colour tissue Doppler imaging were performed by the examiners blinded to the animals’ group information. Myocytes were prepared from LV subendocardial and subepicardial strips and force–calcium relationships were examined in permeabilized myocytes.16,17 Western blot analyses were performed to measure neuronal and endothelial nitric oxide synthase (nNOS and eNOS), cardiac myosin-binding protein C (cMyBP-C), phosphorylated cMyBP-C (p-MyBP-C), cardiac troponin I (Tnl), phosphorylated Tnl (p-Tnl), ventricular myosin light chain 2 isoforms (VLC2, VLC2*), and phosphorylated forms (p-VLC2 and p-VLC2*) in LV tissues. The NOS activity was assessed by measuring the rate of L-arginine to nitrite/nitrate conversion in tissue lysates using a colorimetric NOS assay kit (NB78, Oxford Biomedical Research, Inc.) following the manufacturer’s instructions.

2.2 Statistical analysis

Results were expressed as mean ± SEM. One-way ANOVA for repeated measures was used for intra-group studies (StatView software, Abacus Concepts Inc.). Two-way ANOVA was performed for comparisons between groups and if there was a significant difference, the Student–Newman–Keuls test was used to identify differences between means. When only two means were compared, an appropriate Student’s t-test was used. The linear least-squares regression was performed to evaluate the cause–effect relationships between the e/nNOS protein levels or sarcomeric protein phosphorylation and functional changes observed in intact animal and isolated myocytes as well as between sarcomeric protein phosphorylation and e/nNOS protein levels. A P < 0.05 was considered significant.

3. Results

3.1 LV dysfunction and its normalization by bradykinin infusion in GRMD dogs

GRMD dogs had lower body weight, higher heart rate, greater LV end-diastolic diameter/body weight ratio, and thinner LV free wall and interventricular septum than control dogs (Table 1). GRMD dogs exhibited major LV contractile dysfunction as revealed by reduced fractional shortening, LV free wall, and interventricular septal wall thickenings (Figures 1b–d). LV dysfunction occurred essentially in the subendocardium as indicated by the decreased systolic velocity in the subendocardium and conserved systolic velocity in the subepicardium, which resulted in a reduced endo-epicardial gradient of radial systolic velocity (Figure 1e). GRMD dogs had also a reduced mitral E/A (Table 1).

Before placebo or bradykinin infusion, there was no difference between the two groups of control dogs or between the two groups of GRMD dogs (Supplementary data). Figure 2a illustrates LV myocardial velocities in one GRMD dog before and 4 weeks after bradykinin infusion. Bradykinin treatment did not modify the LV end-diastolic diameter/body weight ratio in control and GRMD dogs (Figure 2b). LV contractile dysfunction persisted throughout the protocol in placebo-treated GRMD dogs (Figure 2c and d), while bradykinin-treated GRMD dogs exhibited normal LV systolic performance as indicated by normalized fractional shortening and LV free-wall systolic thickening after 2 and 4 weeks of bradykinin infusion (Figure 2c and d). This may be due to an increase in the subendocardial systolic
velocity (Figure 2e). The radial epicardial systolic velocity was unchanged (Figure 2f), resulting in a normalized endo-epicardial gradient of the radial systolic velocity in these dogs (Figure 2g).

3.2 Impaired contractile properties of LV subendocardial myocytes in GRMD dogs were normalized by bradykinin treatment

The regional properties of the contractile machinery were investigated in permeabilized cardiomyocytes by establishing force–calcium relationships. In subendocardial myocytes, the forces generated at sub-maximal and maximal calcium activation at 1.9 and 2.3 μm sarcomere lengths were reduced in GRMD dogs (Figure 3a). In subepicardial myocytes, tension–pCa relationships were superimposable at each sarcomere length in control and GRMD dogs (Figure 3b). Maximal tensions generated at the two sarcomere lengths in subendocardial cells were lower in GRMD dogs than in control dogs (Figure 3c), but no difference was observed in subepicardial cells between GRMD and control dogs (Figure 3d). In subendocardial and subepicardial cells, stretching myocyte from short to long sarcomere length induced a leftward shift of the tension–pCa relationship (Figure 3e) and an increase in pCa50 (the pCa for half maximum activation), both indicating an increased myofilament Ca2+ sensitivity, which is referred to as the length-dependent activation and reflects the Frank–Starling mechanism at the cellular level. The myofilament Ca2+ sensitivity was higher only at 1.9 μm sarcomere length in subendocardial cells of GRMD dogs than in control dogs (Figure 3e). The myofilament Ca2+ sensitivity in subepicardial
cells was not different between control and GRMD dogs (Figure 3f). In control dogs, $\Delta pC_{a_{50}}$ was higher in subendocardial myocytes than in subepicardial myocytes, resulting in a transmural gradient of the length-dependent activation (Figure 3g), reflecting a higher endocardial reserve of $C_{a_{50}}$ sensitivity in response to increased sarcomere length. This gradient was lost in GRMD dogs due to a reduced length-dependent activation in subendocardial cells. Thus, the properties of the contractile machinery were altered in subendocardial myocytes of GRMD dogs.

Bradykinin treatment thoroughly improved the properties of the contractile machinery in subendocardial cells of GRMD dogs (Figure 4a) as indicated by restoration of maximal active tensions to levels of control dogs (Figure 4b). Bradykinin did not modify myofilament $C_{a_{50}}$ sensitivity in control dogs but reduced $pC_{a_{50}}$ at 1.9 µm in subendocardial cells of GRMD dogs compared with placebo-treated ones. The myofilament $C_{a_{50}}$ sensitivity of subendocardial cells at both 1.9 and 2.3 µm sarcomere lengths was lower in bradykinin-treated GRMD dogs than in bradykinin-treated control dogs (Figure 4c). The endo-epicardial gradient of $\Delta pC_{a_{50}}$ in bradykinin-treated GRMD dogs was not different from that of control dogs (Figure 4d), indicating a restoration of endo-epicardial length-dependent activation gradient in GRMD dogs.

### 3.3 Phosphorylation of cMyBP-C, TnI, and VLC2 isoforms in LV myocardium of GRMD dogs is normalized by Bradykinin administration

Since sarcomeric protein phosphorylation regulates the properties of the contractile machinery, we analysed the phosphorylation levels of Ser$^{282}$ cMyBP-C, Ser$^{23/24}$ TnI, and two VLC2 isoforms in LV tissues. p-MyBP-C levels were similar in subepicardial and subendocardial regions in control dogs and were not modified by the bradykinin treatment (Figure 5a and b). Compared with control dogs, p-MyBP-C levels were decreased in the subepicardial and subendocardial regions in GRMD dogs. In contrast, p-MyBP-C levels in bradykinin-treated GRMD dogs were not statistically different from those of control dogs (Figure 5a and b). The amount of non-phosphorylated TnI was not different between groups. In control dogs, p-TnI levels were not different between the subepicardium and subendocardium and were not modified by bradykinin treatment (Figure 5a and c). The p-TnI level in the subendocardium was higher in GRMD dogs than in control dogs, which was normalized by bradykinin treatment (Figure 5a and c). There was an inverse linear relationship between the p-TnI levels and Tmx at 1.9 µm sarcomere length in the subendocardial cells (Figure 5d). VLC2 isoform phosphorylation levels were similar in subepicardial and subendocardial regions in placebo- and bradykinin-treated control and GRMD dogs (Figure 5e and f). The VLC2 phosphorylation level decreased significantly only in the subepicardium of bradykinin-treated GRMD dogs (Figure 5e and f). The p-VLC2*/VLC2* level was significantly lower in the subendocardium than in the subepicardium in control dogs. This endo-epicardial difference was lost in bradykinin-treated control dogs and in placebo-treated GRMD dogs due to increased p-VLC2*/VLC2* level in the subendocardium (Figure 5g). Bradykinin treatment in GRMD dogs decreased p-VLC2*/VLC2* in the subepicardial and subendocardial regions (Figure 5g). An inverse linear relationship between subendocardial p-VLC2*/VLC2* levels and fraction shortening was described (Figure 5h). Altogether, the phosphorylation of sarcomeric regulatory proteins was mainly altered in the subendocardium of GRMD dogs and was reversed by bradykinin treatment.

### 3.4 Reduced nNOS and eNOS levels and NOS activity in LV myocardium of GRMD dogs and restoration by bradykinin treatment

Dystrophin deficiency in skeletal muscles leads to a selective loss and delocalization of nNOS. We therefore explore nNOS and eNOS content in GRMD hearts. Figure 6a shows representative western blots of nNOS and eNOS. In control dogs, nNOS protein levels were similar in the subcendocardial and subepicardial regions of placebo- or bradykinin-treated dogs. nNOS protein levels were lower in the LV subendocardium and subepicardium of placebo-treated GRMD dogs than in those of control dogs (Figure 6a and b). In contrast, in bradykinin-treated GRMD animals, nNOS levels increased by 156% ($P < 0.02$) in the subepicardium and 70% ($P < 0.05$) in the subendocardium compared with placebo-treated GRMD dogs and reached similar levels of placebo- or bradykinin-treated control dogs. eNOS levels were similar in LV subendocardium and subepicardium in control dogs and were not modified by the bradykinin treatment. Compared with control dogs, eNOS levels were significantly decreased by 66 and 77% in the LV subendocardium and subepicardium of placebo-treated GRMD dogs, but were similar in both regions of bradykinin-treated GRMD dogs (Figure 6a and c). These data indicate a down-regulation of nNOS and eNOS in the left ventricle of GRMD dogs, which can be restored by bradykinin treatment.

There was an inverse linear relationship between p-VLC2* and eNOS levels in the subendocardium ($r = -0.54, P < 0.05$) but not in the subepicardium. A linear relationship between p-cMyBP-C and
nNOS levels was described in the subepicardium and subendo-
cardium ($r = 0.70$, $P < 0.01$ and $r = 0.50$, $P < 0.05$, respectively),
suggesting a substantial cause–effect relationship between nNOS
and cMyBP-C phosphorylation. There was no linear relationship
between p-TnI levels and eNOS or nNOS in the LV myocardium.
Fractional shortening was linearly related to nNOS levels in the
LVFW.}

**Figure 2** Effects of bradykinin (BK) on LV contractile function in control and GRMD dogs. (a) Radial myocardial velocity profiles in a GRMD dog at
day 0 and 4 weeks after bradykinin infusion using 2D colour tissue Doppler imaging. Myocardial velocities in subendocardial and subepicardial seg-
ments (yellow and green curves, respectively) were recorded within the LVFW. Note increased systolic endo-epicardial gradient (red arrow) after
bradykinin treatment owing to higher systolic subendocardial velocities. S, E, and A are the peak mean velocity of the LVFW during systole, early
diastole, and late diastole, respectively. (b) No change in LV end-diastolic diameter normalized by the body weight. (c–e) Normalization of fractional
shortening, LVFW thickening, and radial systolic velocity in LV subendocardial regions of GRMD dogs after 2 and 4 weeks of bradykinin infusion. (f)
No change in the radial systolic velocity in the LV subepicardial regions among the groups. (g) Restoration of the endo-epicardial gradient of the radial
systolic velocity in bradykinin-treated GRMD dogs. $N = 4$, 4, 5, and 5 for control-placebo, control-bradykinin, GRMD-placebo, and GRMD-bradykinin
groups, respectively. *$P < 0.05$ vs. control-placebo and †$P < 0.05$ vs. GRMD-placebo by ANOVA.
The endo-epicardial systolic velocity gradient was linearly related to nNOS levels in the subepicardium ($r = 0.8$, $P < 0.01$) and subendocardium ($r = 0.65$, $P < 0.005$). Similar relationships between fractional shortening or endo-epicardial systolic velocity gradient and eNOS were observed. Changes in pCa$_{50}$ in subendocardial cells were inversely related to subendocardial eNOS levels ($r = -0.53$, $P < 0.05$) but not related to subendocardial nNOS levels.

In control dogs, the NOS activity was lower in the subendocardium than in the subepicardium ($r = 0.65$, $P < 0.005$). The endo-epicardial systolic velocity gradient was linearly related to nNOS levels in the subepicardium ($r = 0.8$, $P < 0.01$) and subendocardium (Figure 6d). Similar relationships between fractional shortening or endo-epicardial systolic velocity gradient and eNOS were observed. Changes in pCa$_{50}$ in subendocardial cells were inversely related to subendocardial eNOS levels ($r = -0.53$, $P < 0.05$) but not related to subendocardial nNOS levels.

In control dogs, the NOS activity was lower in the subendocardium than in the subepicardium ($P < 0.05$). This difference disappeared in bradykinin-treated control dogs. The NOS activity in the LV myocardium was lower in GRMD dogs than in control dogs (Figure 6f). In contrast, NOS activity in the subepicardium and subendocardium were similar between bradykinin-treated GRMD dogs and placebo- or bradykinin-treated control dogs, indicating a restoration of NOS activity by bradykinin treatment. More importantly, NOS activity increased significantly by 166% in the subendocardium of bradykinin-treated GRMD dogs when compared with placebo-treated GRMD dogs.

4. Discussion

This study demonstrated that LV dysfunction of GRMD dogs was characterized by a reduced LV endo-epicardial gradient of the radial systolic velocity due to a pronounced subendocardial dysfunction. This was related to altered myofibrillar properties in subendocardial cells and disappearance of transmural gradient of myofilament length-dependent activation. These changes were associated with altered cMyBP-C, TnI, and VLC2* phosphorylation as well as reduced nNOS and eNOS in the LV myocardium. Moreover, our data showed that chronic bradykinin treatment normalized LV performance as indicated by normalized LV wall thickening and fractional
shortening, and restored the subendocardial function and endo-epicardial systolic velocity gradient. This in vivo effect of bradykinin was reflected at the cellular level by normalized myofibrillar properties of subendocardial cells.

In GRMD dogs, subendocardial dysfunction occurred even before LV global dysfunction, leading to a loss of the transmural contractile gradient. This loss is highlighted by the disappearance of the endo-epicardial systolic velocity gradient, resulting in overall LV dysfunction. Concomitantly, subendocardial myocytes exhibited decreased capacity to generate force, increased Ca$^{2+}$ sensitivity at short sarcomere length, and abolished endo-epicardial length-dependent activation gradient that reduced the capacity of subendocardial cells to use the Frank–Starling mechanism when necessary. The preferential alteration of the subendocardium compared with the subepicardium has been described for various cardiac pathologies. This may rely on functional differences between subepicardial and subendocardial layers. A normal heart displays a LV transmural contractile gradient due to higher contractility in the subendocardium than in the subepicardium, resulting from the transmural excitation–contraction coupling heterogeneity and higher sarcoplasmic reticulum Ca$^{2+}$ release in the subendocardium than in the subepicardium. The subendocardium has higher blood flow and oxygen consumption than the subepicardium. During systole and diastole, vessel patency remains constant at the subepicardium, while during systole, subendocardial layers suffer transient ischaemia due to the low blood flow which requires compensatory replenishment from diastolic perfusion. These features result in greater susceptibility of subendocardial layers than subendocardial layers to be dysfunctional in many circumstances. Additionally, the subepicardium can adapt to increased stress by lengthening the action potential to release more calcium. This adaptation is limited in subendocardial cells that have long action potential duration in basal conditions. In GRMD dogs, heart rate was accelerated. This shortened diastolic time and altered compensatory replenishment from diastolic perfusion needed for subendocardial cells. Moreover, changes in phosphorylation of sarcomeric regulatory proteins such as TnI and VLC2* in the subendocardium of GRMD dogs indicate functional maladaptation.

cMyBP-C phosphorylation increases the force generation by accelerating the kinetics of force development through increasing the proximity of cross-bridges to actin and cross-bridge kinetics. When dephosphorylated, cMyBP-C interacts with myosin to prevent actin–myosin interaction, reducing Ca$^{2+}$-activated force generation. A reduced cMyBP-C phosphorylation seems to be a common mechanism for human dilated and ischaemic cardiomyopathy and canine pacing-induced cardiomyopathy. Such mechanism also occurs in GRMD dogs and underlies reduced force-generating capacity in GRMD dogs. Accordingly, restoration of cMyBP-C phosphorylation following bradykinin treatment should participate in normalizing force-generating capacity of subendocardial cells in GRMD dogs.

Tnl phosphorylation by protein kinase A reduces the myofilament Ca$^{2+}$ sensitivity and increases the cross-bridge cycling rate. This accelerates relaxation and increases force generation but increases

**Figure 4** Effects of bradykinin on the contractile machinery properties in control and GRMD subendocardial myocytes. (a) The tension–pCa curves at two sarcomere lengths (SL) in subendocardial cells of bradykinin-treated control and GRMD dogs. (b) Normalized maximal tension in response to Ca$^{2+}$ in subendocardial cells of bradykinin-treated control and GRMD dogs. (c) pCa50 at 1.9 or 2.3 µm SL in subendocardial cells of placebo- or bradykinin-treated control and GRMD dogs. (d) The endo-epicardial gradient of pCa50 changes (ΔpCa50) relative to SL change from 1.9 to 2.3 µm in response to Ca$^{2+}$ in bradykinin-treated control and GRMD dogs. Endo, endocardial; Epi, epicardial. Averaged data from four control and five GRMD dogs in each condition, and three to four cells per animal and region. *P < 0.05.
TnI phosphorylation was unchanged or increased in the rat myocardial infarction model, but decreased in human hypertrophic or dilated failing hearts. In GRMD dogs, TnI phosphorylation was increased in the subendocardium but not in the subepicardium. This pattern of TnI phosphorylation seems to be unique for the failing heart of GRMD dogs and might compensate for LV subendocardial dysfunction in GRMD dogs. However, the energy-consuming feature of such compensation would increase the workload of subendocardial cells and played a deleterious role as suggested by an inverse relationship between Tmax and p-TnI. Bradykinin-induced normalization of TnI phosphorylation in GRMD dogs may correct this deleterious effect. The effect of bradykinin on TnI phosphorylation can be mediated through activation of p21-activated kinase I, which then dephosphorylates Tnl in cardiomyocytes.

**Figure 5** Phosphorylation levels of sarcomeric regulatory proteins in subepicardial (Epi) and subendocardial (Endo) tissues. (a) Western blots of cMyBP-C, p-MyBP-C, troponin-I (Tnl), p-troponin-I (p-Tnl), and calsequestrin (Calsq) in placebo- or bradykinin (BK)-treated control and GRMD dogs. (b) Reduced p-MyBP-C/cMyBP-C in GRMD dogs and its normalization in bradykinin-treated GRMD dogs. (c) Increased p-Tnl/Tnl in the subendocardium of GRMD but normalized p-Tnl/Tnl in bradykinin-treated GRMD dogs. (d) The linear relationship between Tmax obtained at 1.9 μm sarcomere length and p-Tnl/Tnl levels in subendocardial cells of placebo- and bradykinin-treated control and GRMD dogs. (e) Example of western blot of VLC2, VLC2*, and their phosphorylated forms, p-VLC2 and p-VLC2*. (f) No difference in p-VLC2 between control and GRMD dogs. (g) Increased p-VLC2* level in the subendocardium of GRMD and bradykinin-treated control dogs but reduced in bradykinin-treated GRMD dogs. (h) The linear relationship between fractional shortening (FS) and subendocardial p-VLC2*/VLC2* levels in placebo- and bradykinin-treated control and GRMD dogs. Averaged data from four control and five GRMD dogs in each condition in duplicate. *P < 0.05 vs. control dogs, †P < 0.05 vs. corresponding placebo-treated dogs, and ‡P < 0.05 vs. the subepicardium.

Cardiac effects of bradykinin in GRMD dogs
Infarcted porcine myocardium where neither VLC2 nor VLC2* phosphorylation was changed. The increased VLC2* phosphorylation may be responsible for the increased $\text{Ca}^{2+}$ sensitivity at short sarcomere length in subendocardial cells leading to reduced transmural length-dependent activation in GRMD dogs. Consistently, normalized VLC2* phosphorylation by bradykinin explains the decreased $\text{Ca}^{2+}$ sensitivity at short sarcomere length in subendocardial cells of bradykinin-treated GRMD dogs.

In DMD patients, dystrophin deficiency in skeletal muscles leads to selective loss and delocalization of nNOS and reduced blood flow in skeletal muscles, accounting for muscle lesions. However, there is no information about nNOS in the DMD heart. We found a marked reduction in the myocardial nNOS levels in GRMD dogs. This is in line with a study in mdx mice showing a decreased cardiac nNOS activity and contrast with another showing unchanged myocardial nNOS levels in mdx mice at different ages. Interestingly, increased myocardial nNOS expression and activity were found in patients with dilated cardiomyopathy. Thus, dystrophin-deficiency cardiomyopathy in this regard differs from dilated cardiomyopathies of other aetiologies. nNOS participates in the regulation of coronary blood flow and intracellular $\text{Ca}^{2+}$ homeostasis through its action on the $\text{Ca}^{2+}$ release channel and $\text{Ca}^{2+}$ handling proteins, a decreased nNOS level may contribute to LV contractile dysfunction. Our study is the first one to demonstrate an impaired eNOS level in dystrophin-deficiency cardiomyopathy. eNOS-derived NO regulates myocardial blood perfusion and LV endocardial reserve, myocardial $\text{O}_2$ consumption, and $\text{Ca}^{2+}$ release from ryanodine-receptor channels. eNOS-derived NO enhances the Frank–Starling mechanism in the isolated heart, and eNOS gene expression is depressed in the subendocardium of patients with dilated cardiomyopathy and correlated

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**Figure 6** e/nNOS expression and NOS activity in control and GRMD dogs. (a) Example of western blot of nNOS, eNOS, and calnexin in LV subepicardium (Epi) and subendocardium (Endo) of placebo- or bradykinin-treated control and GRMD dogs. (b) and (c) Average values of nNOS and eNOS normalized by calnexin in the subendocardium and subepicardium. (d) The linear relationship between fractional shortening (FS) and subendocardial nNOS protein levels. (e) The linear relationship between the endo-epicardial gradient of the radial systolic velocity and subendocardial nNOS protein levels. (f) NOS activity measured by the rate of l-arginine to nitrite/nitrate conversion. Averaged data from four control and five GRMD dogs in each condition in duplicate. *$P < 0.05$ vs. placebo-treated control dogs, †$P < 0.05$ vs. placebo-treated GRMD dogs.
with LV stroke work. Decreased myocardial eNOS levels may also account for LV dysfunction in GRMD dogs. In the control heart, bradykinin treatment improves LV contractility without significant effects on protein phosphorylation and eNOS and nNOS protein levels. This can be explained by the fact that in the control heart, eNOS and nNOS expression and myofilament protein phosphorylation are normal, and bradykinin is a vasodilator that can increase myocardial coronary perfusion by liberating eNOS- and nNOS-derived NO. It has been shown that the myocardial systolic velocity measured by tissue Doppler imaging is closely correlated with myocardial blood flow measured by the microsphere technique. Accordingly, our data showed an increased myocardial systolic velocity in the subendocardium but not in the subepicardium after bradykinin infusion in control dogs. This mechanism may also contribute to the improvement of the subendocardial function in GRMD dogs. However, since eNOS and nNOS system and myofilament protein phosphorylation are altered in GRMD hearts, this mechanism would be functional after restoration of the eNOS and nNOS system as well as responsiveness of cardiomyocytes.

Bradykinin is a full B2 agonist and exerts its actions essentially through B2 receptors constitutively presented in various tissues. In endothelial cells, B2 receptor activation increases intracellular Ca2+ that activate eNOS to release NO and phospholipase A2 to produce arachidonic acid that is metabolized into prostacyclin or endothelium-derived hyperpolarizing factor. Bradykinin releases NO by modulating eNOS phosphorylation/dephosphorylation. This should be impaired when the eNOS level is reduced in the heart. One of our new findings is that bradykinin upregulated both eNOS and nNOS levels in the left ventricle of GRMD dogs. This was in accordance with the upregulation of e/nNOS in arterial vessels of GRMD dogs. This allowed bradykinin to enhance NO production leading to improved myocardial function. The mechanism by which bradykinin regulates eNOS and nNOS levels needs further investigation. A limitation of the NOS activity assay used here was that the activity as measured was not verified to be blockable by a NOS inhibitor. Finally, linear relationships between e/nNOS and specific sarcomeric protein phosphorylation and between e/nNOS or specific sarcomeric protein phosphorylation and functional changes in intact animals or in isolated cardiomyocytes suggest substantial cause-effect between related parameters.

In conclusion, this study extended our knowledge about dystrophin-deficiency cardiomyopathy, showing marked subendocardial contractile impairment, loss of endo-epicardial length-dependent activation gradient, altered phosphorylation of sarcomeric regulatory proteins, and reduced myocardial eNOS and nNOS levels. Bradykinin treatment normalized these abnormalities and LV contractile performance in GRMD dogs. Although little is known about these aspects in DMD patients with cardiomyopathy, because of aetiological similarity between GRMD and DMD, abnormalities observed in GRMD may occur in DMD patients and the effects of bradykinin may be expected in DMD patients. Finally, our data suggest that the sarcomeric protein and e/nNOS are potential targets for fighting DMD cardiomyopathy.

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**References**


**Supplementary material**

Supplementary material is available at Cardiovascular Research online.


