Malignant Hyperthermia Phenotype

Hypotension Induced by Succinylcholine in Susceptible Swine

Daniel C. Sigg, M.D.,* Paul A. Iaizzo, Ph.D.†

Background: Succinylcholine causes immediate and severe arterial hypotension in swine with the malignant hyperthermia phenotype. The underlying mechanisms are unknown.

Methods: Malignant hyperthermia-susceptible (MHS; n = 10) and normal swine (n = 5) were anesthetized with thiopental. The following were monitored: electrocardiogram; arterial blood pressure; pulmonary artery, central venous, and left and right ventricular pressure; cardiac output; end-tidal carbon dioxide; core temperature; peripheral-blood flows; and arterial blood gases. After a control period, 2 mg/kg succinylcholine was given intravenously. Three MHS animals received 1 mg/kg vecuronium and two MHS animals received 2.5 mg/kg dantrolene intravenously. The effects of succinylcholine on left and right ventricular pressure and contractility were analyzed in isolated hearts. The effects of 0.06 mg/kg succinylcholine on isotropic tension development were recorded in isolated femoral artery rings.

Results: Succinylcholine caused an early, severe decrease in blood pressure, cardiac output, left ventricular pressure, and left ventricular contractility in MHS swine but not in normal swine; no significant differences were found in heart rate, right ventricular parameters, systemic vascular resistance, and preload (pulmonary diastolic pressure, central venous pressure). The succinylcholine-induced hypotension and associated effects were not prevented by dantrolene. However, pretreatment with high-dose vecuronium prevented not only the cardiovascular depression, but also MH. In addition, no phenotypic differences of succinylcholine on contractility or left ventricular pressure were observed in the isolated working hearts. Similarly, succinylcholine did not cause a significantly different relaxation in rings in either phenotype.

Conclusion: Succinylcholine-induced hypotension occurred before muscle hypermetabolism in MHS swine. Succinylcholine had no differential physiologic effects on either the isolated heart or on isolated arteries. This hypotension could not be prevented by dantrolene but was prevented by pretreatment with high-dose vecuronium. Thus, an indirect mechanism such as the release of a cardiac depressant from skeletal muscle may have caused this hypotensive response. (Key words: Anesthetics; depolarizing neuromuscular blocking agents; nondepolarizing neuromuscular blocking agents.)

MALIGNANT hyperthermia (MH) is a genetic disease characterized by muscle hypermetabolism, and its pathophysiologic basis is considered to be defects in the calcium regulation metabolism within skeletal muscle. In humans, this disorder has a heterogenetic origin. In the swine model, a single point mutation in the RYR1 gene is responsible for this phenotype.

Succinylcholine, a depolarizing muscle relaxant, is a potent trigger of MH. Administration of succinylcholine to MH-susceptible (MHS) swine causes a severe arterial hypotension before the animals actually display hypermetabolism. The hypotension has been observed to occur immediately (within 2 min of succinylcholine administration), even when clinically used doses of pancuronium are given as prior treatment. Thus, the cardiovascular depression was not considered to be caused by the effects of succinylcholine on the skeletal muscle itself (e.g., due to hyperemia and consecutive vasodilation after muscle fasciculations); rather, it was considered to be due to direct effects on the cardiovascular system. In other words, the MHS phenotypic response to succinylcholine is not easily explained by the genotypic defect of the skeletal muscle calcium release channel. Several studies have concluded that tissues other than the skeletal muscle may be altered in MH, with described effects on the heart being controversial. Therefore, it was of interest to reinvestigate the effects of succinylcholine on the cardiovascular system in vivo and in vitro. The purpose of the present study was to gain new insights into the hypotensive response mechanism caused by succinylcholine in MHS swine. To do so, both in vivo and in vitro experiments were performed. The latter were undertaken to deter-

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mine whether observed effects of succinylcholine were
due to either direct effects on the heart or arteries, or
due to their responses to either a secondarily released
substance or reflex mechanism.

Methods

In Vivo Effects of Succinylcholine

After obtaining approval from the Institutional Animal
Care and Use Committee of the University of Minnesota,
the following experiments were conducted on pure-
bred Pietrain swine with the homozygous mutation of
arginine 615 in the ryanodine receptor (RYR1). These
MHS animals, as well as nonsusceptible normal mongrel
swine, were obtained from the University of Minnesota
Rosemount Animal Facility (weight of MHS swine:
42.1 ± 5.1 kg; normals: 47.5 ± 7.6 kg, mean ± SD).

Malignant hyperthermia–susceptible swine (n = 10)
and normal swine (n = 5) were initially anesthetized
with 20 mg/kg intramuscular ketamine (Ketavet; Phoe-

catheter (Jelco; Johnson & Johnson, Arlington, TX) was
placed, and thiopental 20–25 mg/kg (Gensia Pharma-
cueticals, Inc., Irvine, CA) was administered intravenously.
The animals were intubated with a 6.5–7-mm ID
endotracheal tube and mechanically ventilated with 65%
N2O and 35% O2 to maintain an arterial carbon dioxide
partial pressure (PaCO2) of 40 ± 2 mmHg. End-tidal
carbon dioxide was monitored using a gas analyzer (Nell-
cor, Hayward, CA). No muscle relaxants were adminis-
tered at this time. A thiopental infusion was then titrated
to effect at a rate of approximately 100–200 mg/min. A
femoral artery cannula (A. femoralis superficialis) was
used for monitoring invasive blood pressure, and an
axillary artery cannula was used for blood sampling.
Arterial oxygen partial pressure (PAO2), PAH, pH, base
excess, K+, and Ca2+ were determined from fresh arte-
rial samples using a blood gas analyzer with temperature
compensation (Model 1304; Instrumentation Labo-
ratories, Inc., Lexington, MA). Mikro-Tip catheter transduc-
ers (5 French, Model MPC-500; Millar Instruments, Inc.,
Houston, TX) were placed in the right and left ventricles
via access through the right external jugular vein and
the right carotid artery, respectively. In addition, a bal-
loon-tipped pulmonary artery thermodilution catheter
(Swan-Ganz catheter model 93A-131-7F; American Ed-
wards Laboratories, Santa Ana, CA) was inserted via the
right external jugular vein and advanced into the pulmo-

nary artery to measure pulmonary artery pressures,

blood temperatures, and thermodilution cardiac outputs
(Cardiac output monitor model 9520A; American Ed-
wards Laboratory). A five-electrode lead configuration
was used to monitor electrocardiograms (Spacelabs
model 1020; Spacelabs Inc., Chatsworth, CA). The com-
mon femoral artery and veins were surgically exposed,
and femoral artery and vein blood flow was monitored
using ultrasonic transit-time flow meters (Transonic Sys-
tems Inc., Ithaca, NY). In one MHS animal (MHS 3), flow
artery data were not collected because of a technical
problem. Core temperatures were measured using axil-
lar, rectal, and pulmonary artery probes.

A specially designed pressure bulb was positioned be-
tween the upper and lower incisors to assess the relative
force output of the muscles of mastication, especially the
masseter muscle. The signal from this unit was con-
vected to voltage using a pressure transducer connected
to the SpaceLabs monitor model 1020.

An additional two normal and three MHS animals were
used for the isolated heart studies only and not for the in
vivo protocol.

The following data were automatically collected using
data acquisition hardware and LabVIEW software (Na-
tional Instruments, Austin, TX): heart rates, arterial
blood pressures, femoral artery and vein blood flows,
and end-tidal carbon dioxide levels. Blood gas data, core
temperatures, and cardiac outputs were recorded
manually.

Epochs of the following data were collected at a sam-
ping frequency of approximately 670 Hz by an AT-
CODAS analog-to-digital data acquisition system (Dataq
Instruments Inc., Akron, OH): pulmonary artery pres-

dures, central venous pressures, right ventricular pres-
sures, and left ventricular pressures. The first derivative
of left and right ventricular pressures (dP/dt) was deter-
mined by off-line differentiation of the pressure signal.
Maximum positive (+dP/dt) measurements were taken from
the differentiated left and right ventricular pressure
waves. Furthermore, systemic vascular resistance was
calculated using the following simplified formula: sys-
temic vascular resistance = mean arterial pressure/car-
diac output.

For these investigations, all animals were maintained
normothermic (38.05 ± 0.2°C) using convective-air
warming as needed (Bair Hugger; Augustine Medical
Inc., Eden Prairie, MN). The animals received NaCl 0.9%
for intravenous fluid administration via the ear vein

catheter (approximately 600–800 ml/h during the con-
trol periods).

After the control periods, (PaCO2 40 ± 2 mmHg, tem-
SUCCYNLCHOLINE-INDUCED HYPOTENSION IN MHS SWINE

Table 1. Time to Trigger Malignant Hyperthermia, Malignant Hyperthermia Diagnosis, Masseter Bulb Pressures, and Epinephrine Administration in Malignant Hyperthermia-Susceptible Animals Exposed to Succinylcholine 2 mg/kg In Vivo

<table>
<thead>
<tr>
<th>Triggering time</th>
<th>MHS 1</th>
<th>MHS 2</th>
<th>MHS 3</th>
<th>MHS 4</th>
<th>MHS 5</th>
<th>MHS D1</th>
<th>MHS D2</th>
<th>MHS V1</th>
<th>MHS V2</th>
<th>MHS V3</th>
</tr>
</thead>
<tbody>
<tr>
<td>MH (min, PaCO₂ &gt; 70 mmHg)</td>
<td><strong>20</strong></td>
<td>5</td>
<td>22</td>
<td>7</td>
<td>*</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>MH diagnosis</td>
<td>In vivo</td>
<td>In vivo</td>
<td>In vivo</td>
<td>In vivo</td>
<td>IVCT</td>
<td>IVCT and in vivo†</td>
<td>IVCT</td>
<td>IVCT</td>
<td>In vivo‡</td>
<td>In vivo§</td>
</tr>
<tr>
<td>Maximal developed masseter bulb pressure (mmHg)</td>
<td>—</td>
<td>254</td>
<td>—</td>
<td>42</td>
<td>89</td>
<td>30</td>
<td>49</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Epinephrine</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>50 μg at 5 min</td>
<td>3 mg at 5 min</td>
<td>No</td>
<td>100 μg at 7 min</td>
<td>100 μg at 12 min</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

* Died at 5 min.
† 30 min after first dose of succinylcholine, second dose of succinylcholine and halothane 2 minimum aveolar concentration; 10 minutes until PaCO₂ > 70 mmHg.
‡ 90 min after first dose of succinylcholine, second dose of succinylcholine; 15 minutes until PaCO₂ > 70 mmHg.
§ 70 min after first dose of succinylcholine, 10 min after second dose of vecuronium; exposure to halothane 1 minimum aveolar concentration (0.67%); 30 minutes until PaCO₂ > 70 mmHg.

MH = malignant hyperthermia; MHS = malignant hyperthermia-susceptible (no pretreatment); MHS D = pretreatment with dantrolene 2.5 mg/kg intravenous; MHS V = pretreatment with vecuronium 1 mg/kg intravenous; IVCT = in vitro contracture test.

Perature 38 ± 0.5°C) and just before succinylcholine was given, all data were collected using the methods previously described (indicated as t = 0 min). Succinylcholine (Quelicin; Abbott Laboratories, North Chicago, IL), as a bolus dose of 2 mg/kg, was administered intravenously by injection into the central port of the pulmonary artery catheter; all data were sampled for a subsequent 15 min (manually recorded data were obtained at t = 1.5, 3, 5, 10, and 15 min). Five MHS animals and five normal swine did not receive any pretreatment (table 1). Two MHS animals received an intravenous pretreatment of 2.5 mg/kg dantrolene (Norwich-Eaton Pharmaceuticals, Norwich, NY) in 250 ml mannitol 1% 30 min before the bolus succinylcholine injection. Similarly, three MHS animals received a 1-mg/kg intravenous pretreatment with vecuronium (Norcon; Organon Pharmaceuticals, West Orange, NJ) 10 min before succinylcholine was administered (table 1).

In pilot studies, two MH animals were pretreated with either: (1) 1 mg/kg ranitidine intravenously (Zantac; Glaxo Pharmaceuticals, Research Triangle Park, NC) and 1 mg/kg diphenhydramine intravenously (Elkins-Sinn, Inc., Cherry Hill, NJ); or (2) atropine 20 μg/kg intravenously (Elkins-Sinn, Inc.). The ranitidine/diphenhydramine and atropine were administered a minimum of 30 min before the bolus dose of succinylcholine was injected.

Treatment of severe, succinylcholine-induced arterial hypotension included intravenous fluids (NaCl 0.9%) as needed, initiated not before 5 min after the succinylcholine administration. If hypotension persisted beyond 5 min, administration of sympathicomimetic agents, such as epinephrine, was also provided (table 1).

Susceptibility to MH was verified by the initiation of MH in vivo (PaCO₂ > 70 mmHg at constant ventilation) and/or by in vitro contracture testing. For the latter, bundles of rectus abdominis muscle were used for testing with the protocol recommended by the North American Malignant Hyperthermia Registry, on equipment previously described (table 1).13,14

Effects on an Ex Vivo Isolated Heart Model

After median sternotomy was performed, a cardioplegia cannula (9 French double lumen, Medtronic, Minneapolis, MN) was introduced into the aorta, and refrigerated modified St. Thomas’ cardioplegia (NaCl 110 mm, KCl 16 mm, CaCl₂ 1.2 mm, MgCl₂ 16 mm, NaHCO₃ 10 mm) was prepared for antegrade flow through the coronary vessels. A total of 10,000 USP units of heparin and 25 mg of adenosine were administered intravenously. Immediately after cardioplegia introduction, the excised hearts were placed in an iced saline slurry while transported to the apparatus, as well as during the (re)cannulation process. After removal of excess tissue and isolation of the great vessels, an aortic cannula (24 French) was directly inserted distal to the cardioplegia cannula. In addition, cannulas were inserted into the pulmonary artery (28 French), pulmonary vein (28 French), and directly into the right atrium (56 French). The cannulas were secured
into place, with remaining apertures into the heart either tied or sutured closed. The Millar pressure catheters were placed in vitro as they were used in the in vivo preparations described previously. The flow of cardioplegia was then stopped, and warm (38°C) perfusate (NaCl 118.0 mM, mannitol 16.0 mM, glucose 11.5 mM, NaHCO₃ 20.0 mM, EDTA 0.32 mM, KCl 4.5 mM, MgCl₂ 1.2 mM, NaH₂PO₄ 1.2 mM, Na pyruvate 2.27 mM, CaCl₂ 2.5 mM, insulin 10 U/l) was supplied to the cardiac chambers. If there was no spontaneous atrial-ventricular rhythm, the heart was defibrillated using an electrocardiac monitor unit (9790C Vitatron, Medtronic). The heart was allowed to function in a Langendorff perfusion mode for recuperation from ischemia until atrial-ventricular rhythm stabilized and the heart became self sustaining. Both sides of the heart were then allowed to work by supplying fluid pressure heads into the preload and afterload chambers. If there was no spontaneous atrial-ventricular rhythm, the heart was defibrillated using an electrocardiac monitor unit (9790C Vitatron, Medtronic). The heart was allowed to function in a Langendorff perfusion mode for recuperation from ischemia until atrial-ventricular rhythm stabilized and the heart became self sustaining. Both sides of the heart were then allowed to work by supplying fluid pressure heads into the preload and afterload chambers. The preload was held constant throughout the experiment (mean right atrial pressure 11 mmHg, range 5-12 mmHg; mean left atrial pressure 14 mmHg, range 12-15 mmHg); the afterload was defined as the diastolic aortic root pressure (mean, 24 mmHg; range, 14-30 mmHg).

Isolated hearts from six MHS animals and five normals were investigated. In MHS hearts that had been exposed to succinylcholine in vivo, the time between in vivo and in vitro administration was 90, 150, and 200 minutes, respectively. From an additional three MHS and two normal animals, the hearts were removed without having been exposed to succinylcholine in vivo. For these MHS animals, which were therefore not used for in vivo effects of succinylcholine, MH susceptibility was verified by in vitro contracture testing as previously described.

After a control phase, i.e., stabilized function with a normal sinus rhythm, succinylcholine 2 mg/kg was added to the Krebs solution, and the effects on left and right ventricular pressures and contractility (dP/dt) were analyzed at 1.5, 3, 5, and 10 min.

In Vitro Effects on Femoral Artery Rings

The common femoral arteries (opposite side from where the femoral cannula was placed) were removed from normal (n = 6) and MHS (n = 4) swine before succinylcholine exposure. Subsequently, no ischemia in the limbs was observed. The femoral arteries were prepared under a stereo-microscope as vessel rings without removing the endothelium. Care was taken to remove as much surrounding tissue as possible without damaging the intimal surface. The presence of endothelium was later verified by histologic assessment of selected preparations. The vessel rings (15 MH, 32 normals) were approximately 0.5-1 mm in diameter and weighed between 10 and 20 mg. The experiments were performed in organ chambers (42 ml) containing Krebs solution (NaCl 118.3 mM, KCl 4.7 mM, MgSO₄ 1.2 mM, KH₂PO₄ 1.2 mM, CaCl₂ 2.5 mM, NaHCO₃ 25 mM, glucose 11.1 mM, CaCl₂ EDTA 0.026 mM) that was gassed with 95% O₂/5% CO₂. Temperature of the bathing solution was kept constant at 37°C. The vessel rings were suspended between a fixed clip and a force transducer by two stainless-steel wires inserted into the lumen. Isometric tensions were recorded continuously. After this procedure, the preparations were allowed to equilibrate at their optimal length for approximately 30 min before drug administration. After a stable baseline reading was obtained, the following agents were studied: (1) phenylephrine added as incremental doses (0.5 μM per dose, up to 2 μM); (2) succinylcholine at a final bath concentration of 0.06 mM; and (3) acetylcholine at a 0.1-μM concentration (Sigma Chemical Co., St. Louis, MO). Vessel rings that did not elicit a response to phenylephrine or acetylcholine were excluded.

Statistical Analysis

Statistical analyses were performed using either repeated measures analysis of variance with a Bonferroni multiple comparison posttest or the two-tailed Mann-Whitney test, as appropriate. A P value < 0.05 was considered significant. The data were presented on an animal-by-animal basis or as mean ± SD unless otherwise indicated.

Results

In Vivo Study

The MH phenotype was verified by in vivo triggering (PaCO₂ > 70 mmHg at constant minute ventilation) and/or by in vitro muscle contracture testing as previously described (table 1).

Hemodynamic Data

Succinylcholine (2 mg/kg intravenously) caused a significant, severe decrease in arterial blood pressure in the MHS animals, including those pretreated with dantrolene (fig. 1A). In two MHS animals, epinephrine was necessary for blood pressure support 5 min after succinylcholine administration; for statistical comparisons between groups, hemodynamic data were provided only at 0, 1.5, and 3 min. In animals pretreated with 1 mg/kg...
Succinylcholine-Induced Hypotension in MHS Swine

A. 200 I" 150 100 50 0 E
B. 200 150 100 E

Fig. 1. In vivo mean arterial blood pressure (MAP), heart rate (HR), and cardiac output (CO) after administration of 2 mg/kg succinylcholine at time = 0 min for (1) individual MHS animals (MHS 1–5); (2) MHS animals pretreated with 2.5 mg/kg dantrolene (MHS D1 and 2); (3) MHS animals pretreated with 1 mg/kg vecuronium (MHS V1–3); and (4) normals (N 1–5). It can be observed that MAP and CO decreased significantly in MHS and MHS D, but not in MHS V or normals (N). MHS 4 and MHS D2 both required epinephrine therapy at 5 and 7 min, respectively (indicated by number sign). A decrease of MAP and CO in MHS V1 was considered to be caused by an air embolus (indicated by asterisk).

vecuronium (n = 3) and in normal swine, severe arterial hypotension was not observed (fig. 1B). However, one animal in this group developed a fatal hypotension 10 min after succinylcholine administration, probably caused by an air embolism, and died at 20 min; no acute effects of succinylcholine on the cardiovascular system were detected.

Another MHS animal without pretreatment died shortly after succinylcholine administration during the hypotensive period (t = 5 min). Neither of these animals displayed signs of a MH episode (Paco2 > 70 mmHg at constant ventilation); their MH susceptibility was confirmed by in vitro contracture testing.

In swine with the MH mutation, the mean arterial pressure just before succinylcholine administration was 96 ± 11 mmHg and subsequently decreased to 35 ± 7 mmHg at 1.5 min (P < 0.001; intragroup comparison), and to 41 ± 25 at 3 min (P < 0.01). In normal swine, the mean arterial pressure before succinylcholine administration was 89 ± 20 mmHg, and was 84 ± 15 mmHg and 86 ± 15 mmHg at 1.5 and 3 min posttimes, respectively. Importantly, the mean arterial pressures were statistically different between the genotypes at both 1.5 min (P < 0.001) and 3.0 min posttimes. Interestingly, pretreatment with vecuronium abolished the succinylcholine-induced hypotension completely (fig. 1B).

In three of the seven MHS animals, heart rates increased; however, these effects were relatively inconsistent and thus not significant (fig. 1C). No changes in heart rates were observed in MHS animals pretreated with vecuronium or in normals (fig. 1D).

Cardiac output decreased for only the MH animals (fig. 1E) after succinylcholine administration (from 4.1 ± 1
The succinylcholine-induced arterial hypotension in the MH genotype was associated with decreased left ventricular contractility (+dP/dt) at 1.5 min as well as 3 min after succinylcholine administration (P < 0.01 vs. normals and MHS with vecuronium; fig. 2A). Pretreatment with vecuronium abolished such decreases in left ventricular contractility in the MHS animals. Contractility was stable throughout in normals (fig. 2B). Associated with the abnormal changes in contractility in the MHS animals were concomitant and significant changes in left ventricular pressures (both at 1.5 and 3 min postadministration; P < 0.05) compared with preadministration values (fig. 2C); no contractility changes were observed in MHS swine pretreated with vecuronium or in normals (fig. 2D).

There was a significant decrease in systemic vascular resistance in MHS swine only at 5 min after succinylcholine injection, but not at 1.5 or 3 min (when excluding one animal pretreated with dantrolene; P < 0.05, intra-group comparison; table 2).

No genotype-specific changes were observed in either right ventricular pressures or contractilities (table 2). The mean pulmonary artery pressures before succinylcholine administration did not change significantly and were 22 ± 4 mmHg in normals and 26 ± 3 mmHg in MHS animals; at 1.5 min, they were 25 ± 5 mmHg in normals and 29 ± 4 mmHg in MHS animals; and at 3 min, they were 24 ± 5 mmHg in normals and 21 ± 9 mmHg in MHS animals. In particular, pulmonary diastolic pressures (table 2) and central venous pressures (data not shown) remained stable for both genotypes after succinylcholine was administered.

In pilot studies, pretreatment with either atropine or diphenhydramine/ranitidine did not prevent immediate cardiovascular depression or MH in susceptible animals (data not shown).

In Vivo Study: Metabolic Data
No significant changes of K+ and Ca2+ were detected during the hypotensive period in MHS swine (table 2). The mean time to trigger significant episodes of MH in susceptible swine (i.e., PaCO2 > 70 mmHg, fixed ventilation) was 13.5 min (table 1). Significant decreases in pH were observed at 5 and 10 min after succinylcholine administration (P < 0.05). Statistically significant changes in mean PaCO2 did not occur within the first 10 min postsuccinylcholine, but a clear trend of increased PaCO2 was observed (table 3). Changes in individual end-tidal carbon dioxide values are presented in figures 3A and B. Core temperatures were significantly elevated postsuccinylcholine in these MH animals, but not until
Table 2. Changes in Cardiovascular Variables and Metabolic Parameters after the Administration of Succinylcholine 2 mg/kg Intravenous (t = 0) in MHS Swine.† MHS Swine with Vecuronium Pretreatment† and Normal Swine

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Right Ventricular dp/dt (mmHg/s)</th>
<th>Mean Right Ventricular Pressure (mmHg)</th>
<th>Peripheral Vascular Resistance (mmHg · min⁻¹ · l⁻¹)</th>
<th>Pulmonary Diastolic Pressure (mmHg)</th>
<th>K⁺ (mM/l)</th>
<th>Ca²⁺ (mM/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHS swine (n = 7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>259 ± 65</td>
<td>14 ± 5</td>
<td>25 ± 7</td>
<td>21 ± 7</td>
<td>4.15 (3.8-4.4) ± 0.2</td>
<td>1.2 (0.96-1.5) ± 0.2</td>
</tr>
<tr>
<td>1.5 min</td>
<td>295 ± 45</td>
<td>19 ± 3</td>
<td>22 ± 13</td>
<td>26 ± 6</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3 min</td>
<td>267 ± 102</td>
<td>15 ± 6</td>
<td>—</td>
<td>21 ± 8</td>
<td>4.2 (3.6-4.7) ± 0.5</td>
<td>1.2 (0.84-1.29) ± 0.2</td>
</tr>
<tr>
<td>5 min</td>
<td>323 ± 152</td>
<td>20 ± 5</td>
<td>16 ± 14</td>
<td>21 ± 5</td>
<td>4.1 (3.4-4.7) ± 0.5</td>
<td>1.1 (0.77-1.32) ± 0.2</td>
</tr>
<tr>
<td>10 min</td>
<td>423 ± 196</td>
<td>23 ± 8</td>
<td>23 ± 14</td>
<td>28 ± 14</td>
<td>4.5 (3.8-5.3) ± 0.6</td>
<td>1.2 (0.92-1.31) ± 0.2</td>
</tr>
<tr>
<td>MHS swine with vecuronium pretreatment (n = 3)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Control</td>
<td>352 ± 34</td>
<td>19 ± 1</td>
<td>27 ± 3</td>
<td>24 ± 6</td>
<td>3.9 (3.6-4.3) ± 0.4</td>
<td>1.3 (1.19-1.44) ± 0.1</td>
</tr>
<tr>
<td>1.5 min</td>
<td>367 ± 34</td>
<td>20 ± 1</td>
<td>28 ± 4</td>
<td>29 ± 4</td>
<td>4.3 (3.8-4.2) ± 0.2</td>
<td>1.3 (1.25-1.3) ± 0.0</td>
</tr>
<tr>
<td>3 min</td>
<td>405 ± 17</td>
<td>22 ± 2</td>
<td>—</td>
<td>25 ± 12</td>
<td>4.3 (3.8-4.3) ± 0.3</td>
<td>1.3 (1.17-1.38) ± 0.1</td>
</tr>
<tr>
<td>5 min</td>
<td>375 ± 35</td>
<td>21 ± 2</td>
<td>30 ± 3</td>
<td>30 ± 6</td>
<td>3.9 (3.5-4.3) ± 0.4</td>
<td>1.2 (1.04-1.39) ± 0.2</td>
</tr>
<tr>
<td>10 min</td>
<td>395 ± 1</td>
<td>23 ± 4</td>
<td>29 ± 2</td>
<td>33 ± 10</td>
<td>3.8 (3.4-4.3) ± 0.3</td>
<td>1.1 (0.92-1.26) ± 0.2</td>
</tr>
<tr>
<td>Normal swine (n = 5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>265 ± 47</td>
<td>11 ± 3</td>
<td>21 ± 7</td>
<td>13 ± 7</td>
<td>4.1 (3.7-4.4) ± 0.3</td>
<td>1.2 (1.01-1.39) ± 0.2</td>
</tr>
<tr>
<td>1.5 min</td>
<td>265 ± 41</td>
<td>12 ± 2</td>
<td>20 ± 4</td>
<td>16 ± 8</td>
<td>4.3 (3.6-4.6) ± 0.5</td>
<td>1.1 (0.99-1.32) ± 0.2</td>
</tr>
<tr>
<td>3 min</td>
<td>261 ± 33</td>
<td>12 ± 1</td>
<td>—</td>
<td>14 ± 7</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>5 min</td>
<td>268 ± 55</td>
<td>12 ± 2</td>
<td>20 ± 6</td>
<td>15 ± 6</td>
<td>4.4 (4.1-4.6) ± 0.2</td>
<td>1.2 (1.01-1.34) ± 0.1</td>
</tr>
<tr>
<td>10 min</td>
<td>265 ± 42</td>
<td>12 ± 2</td>
<td>18 ± 6</td>
<td>15 ± 7</td>
<td>4.3 (3.9-4.6) ± 0.3</td>
<td>1.1 (1.06-1.33) ± 0.1</td>
</tr>
</tbody>
</table>

* Including swine with dantrolene pretreatment.
† 1 mg/kg.
‡ Pooled data from MHS 1-5 and MHS D1,2 (see table 1).
MHS = malignant hyperthermia susceptible; dp/dt = contractility.

several minutes later. For example, the esophageal temperatures before succinylcholine were 37.9 ± 0.3°C in susceptible swine (n = 4), and at 10 min after succinylcholine administration, they increased to 38.3 ± 0.3°C (P < 0.05, intragroup comparison; table 3).

The initial administration of succinylcholine did not induce episodes of MH in animals pretreated with either dantrolene or vecuronium. However, MH was triggered subsequently in two animals pretreated with vecuronium and in one MHS animal pretreated with dantrolene. The readministration of succinylcholine in one vecuronium animal 90 min after the first dose induced a cardiovascular reaction very similar to that without pretreatment; the mean arterial pressure decreased from 95 to 45 mmHg (table 1).

The maximum change in masseter force after succinylcholine administration (within 90 s) was 92 mmHg in MHS swine (n = 5) and 2 mmHg in normal animals (n = 4; P < 0.05). No change in masseter force was observed in MHS animals with vecuronium pretreatment (n = 3; table 1).

Femoral artery blood flow of MHS animals decreased at 3-4 min after succinylcholine administration and increased significantly at 8-11 min (P < 0.05, intragroup

Table 3. Changes in Metabolic Parameters after the Administration of Succinylcholine 2 mg/kg Intravenous (t = 0) in MHS and Normal Swine

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>P&amp;ksi;&amp;agr;ο&amp;agr;ο (mmHg)</th>
<th>pH₀</th>
<th>Esophageal Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHS swine (n = 4)*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>40.3 ± 2</td>
<td>7.5 ± 0</td>
<td>37.9 ± 0.3</td>
</tr>
<tr>
<td>5 min</td>
<td>62 ± 14</td>
<td>7.3 ± 0.1</td>
<td>37.9 ± 0.4</td>
</tr>
<tr>
<td>10 min</td>
<td>63 ± 8</td>
<td>7.2 ± 0.1</td>
<td>38.3 ± 0.3</td>
</tr>
<tr>
<td>MHS and dantrolene (n = 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>40 ± 2</td>
<td>7.5†</td>
<td>38.1 ± 0.6</td>
</tr>
<tr>
<td>5 min</td>
<td>21 ± 11</td>
<td>7.6†</td>
<td>38 ± 0.4</td>
</tr>
<tr>
<td>10 min</td>
<td>46 ± 9</td>
<td>7.3†</td>
<td>37.9 ± 0.5</td>
</tr>
<tr>
<td>MHS and vecuronium (n = 3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>39 ± 2</td>
<td>7.5 ± 0</td>
<td>38 ± 0.2</td>
</tr>
<tr>
<td>5 min</td>
<td>38 ± 3</td>
<td>7.5 ± 0</td>
<td>37.9 ± 0.2</td>
</tr>
<tr>
<td>10 min</td>
<td>36 ± 3</td>
<td>7.4 ± 0.1</td>
<td>37.9 ± 0.2</td>
</tr>
<tr>
<td>Normal swine (n = 5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>42 ± 4</td>
<td>7.5 ± 0.03</td>
<td>38.1 ± 0.2</td>
</tr>
<tr>
<td>5 min</td>
<td>41 ± 2</td>
<td>7.5 ± 0.02</td>
<td>38 ± 0.2</td>
</tr>
<tr>
<td>10 min</td>
<td>41 ± 2</td>
<td>7.5 ± 0.05</td>
<td>37.9 ± 0.2</td>
</tr>
</tbody>
</table>

* One animal died 5 min after succinylcholine administration.† Data from one animal.
MHS = malignant hyperthermia susceptible.

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A. End-tidal carbon dioxide (ET CO₂) increased after intravenous succinylcholine 2 mg/kg at time = 0 min in MHS animals but not in those pretreated with dantrolene (MHS D), vecuronium (MHS V), or in normals (N). A temporary decrease of ET CO₂ was considered to be caused by an air embolus in this animal (*). This animal required bolus doses of epinephrine to maintain normal blood pressure (table 1).

B. Comparison, fig. 4). In the susceptible swine, a similar decrease of venous blood flows at 3 and 4 min and significant increases were observed at 9, 10, 11, and 12 min (P < 0.05, analysis of variance). Arterial and venous flows were stable throughout in normals and in the vecuronium-pretreated MH animals.

Ex Vivo Isolated Heart Studies
Administration of succinylcholine at an equivalent dose to 2 mg/kg to the Krebs perfusate had no effect on either right and left ventricular contractility or pressures, or on heart rates in hearts isolated from either genotype. The left ventricular contractility and left ventricular pressures of isolated MH and normal swine hearts are shown in figure 5.

Isolated Femoral Artery Rings
The results from these investigations are summarized in figure 6. The baseline force was 0.88 ± 0.32 g in rings isolated from normal swine and 0.91 ± 0.3 g from the MHS swine. After an average dose of 1.65 ± 0.37 μg phenylephrine in normal swine and 1.85 ± 0.39 μg in MHS swine, the mean force was 3.68 ± 3.02 g in normal swine and 2.93 ± 2.46 g in rings from MHS swine, which for both cases were significantly different when compared with baseline values (P < 0.001, repeated measures analysis of variance and Bonferroni posttest). When comparing means of normal versus MHS animals, no differences could be detected, although the mean forces of the vascular rings from normal animals tended to be higher after phenylephrine administration (fig. 6).

The administration of 0.06 mM succinylcholine caused a small but insignificant reduction in mean force in rings isolated from either genotype: 0.25 ± 0.41 g for MHS swine, 0.63 ± 0.72 g for normal animals (P < 0.05, analysis of variance). Arterial and venous flows were stable throughout in normals and in the vecuronium-pretreated MH animals.
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Fig. 5. Succinylcholine administration caused no significant changes in in vitro left ventricular contractilities (LV dP/dt) or mean left ventricular pressures (LVP) in hearts isolated from MHS animals. Control data were obtained from hearts isolated from normal animals (N; n = 5).

was 49 ± 34.4% in MHS swine and 78 ± 29.7% for normal swine (P < 0.001, unpaired two-tailed t test).

Discussion

Despite advances in the understanding of the molecular basis of MH, further knowledge of the genotype-phenotype association is desirable. Although abnormal increases of myoplasmic calcium of isolated MHS skeletal muscle fibers in response to halothane exposure is routinely used for the in vitro diagnosis, succinylcholine rarely causes abnormal contractions or contractures in vitro. Nevertheless, succinylcholine in vivo can readily induce episodes of MH in susceptible swine. Somewhat surprising, the pathologic mechanism by which succinylcholine initiates MH remains largely un-

Fig. 6. Isometric forces of femoral artery vascular rings obtained from MHS (black columns, n = 15 rings) and normal swine (white columns, n = 32 rings). At baseline, no significant differences in forces were detected between the groups. The addition of 0.2 μM phenylephrine (PHE) increased force development significantly in all preparations. The addition of succinylcholine 0.06 mM, the equivalent dose to 2 mg/kg intravenously, did not lead to a significant relaxation in rings from either group. Finally, 0.1 μM acetylcholine increased relaxation in both groups but more significantly in preparations from normal animals.
known. Furthermore, bolus succinylcholine administration causes severe hypotension in MH animals, and this response is also poorly understood.\textsuperscript{3} It was previously reported that pancuronium pretreatment at clinical doses greatly attenuated the succinylcholine-induced skeletal muscle fasciculations but did not prevent either arterial hypotension or subsequently induced MH episodes.\textsuperscript{3} In addition, increases in circulating catecholamines were not responsible for either the hypertensive response or subsequent initiation of a MH episode; yet, the pancuronium pretreatment that did not prevent these responses was associated with a suppressed catecholamine release.\textsuperscript{5}

Dantrolene pretreatment has been described to prevent myocardial necrosis by suppressing catecholamine release that is normally associated with succinylcholine administration.\textsuperscript{17} It was speculated that succinylcholine may have additional effects such as an altered calcium release in the sympatho-adrenergic system. Pancuronium pretreatment prevented the succinylcholine-induced increase in catecholamines in MHS swine.\textsuperscript{5}

Several reports support the hypothesis that an altered calcium metabolism may be found in tissues other than the skeletal muscle in humans or swine.\textsuperscript{5,7-10} For example, abnormal action potential responses to halothane in cardiac muscle, increased inositol phosphate concentrations, and disordered catecholamine release and consecutive myocardial necrosis after succinylcholine administration have been described in susceptible swine.\textsuperscript{1,6,17} Inotropic effects of isoproterenol on force of contraction were considered more pronounced in heart muscle isolated from the right ventricles of susceptible swine, and this effect was potentiated by succinylcholine.\textsuperscript{18} However, in other reports, no differences between heart muscle isolated from normal swine or those with MH genotype could be found. For example, no significant differences in the effects of \( \beta \)- and \( \alpha \)-adrenergic agonists, adenosine, and carbachol were shown by the same investigators in heart muscles isolated from the left ventricle of normal and MHS swine.\textsuperscript{11} Altered myocardial oxygen consumption or lactate production has not been associated with MH swine.\textsuperscript{12} In one study investigating the potential for cardiomyopathy in MH, nine endomyocardial biopsy results from susceptible humans did not provide a morphologic explanation for abnormal cardiac function, which was present in three of the nine patients.\textsuperscript{19}

Our study clearly demonstrated that the \textit{in vivo} administration of succinylcholine to MHS swine produces a significant and early onset (after 1.5 min) decrease in arterial blood pressure, which confirms an earlier study by one of the present investigators.\textsuperscript{3} This arterial hypotension occurs before classically described features of a MH episode.\textsuperscript{5} This hypotension was associated with: (1) a severe decrease in left ventricular contractility; (2) a decrease in cardiac output; (3) little or no significant changes in systemic vascular resistance; and (4) unchanged preload. Thus, succinylcholine administered \textit{in vivo} has a negative inotropic effect in Pietrain swine with the \textit{RYR1} MH genotype. Interestingly, no effects of similar bolus doses of succinylcholine on either \textit{ex vivo} isolated hearts or on isolated femoral artery rings from these same swine could be demonstrated. This suggests an indirect or secondary effect of succinylcholine on the heart in susceptible animals. However, pretreatment with mega doses of vecuronium not only completely abolished the cardiovascular depression associated with the administration of succinylcholine to MHS swine, but also prevented subsequent signs of a MH crisis. Thus, it is hypothesized that the succinylcholine-induced cardiovascular depression is directly associated with a primary defect within the skeletal muscle and that the interaction of succinylcholine with functional and extrajunctional nicotinic acetylcholine receptors is required. For example, succinylcholine could release a transmitter by a mechanism yet to be identified; such cardiodepressant could be directly released from skeletal muscle.

Although the finding that vecuronium prevented cardiovascular depression and MH may not necessarily have primary clinical significance, hypertensive responses after succinylcholine administration can be observed clinically. Such responses are commonly caused by an anaphylactic or anaphylactoid reaction leading to histamine release.\textsuperscript{20} Yet, pretreatment with antihistamines in the present study did not attenuate the cardiovascular depression induced by succinylcholine in MHS swine (a pilot study). On the other hand, an abnormal cardiovascular reflex could lead to the observed cardiovascular depression. However, it was noted that the hypotension was not associated with increased vagal activities (\textit{i.e.}, bradycardia). Furthermore, pretreatment with atropine, a blocker of the muscarinic receptors, did not prevent succinylcholine-induced cardiovascular depression in one MH swine (pilot study). Altered potassium and calcium levels were ruled out as possible sources of cardiovascular depression. In addition, in a recent pilot study, no associated changes in magnesium, histamine, or bradykinin levels were detected during succinylcholine-induced hypotension in susceptible swine (unpublished observation by our laboratory). Interestingly, pretreat-
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ment with clinical doses of dantrolene did not prevent the succinylcholine-induced hypotension, although it was effective in preventing any subsequent episodes of MH. This may support the notion that the initial acetylcholine receptor activation is more important than secondary effects on intracellular \[^{2+}\text{Ca}\] for induction of hypotensive responses.

Potential limitations of our study may include the following: the slope of the left and right ventricular pressure curves that determines the change of pressure over time (dP/dt) is subject to confounding factors. One could speculate that hypotension per se could artificially produce a decrease in left and right ventricular pressures by changing the slope of the curves. To test this limitation, severe arterial hypotension was induced by vasodilators (nitroglycerine and nitroprusside) in several control swine and did not induce changes in contractility (results not shown). Furthermore, we have no clear explanation why only the left ventricle showed a significant decrease in contractility; the sustained pulmonary pressures support the hypothesis that the right ventricle was less affected by succinylcholine. It may be that significant changes were easier to detect for left ventricular contractility simply because slopes were larger.

It is unclear why a clinical dose of pancuronium did not prevent the succinylcholine-induced hypotension, whereas the megadose of vecuronium pretreatment did. Our present opinion is that this is a dose-dependent phenomenon, and in our first study, an incomplete blocking of the acetylcholine receptors had occurred. This argument may be further substantiated by the notion that fasciculations were reduced but not completely prevented in the MHS animals receiving pancuronium pretreatment.

To eliminate the argument that the isolated heart studies were performed after the animals were exposed to succinylcholine in vitro, and that this lead to the null result, five animals (three MHS, two normal) were exposed to succinylcholine only in vitro, and yet the results obtained were similar.

In the current study, the femoral artery was chosen for the investigation of the effects of succinylcholine on isolated vascular rings. Succinylcholine could have differential effects on any kind and diameter of vessels. In preliminary studies, femoral vein preparations turned out to be too fragile to use for analyses. Thus, even though one cannot rule out an effect of succinylcholine on capacitance vessels (veins), we did not observe an initial significant reduction in systemic vascular resistance that should have been detected in case of a massive vasodilation. However, in several cases, a slight decrease of systemic vascular resistance was detected in both MHS and normal animals; this was considered to contribute to the hypotension in the MHS animals but was not the primary cause. Acetylcholine induced a significantly greater amount of relaxation in vascular rings from normal animals compared with those from MH animals. One possible explanation for this phenomenon is that the MHS bundles might have been more responsive to acetylcholine, for example, by an upregulation of acetylcholine receptors. However, there was no difference in response to succinylcholine between the genotypes.

Succinylcholine causes an early severe, sometimes fatal, cardiovascular depression in MHS swine. This was associated with decreased left ventricular function, a normal preload, and no significant changes in systemic vascular resistance. This cardiovascular depression can be completely prevented by pretreatment with a megadose of vecuronium, but not with dantrolene, yet both agents prevented the initiation of MH episodes. The cardiovascular depression cannot be explained by direct effects of succinylcholine on the heart or vasculature of these MHS swine. These findings suggest a primary involvement of acetylcholine receptors in triggering MH and causing cardiovascular depression. However, whether the receptors responsible for this reaction are located solely within the skeletal muscle and/or extrajunctional remains unknown. Our laboratory is conducting further investigations to determine the exact cause of succinylcholine-induced hypotension in MHS swine.

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References


