Rested-State Contractions and Rest Potentiation in Spontaneously Hypertensive Rats

Gustavo N. Pérez, Martín Vila Petroff, Alicia Mattiazi

To gain further insight into the excitation-contraction coupling mechanisms in hypertrophy, we studied rested-state contractions, rest decay curves, and rest potentiation under different experimental conditions using papillary muscles of spontaneously hypertensive rats (SHR) and age-matched normotensive Wistar and Wistar-Kyoto (WKY) rats. Under constant stimulation at 1.1 Hz, contractility and relaxation were not significantly different in hypertensive when compared with normotensive animals. Rested-state contraction (the first beat after a rest interval of 15 minutes) increased to 159.2 ± 23% and 123.5 ± 7.5% of prerest values in Wistar and WKY rats, respectively, whereas in SHR it did not differ from prerest values (92.8 ± 9.8%). Ryanodine, used to preferentially inhibit sarcoplasmic reticulum function, eliminated the differences in rested-state contractions observed between hypertensive and normotensive rats. Maximal rest potentiation (the first beat after a rest interval of 1 minute) was also significantly higher in Wistar and WKY rats than in SHR. These differences persisted at low extracellular Na+, when Ca2+ efflux via the Na+-Ca2+ exchanger was inhibited. Rest decay curves (the decay in contractility from maximal rest potentiation to rested-state contraction) showed a similar pattern in the three rat strains. The results suggest that the altered inotropic responses of the SHR arise from an alteration in calcium handling by the sarcoplasmic reticulum. Experiments on saponin-skinned trabeculae indicated that fractional calcium release induced by caffeine was significantly reduced in the SHR. We conclude that the altered inotropic response observed in SHR may reflect a diminished release of calcium from the sarcoplasmic reticulum. (Hypertension. 1993;22:306-314.)

Key Words • hypertrophy • myocardial contraction • papillary muscles • rat, inbred SHR

Myocardial function in different models of hypertrophy and heart failure has been the subject of considerable study. The question of whether hypertrophy is associated with a depressed or normal inotropic state has been raised by numerous investigators and remains controversial. It has been shown that the mechanical performance of the hypertrophied heart in spontaneously hypertensive rats (SHR) is preserved at 6 and even 12 months of age when conventionally evaluated; ie, no significant changes were observed in either maximum shortening velocity or peak developed tension. By contrast, in vitro studies have shown several types of alterations at different stages of the excitation-contraction coupling mechanism, ie, the cellular membrane—including the regulatory activity of both α- and β-adrenergic receptors—the sarcoplasmic reticulum (SR), and the myofibrils. All these results were obtained in nonfailing hypertrophied hearts of SHR younger than 12 months.

In ventricular myocardium of most mammalian species, the force of contractions induced by rhythmic stimulation reflects the brief increase in cytosolic free calcium produced by calcium entry through the sarcolemma and calcium release from intracellular stores. By contrast, contractions observed after rest intervals long enough to permit the development of a rested state (rested-state contractions, RSCs) appear to depend primarily on calcium entry during membrane depolarization. If rest intervals, longer than the basal interval but shorter than those required for the development of RSCs, are imposed, the first beat after the pause is potentiated (rest potentiation). As the rest interval is prolonged, the first beat after the pause increases up to a point (maximal rest potentiation) and then decreases, approaching the rested state asymptotically. This rest-dependent decay of contractility is thought to reflect the gradual loss of calcium from intracellular stores. In contrast to what has been described for most mammalian species, the RSC in rat ventricle is higher than steady-state contractions, suggesting that the rat ventricle maintains its store of releasable calcium more effectively over the rest period than other mammalian species.

The study of rest potentiation, RSCs, and rest decay curves under different experimental conditions has provided a simple approach for obtaining important, albeit indirect, information on calcium movements and calcium stores of normal myocardium of different species, including the rat. In the present investigation, we studied rest-dependent changes in contractile parameters to determine whether hypertrophy associated with the occurrence of spontaneous hypertension in the rat affects some of the mechanisms involved in the excitation-contraction coupling of the myocardium. We used interventions such as the addition of ryanodine and...
reduction of extracellular sodium as experimental tools to "preferentially" inhibit either SR\textsuperscript{36-38} or Ca\textsuperscript{2+} efflux.\textsuperscript{20} Additional experiments with saponin-treated trabeculae allowed us to evaluate in situ SR function and myofilament Ca\textsuperscript{2+} responsiveness of the hypertrophied myocardium. Our results demonstrate that both RSC and rest potentiation are depressed in the SHR with respect to Wistar-Kyoto (WKY) and Wistar rats at a stage of evolution of hypertrophy in which basal contractility is still preserved. The data support the contention that this altered response of the SHR arises from an alteration in the mechanism of calcium release from intracellular calcium stores.

**Methods**

Male SHR and sex-matched normotensive Wistar and WKY rats were used in this study at 6 months of age. The SHR and WKY strains were originally derived from Charles River Breeding Farms, Wilmington, Mass. All animals were housed under identical conditions and had free access to a standard dry meal and water. Systolic blood pressure was maintained long enough to ensure the disappearance of all the effects of the alteration of the stimulation interval. Any stimulation sequence thus included the perturbation of a single stimulation interval. This protocol was performed for each muscle in control Ringer's solution and in a solution with low extracellular [Na\textsuperscript{+}] (70 mmol/L). In an attempt to minimize the positive inotropic action of lowering extracellular Na\textsuperscript{+}, extracellular [Ca\textsuperscript{2+}] was decreased to maintain a constant [Ca\textsuperscript{2+}]-[Na\textsuperscript{+}] relation.

At the end of the experiment, the cross-sectional area was calculated from muscle length (at L\textsubscript{max}) and weight, assuming a uniform cross section and a specific gravity of 1.0.

**Chemically Skinned Trabeculae**

Loops of fine silk were tied around the ends of selected left ventricular trabeculae (approximately 200 \(\mu\)m wide, 1 mm long). The preparations were excised and mounted horizontally in an acrylic chamber between an adjustable stainless-steel rod and a fixed-tension transducer (AE801 strain gauge, Aksjeselskapet Micro-Electronikk, Horten, Norway) and stretched approximately 30%. Experimental solutions at 22°C were pumped through the muscle bath at 0.35 mL/min and were removed by a vacuum line.\textsuperscript{9}

**Force-pCa relation.** The trabeculae were treated with saponin (100 \(\mu\)g/mL) for 20 minutes\textsuperscript{20} in a relaxing solution containing (mmol/L) KCl, 140; MgCl\textsubscript{2}, 7; ATP, 5; phosphocreatine, 15; EGTA, 3; and imidazole, 25, as well as 0.1 mg/mL creatine kinase, pH 7.0. The calculated ionic strength of the relaxing solution was 0.180 mol/L. After treatment with saponin, the preparations were sequentially exposed to activating solutions containing selected concentrations of Ca\textsuperscript{2+}. The activating solutions were made by adding CaCl\textsubscript{2} to the relaxing solution. The concentration of CaCl\textsubscript{2} was adjusted to obtain a desired concentration of free Ca\textsuperscript{2+}. The free ionic concentrations in relaxing and activating solutions were calculated with a computer program provided by Fabiato and Fabiato.\textsuperscript{31} After a stabilization period of 20 minutes, the relaxing...
solution was replaced by activating solutions. The force induced by different calcium concentrations was recorded until a plateau was reached. For the characterization of the force-calcium curves, the data from each experiment were fitted individually to the Hill equation using a nonlinear least-squares method, where $T (\text{relative force}) = \frac{[\text{Ca}^{2+}]^n}{K + [\text{Ca}^{2+}]^n}$. The slope coefficient $(n_H)$ and the $pCa$ ($-\log [\text{Ca}^{2+}]$) that produced definite percentages of the maximal effect (from 10% to 90%) were computed for each curve.

Sarcoplasmic reticulum $Ca^{2+}$ uptake and release. The experimental protocol used to study SR $Ca^{2+}$ uptake was a modification of the method described by Endo.32 Trabeculae were treated with a lower saponin concentration (50 μg/mL) to ensure preservation of the SR.33,34 After the treatment with saponin, $Ca^{2+}$ in the SR was depleted by exposure to 25 mmol/L caffeine.32 An increase in caffeine concentration to 30 mmol/L does not appear to release additional $Ca^{2+}$. We have therefore used and then compared both methods.

Caffeine was obtained from Calbiochem Corp, San Diego, Calif. Caffeine and saponin were obtained from Sigma Chemical Co, St Louis, Mo. All other chemicals used were of analytical grade.

Data are expressed as mean ± SEM. A multiple comparison test for statistical analysis of differences among group means (Peritz’ $F$ test) was used when more than two groups were studied.38 When data from only two groups were compared, differences were analyzed by applying the Student’s $t$ test for nonpaired samples. A value of $P<.05$ was considered significant.

Results

General Characteristics of Rats and of Isometric Contractile Variables

None of the groups of animals studied showed evidence to suggest the presence of clinical cardiac failure. The general characteristics of the hypertensive and age-matched control rats at the time of the experiment are presented in Table 1. Mean data for isometric contraction parameters are presented in Table 2. There were no significant differences in any of the mechanical parameters between SHR and either WKY or Wistar rats.

Rested-State Contractions

Fig 1 shows the overall changes in DT and $+\tau$ after a 15-minute rest interval and after the RSC in Wistar and WKY rats and SHR. In both groups of normotensive animals, RSC was significantly higher than steady-state contraction values. The magnitude of the RSC in SHR was not significantly different from steady-state values and was significantly lower than the RSC in Wistar and WKY rats. In agreement with a previous study,24 the recovery pattern in Wistar rats consisted of a monotonic decrease to steady state. A similar pattern was observed in WKY rats, although from a lower RSC, whereas there was no obvious difference between RSC and the following beats in SHR.

Effect of Ryanodine on Rested-State Contractions

In another set of experiments, RSCs were studied in the presence of ryanodine. The rationale for this group of experiments was to preferentially inhibit SR function28-30 without affecting other aspects of the excita-
TABLE 2. Isometric Contraction Data From Normotensive and Hypertensive Rats

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Wistar (n=32)</th>
<th>WKY (n=35)</th>
<th>SHR (n=37)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT (mN/mm²)</td>
<td>7.94±1.18</td>
<td>14.01±1.96</td>
<td>11.07±1.67</td>
</tr>
<tr>
<td>+t ([mN/mm²]/s)</td>
<td>144.45±19.99</td>
<td>231.48±29.89</td>
<td>192.18±28.71</td>
</tr>
<tr>
<td>−t ([mN/mm²]/s)</td>
<td>95.26±13.04</td>
<td>150.43±20.09</td>
<td>127.89±20.69</td>
</tr>
<tr>
<td>TTP (msec)</td>
<td>62.53±1.96</td>
<td>72.00±3.51</td>
<td>70.25±2.91</td>
</tr>
<tr>
<td>t½ (msec)</td>
<td>38.57±1.3</td>
<td>45.75±2.49</td>
<td>46.08±3.05</td>
</tr>
<tr>
<td>Cross-sectional area (mm²)</td>
<td>0.77±0.04</td>
<td>0.89±0.05</td>
<td>0.86±0.04</td>
</tr>
</tbody>
</table>

WKY, Wistar-Kyoto rats; SHR, spontaneously hypertensive rats; DT, developed tension; +t, maximal rate of rise of tension; −t, maximal velocity of relaxation; TTP, time to peak tension; t½, half relaxation time. Values are mean±SEM.

Excitation-contraction coupling process. With this approach, tension development would be expected to depend primarily on calcium entry during accompanying membrane depolarization.19,20,24

Fig 2 shows that the recovery pattern from RSC in the presence of 3x10⁻⁸ mol/L ryanodine was virtually identical in the three groups. Ryanodine suppressed the potentiated RSC of Wistar and WKY rats and reversed the recovery pattern from a monotonic decrease to a monotonic increase toward steady state. In SHR, ryanodine produced a depression of RSC similar to that in normotensive rats and also converted the flat pattern of recovery to a monotonic increase to steady state. The inset to Fig 2 shows that ryanodine produced essentially the same decrease relative to steady-state contraction in the three rat groups when muscles were paced at 1.1 Hz. Similar results were obtained when +T was analyzed. These experiments suggest that calcium influx accompanying membrane depolarization was not altered in the SHR.19,20,24 They further suggest that an altered function of cardiac SR of SHR is involved in the difference in RSC observed between normotensive and hypertensive rats.

Postrest Potentiation and Rested-State Contraction: Influence of Low Sodium

The inotropic response of the three rat groups was studied at different rest intervals, from 30 seconds to 15 minutes. Because the decay in the magnitude of the first postrest contraction reflects the time-dependent loss of calcium from intracellular stores,19,20 the main goal of this experimental series was to establish whether the diminished RSC observed in SHR could be explained by an increased time-dependent calcium loss from intracellular stores during the rest interval. The experiments were performed in control Ringer’s solution and in a solution with low [Na⁺] (70 mmol/L) and with Ca²⁺ also reduced by 50%. The latter was used to modify the transmembrane distribution of sodium and calcium in an attempt to inhibit the possible contribution of the Na⁺-Ca²⁺ exchange process to the removal of calcium from intracellular stores.20

The results of these experiments are presented in Fig 3A and 3B. For clarity, only the data obtained for WKY rats and SHR are shown, as the results for WKY and Wistar rats were similar. In control Ringer’s solution, rest potentiation was maximal at rest intervals of 30 seconds and 1 minute in both WKY rats and SHR and then progressively decreased until RSC was reached. Although the decay pattern was similar in both rat groups, maximum rest potentiation was significantly greater in WKY rats than in SHR. Rest potentiation for both WKY rats and SHR in the presence of low sodium was of a lower magnitude than that observed with the control Ringer’s solution, although peak values were similar to those obtained under control conditions. At low sodium, maximal rest potentiation was higher in WKY rats than in SHR, and in both groups the decline in contractility with longer pauses was abolished. Simi-
lar results were obtained when DT instead of +T was analyzed. As shown in Fig 3A and 3B, the positive inotropic effect of lowering extracellular sodium was greater in WKY than in SHR papillary muscles (166±11% vs 133±14% of control). This might explain why maximal rest potentiation and RSC with low sodium were significantly higher in WKY rats than in SHR. However, the differences shown in Fig 3 were still present when the results obtained with low sodium were expressed as a percentage of their own control, ie, the twitch that preceded the pause with low sodium (data not shown).
These experiments provide evidence that the calcium loss from the cell during the rest interval is similar in SHR and WKY and Wistar rats. Rest potentiation is significantly lower in SHR than in WKY and Wistar strains, even when the calcium loss by the Na⁺-Ca²⁺ exchanger is minimized.

**Calcium Sensitivity of Myofilaments**

Fig 4 shows sample recordings of calcium-induced contractions in skinned fibers obtained from WKY and SHR left ventricles. The summarized results of these experiments are presented in Fig 5A. No significant differences were found in either calcium sensitivity of myofilaments or maximal DT when SHR were compared with WKY rats.

**Sarcoplasmic Reticulum Calcium Accumulation and Release**

In the experiments described in this section, SR calcium uptake and release were estimated by the measurements of both the amplitude and integral of transient contraction induced by caffeine. Because caffeine is known to affect calcium sensitivity of the myofilaments, we conducted a pilot series of experiments to determine whether caffeine had a different effect on Ca²⁺ sensitivity of the myofilaments in SHR and WKY rats. Fig 5 through 5D show that, in the presence of 25 mmol/L caffeine, the pCa-tension curve shifted toward lower Ca²⁺ concentrations in both the WKY and SHR groups. The increase in myofilament calcium sensitivity was slightly greater in SHR than in WKY rats, but this difference was not significant.

In a second series of experiments, we examined whether the ability of the SR to accumulate calcium was altered in trabeculae from SHR hearts. The experimental protocol used in these experiments is depicted in Fig 6A. Fig 6B shows the summarized results of experiments from six WKY and five SHR preparations. The data demonstrate that the time course of Ca²⁺ accumulation by the SR was similar in both rat groups. Typical examples of force transients from which the curves were constructed are shown in Fig 6C.

**Discussion**

A major finding of this investigation is that rest potentiation and RSC are depressed in SHR at a stage of evolution of myocardial hypertrophy when basal contractility is still preserved. The results further show that this may represent hypertrophic dependent changes of intracellular calcium handling at the SR level.

It has been shown that the cardiac pump function of the SHR is preserved at 1 year of age. At 18 months and older, changes in isolated muscle performance occur at a time when signs of cardiac failure are reported. The
6-month-old hypertensive rats used in the current study did not show evidence of clinical cardiac failure, and basal contractility was preserved. The depression in RSC and postrest inotropy observed in this study therefore cannot be attributed to cardiac failure and might represent an early sign in the transition of the functional status of the hearts.

In the present study, RSCs and rest potentiation were used as experimental tools to examine qualitative aspects of the dynamics of excitation-contraction coupling in the hypertrophic heart. In the absence of changes in the intrinsic sensitivity to Ca$^{2+}$ of the contractile element (Fig 5A), it seems reasonable to assume that changes in intracellular Ca$^{2+}$ dynamics during the myocardial contraction-relaxation cycle may contribute substantially to the diminished postrest response of SHR. A decrease in calcium influx, an increase in the efflux of this cation, or a diminished release of calcium from intracellular stores on resumption of stimulation should be considered as possible intervening factors. The experiments with ryanodine point to the SR as the likely intracellular locus responsible for the depressed response of hypertrophic heart and suggest that calcium influx accompanying membrane depolarization was not altered in the SHR heart. The results obtained at different rest intervals in control and low-sodium solutions further indicate that calcium leak from cardiac cells was similar in SHR and normotensive animals. These findings are consistent with in vitro experiments on isolated SR membrane vesicles from hypertrophied ventricles of 5- to 6-month-old SHR, as well as in hypertrophy induced by abdominal aortic constriction. Taken together, the results obtained in intact papillary muscles leave us with the third of the alternatives suggested above; ie, an impairment of the calcium release mechanism might be involved in the diminished RSC and rest potentiation of SHR.

The availability of selective membrane-disruptive techniques using the detergent saponin allows an in situ evaluation of SR function in hypertrophic myocardium. Although saponin treatment may destroy the transverse tubular network, SR function appears to be well preserved at the saponin concentration used in this study. Calcium uptake by the SR was not altered in SHR compared with WKY preparations (Fig 6); however, the caffeine-induced calcium release mechanism was depressed (Fig 7). These findings correlate with the conclusions drawn from the current experiments on intact papillary muscles and suggest an alter-
ation of calcium release mechanisms in the hypertrophied heart of SHR. An alternative explanation for our results would be that cellular growth was not accompanied by a parallel development of the SR. Therefore, a given amount of Ca\(^{2+}\) released into a greater cytosolic volume would be expected to result in a lower tension via a simple dilution effect. Other experimental evidence indicates that myocardial growth was accompanied by a parallel or even greater increase in the development of sarcotubular membranes and myofilibrillar proteins in hypertrophic hearts of SHR as well as in other models of hypertrophy.\(^{16,42}\)

The calcium release mechanism has not been previously studied in SHR hearts. Experiments performed on saponin-skinned cardiac trabeculae from hypertrophic hearts of rats with abdominal aortic ligation failed to show significant changes in caffeine-induced calcium release.\(^{43}\) The reason for the discrepancy between these results and ours is not clear and might be attributed either to differences in the inciting stimulus causing the hypertrophy or to a different stage of the hypertrophy. Moreover, more recent experiments from the same group suggested functional abnormalities of SR calcium release in the aortic ligation model of hypertrophy.\(^{44}\) Experiments by Gwathmey and Morgan\(^{45}\) suggest a decrease in the rate of both sequestration and release of calcium in hypertrophied ferret right ventricles. The prolongation of intracellular calcium transient observed in SHR failing hearts\(^{46}\) is also consistent with the concept that hypertrophy impairs intracellular calcium handling.

We are well aware that the differences described between hypertrophic and control hearts may arise from factors not directly studied in our experiments, such as changes in the morphometry or energetics of the myocytes. For the present experiments, papillary muscles from SHR hearts having a cross-sectional area similar to those from Wistar and WKY hearts were chosen. Thus, the influence of different geometric characteristics systematically affecting the response of the papillary muscles of SHR is improbable. For the same reason, the diminished rest potentiation and the RSC of SHR can hardly be associated with a higher degree of hypoxia in the core of these preparations, unless the oxygen consumption of SHR was higher than in normotensive rats. A normal or decreased oxygen consumption with an improved economy of force production has been described in pressure-hypertrophied hearts.\(^{45,48}\) This improvement in the economy of force production is likely to contribute to the ability of these preparations to generate nearly normal isometric twitch tension, even though the preparations may have extremely large cross-sectional areas.\(^{49}\) Another possibility to be considered is that both groups of muscles have a similar degree of hypoxia, the hypertrophic myocardium being affected by hypoxia more than the normal myocardium. This possibility cannot be ruled out in our experiments but seems improbable, because no mechanical signs of hypoxia were detected in any of the preparations. The preparations were stable at least during the last 20 minutes of the stabilization period, and no decrease in DT nor any increase in resting tension\(^{50}\) occurred in any of the preparations used throughout the experiments. Moreover, a similar biochemical and mechanical response to hypoxia has been described in papillary muscles of 6-month-old SHR and WKY rats.\(^{49}\)

In summary, our experiments suggest that the depressed RSC and rest potentiation observed in SHR are determined by modifications in the cellular handling of activator calcium. The experiments further suggest that the intracellular locus of this defective behavior is the SR, possibly through an alteration of the calcium release mechanism. At the stage of the hypertrophy studied here, this defective calcium release would appear only under conditions that require an elevated cardiac inotropism. In connection with this, it is worth emphasizing that in the diminished inotropic response to β-adrenergic stimulation of SHR—a finding generally attributed to an alteration of the β-adrenergic system—postreceptor mechanisms like the one described here may also play a role.

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