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ORIGINAL PAPER

High levels of circulating angiotensin II shift the open-loop baroreflex control of splanchnic sympathetic nerve activity, heart rate and arterial pressure in anesthetized rats

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Abstract Although an acute arterial pressure (AP) elevation induced by intravenous angiotensin II (ANG II) does not inhibit sympathetic nerve activity (SNA) compared to an equivalent AP elevation induced by phenylephrine, there are conflicting reports as to how circulating ANG II affects the baroreflex control of SNA. Because most studies have estimated the baroreflex function under closed-loop conditions, differences in the rate of input pressure change and the magnitude of pulsatility may have biased the estimation results. We examined the effects of intravenous ANG II (10 μg kg^{-1} h^{-1}) on the open-loop system characteristics of the carotid sinus baroreflex in anesthetized and vagotomized rats. Carotid sinus pressure (CSP) was raised from 60 to 180 mmHg in increments of 20 mmHg every minute, and steady-state responses in systemic AP, splanchnic SNA and heart rate (HR) were analyzed using a four-parameter logistic function. ANG II significantly increased the minimum values of AP (67.6 ± 4.6 vs. 101.4 ± 10.9 mmHg, $P < 0.01$), SNA (33.3 ± 5.4 vs. 56.5 ± 11.5%, $P < 0.05$) and HR (391.1 ± 13.7 vs. 417.4 ± 11.5 beats/min, $P < 0.01$). ANG II, however, did not attenuate the response range for AP (56.2 ± 7.2 vs. 49.7 ± 6.2 mmHg), SNA (69.6 ± 5.7 vs. 78.9 ± 9.1%) or HR (41.7 ± 5.1 vs. 51.2 ± 3.8 beats/min). The maximum gain was not affected for AP (1.57 ± 0.28 vs. 1.20 ± 0.25), SNA (1.94 ± 0.34 vs. 2.04 ± 0.42%/mmHg) or HR (1.11 ± 0.12 vs. 1.28 ± 0.19 beats min^{-1} $mmHg^{-1}$). It is concluded that high levels of circulating ANG II did not attenuate the response range of open-loop carotid sinus baroreflex control for AP, SNA or HR in anesthetized and vagotomized rats.

Keywords Systems analysis · Open-loop gain · Equilibrium diagram · Carotid sinus baroreflex · Rats

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Introduction

The arterial baroreflex is an important negative feedback system that stabilizes systemic arterial pressure (AP) during daily activities. The sympathetic arterial baroreflex can be divided into the neural and peripheral arc subsystems [1]. The neural arc characterizes the input–output relation between the baroreceptor pressure input and efferent sympathetic nerve activity (SNA), whereas the peripheral arc defines the input–output relation between SNA and AP. These subsystems operate as a controller and a plant, respectively, in the negative feedback loop. Although the input signal to the neural arc is primarily the absolute input pressure level, the rate of input pressure change [1–3] and the magnitude of pulsatility [4–7] are also important input signals that critically affect the baroreflex function. Many investigators employ pharmacologic interventions, such as intravenous phenylephrine and nitroprusside administration, to estimate baroreflex function under closed-loop conditions. The rate of input pressure change and the

magnitude of pulsatility, however, may vary within and between studies, which could bias the estimation results. In addition, experiments performed under baroreflex closed-loop conditions do not usually permit an evaluation of the baroreflex control of AP, because measured AP cannot be separated into signals for the input pressure and output pressure. An open-loop experiment with isolated baroreceptor regions is therefore required to evaluate the baroreflex function precisely.

Angiotensin II (ANG II) can affect the arterial baroreflex by centrally increasing sympathetic outflow, stimulating sympathetic ganglia and the adrenal medulla, and facilitating neurotransmission at sympathetic nerve endings [8]. Although an acute AP elevation induced by intravenous ANG II does not inhibit SNA compared to an equivalent AP elevation induced by phenylephrine, how circulating ANG II affects the baroreflex control of SNA varies among reports, i.e., intravenous ANG has been shown to attenuate [9, 10] or not attenuate [11, 12] the baroreflex control of SNA. Because it is related to the pathologic sympathoexcitation observed in such cardiovascular diseases as chronic heart failure [13], analyzing the effects of circulating ANG II on the baroreflex open-loop system characteristics will deepen our understanding of the pathologic roles of ANG II. In the present study, we examined the effects of intravenous ANG II (10 $\mu g\ kg^{-1}\ h^{-1}$ or 167 $ng\ kg^{-1}\ min^{-1}$) on the open-loop system characteristics of the baroreflex neural and peripheral arcs in anesthetized rats. We hypothesized that ANG II would increase the minimum SNA and attenuate the range of SNA response because the maximum SNA may be saturated. Contrary to our hypothesis, ANG II increased both the minimum and maximum SNA, preserving the range of SNA response controlled by the arterial baroreflex.

Materials and methods

Animals were cared for in strict accordance with the guiding principles for the care and use of animals in the field of physiological sciences, which has been approved by the Physiological Society of Japan. All experimental protocols were reviewed and approved by the Animal Subjects Committee at the National Cardiovascular Center.

Baroreflex open-loop experiment

Male Sprague–Dawley rats ($n = 8$, 482 ± 14 g body weight, mean $\pm$ SE) were anesthetized with an intraperitoneal injection (2 ml/kg) of a mixture of urethane (250 mg/ml) and α-chloralose (40 mg/ml), and mechanically ventilated with oxygen-enriched room air. A venous catheter was inserted into the right femoral vein, and a tenfold dilution of the anesthetic mixture was administered (2 $ml\ kg^{-1}\ h^{-1}$) to maintain an appropriate level of anesthesia. An arterial catheter was inserted into the right femoral artery to measure AP. A cardiotachometer was used to measure heart rate (HR). Another venous catheter was inserted into the left femoral vein to administer Ringer's solution with or without ANG II.

We exposed a postganglionic branch of the splanchnic nerve through a left flank incision and attached a pair of stainless steel wire electrodes (Bioflex wire AS633, Cooner Wire, CA) to record SNA. The nerve and electrodes were covered with silicone glue (Kwik-Sil, World Precision Instruments, Sarasota, FL) for insulation and fixation. To quantify the nerve activity, the preamplified nerve signal was band-pass filtered at 150–1,000 Hz, and then full-wave rectified and low-pass filtered with a cutoff frequency of 30 Hz. Pancuronium bromide (0.4 $mg\ kg^{-1}\ h^{-1}$) was administered to prevent muscular activity from contaminating the SNA recording. At the end of the experiment, we confirmed the disappearance of SNA after an intravenous bolus injection of hexamethonium bromide (60 mg/kg) and recorded the noise level.

The vagal and aortic depressor nerves were sectioned at the neck to avoid reflexes from the cardiopulmonary region and aortic arch. The bilateral carotid sinuses were isolated from the systemic circulation according to previously reported procedures [14, 15]. Briefly, a fine needle with a 7-0 polypropylene suture (PROLENE, Ethicon, GA, USA) was passed through the tissue between the external and internal carotid arteries, and the external carotid artery was ligated close to the carotid bifurcation. The internal carotid artery was embolized using two or three bearing balls (0.8 mm in diameter, Tsubaki Nakashima, Nara, Japan), which were injected from the common carotid artery. The isolated carotid sinuses were filled with warmed Ringer's solution through catheters inserted via the common carotid arteries. Carotid sinus pressure (CSP) was controlled using a servo-controlled piston pump. Heparin sodium (100 U/kg) was given intravenously to prevent blood coagulation. Body temperature was maintained at approximately 38°C with a heating pad.

Protocols

Sympathetic nerve activity and AP responses to CSP perturbations were monitored for at least 30 min after the surgical preparation was completed. If these responses became smaller within this period, the animal was discarded from the study. Possible causes for deteriorations in the responses include surgical damage to the carotid sinus nerves and brain ischemia due to bilateral carotid occlusion.

The CSP was decreased to 60 mmHg for 4–6 min, and then increased every minute from 60 to 180 mmHg using 20-mmHg increments. At least four step cycles were performed under control conditions while Ringer's solution was continuously administered (6 ml kg^{-1} h^{-1}). After recording the control data, the intravenous Ringer's solution was replaced with that containing ANG II (167 ng kg^{-1} min^{-1}). The dose of ANG II was chosen to induce a significant pressor effect based on previous studies [16, 17]. At least three step cycles were performed during ANG II administration.

Data analysis

Data were sampled at 200 Hz using a 16-bit analog-to-digital converter and stored on the hard disk of a dedicated laboratory computer system. To quantify the open-loop static characteristics of the carotid sinus baroreflex, mean values of SNA, AP and HR were calculated during the last 10 s at each CSP level. The effects of ANG II were assessed during the third step cycle after ANG II administration began, at which point the hemodynamic responses to ANG II appeared to reach steady state. Comparisons were made against two control step cycles (control 1 and control 2, see Fig. 1). In each animal, the SNA noise level recorded after the administration of hexamethonium bromide was set to zero. The SNA values obtained at a CSP level of 60 mmHg during control 1 and control 2 were averaged and defined as 100%.

The open-loop characteristics of the AP, SNA and HR responses as functions of CSP were quantified by fitting a four-parameter logistic function to the obtained data as follows [18]:

$$y = \frac{P_1}{1 + \exp[P_2(\mathrm{CSP} - P_3)]} + P_4.$$

where y represents AP, SNA or HR; P_1 is the response range (the difference between the maximum and minimum values of y); P_2 is a slope coefficient; P_3 is the midpoint in CSP; P_4 is the minimum value of y. The maximum gain or maximum slope of the sigmoidal curve was obtained from $P_1P_2/4$.

The open-loop characteristics of the baroreflex peripheral arc (i.e., SNA–AP relation) were quantified using linear regression analysis as follows:

$$\mathrm{AP} = a \times \mathrm{SNA} + b.$$

where a and b represent the slope and intercept of the regression line, respectively.

Statistical analysis

All parameters were compared among control 1, control 2 and ANG II conditions using repeated-measures analysis of variance [19]. When there was a significant difference among the three conditions, all pairwise comparisons were performed using the Student-Neuman-Keuls test. Differences were considered significant at $P < 0.05$. All data are expressed as mean and SE values.

Results

Typical experimental recordings are shown in Fig. 1. The stepwise input from 60 to 180 mmHg was imposed repeatedly on CSP. An increase in CSP decreased SNA. m-SNA represents the 5-s moving-average signal of the percentage of SNA. AP and HR were also decreased in response to increases in CSP. After ANG II administration was initiated, the levels of SNA, AP and HR all increased compared to the levels before ANG II administration. The responses in SNA, AP and HR to the CSP input appeared to be preserved. Data obtained from the three boxes with dashed lines (control 1, control 2 and ANG II) were used for the statistical analysis.

The open-loop characteristics of the total baroreflex revealed sigmoidal nonlinearity (Fig. 2a). No significant differences were observed between the two control conditions. ANG II significantly increased the minimum AP without affecting the response range, slope coefficient or midpoint in CSP (Table 1). The maximum gain of the total baroreflex was unchanged. The open-loop characteristics of the baroreflex control of HR also approximated sigmoidal nonlinearity (Fig. 2b), and no significant differences were observed between the two control conditions. ANG II significantly increased the minimum HR without affecting the response range, slope coefficient or midpoint in CSP (Table 1). The maximum slope of the baroreflex control of HR was unchanged.

The total baroreflex was decomposed into the neural and peripheral arc subsystems. The open-loop characteristics of the baroreflex neural arc revealed sigmoidal nonlinearity (Fig. 3a). There were no significant differences between the two control conditions. ANG II significantly increased the minimum SNA (Table 1). Although the midpoint in CSP was lower in ANG II than in control 1, the difference was not significant when compared with control 2. ANG II did not affect the response range, slope coefficient or the maximum slope of the baroreflex control of SNA. The open-loop characteristics of the baroreflex peripheral arc approximated a straight line (Fig. 3b). There were no significant differences between the two control conditions. ANG II significantly increased the intercept of the regression line (Table 1). AP at 100% SNA did not change significantly, suggesting that the slope of the regression line could be shallower under the ANG II condition. The slope of the

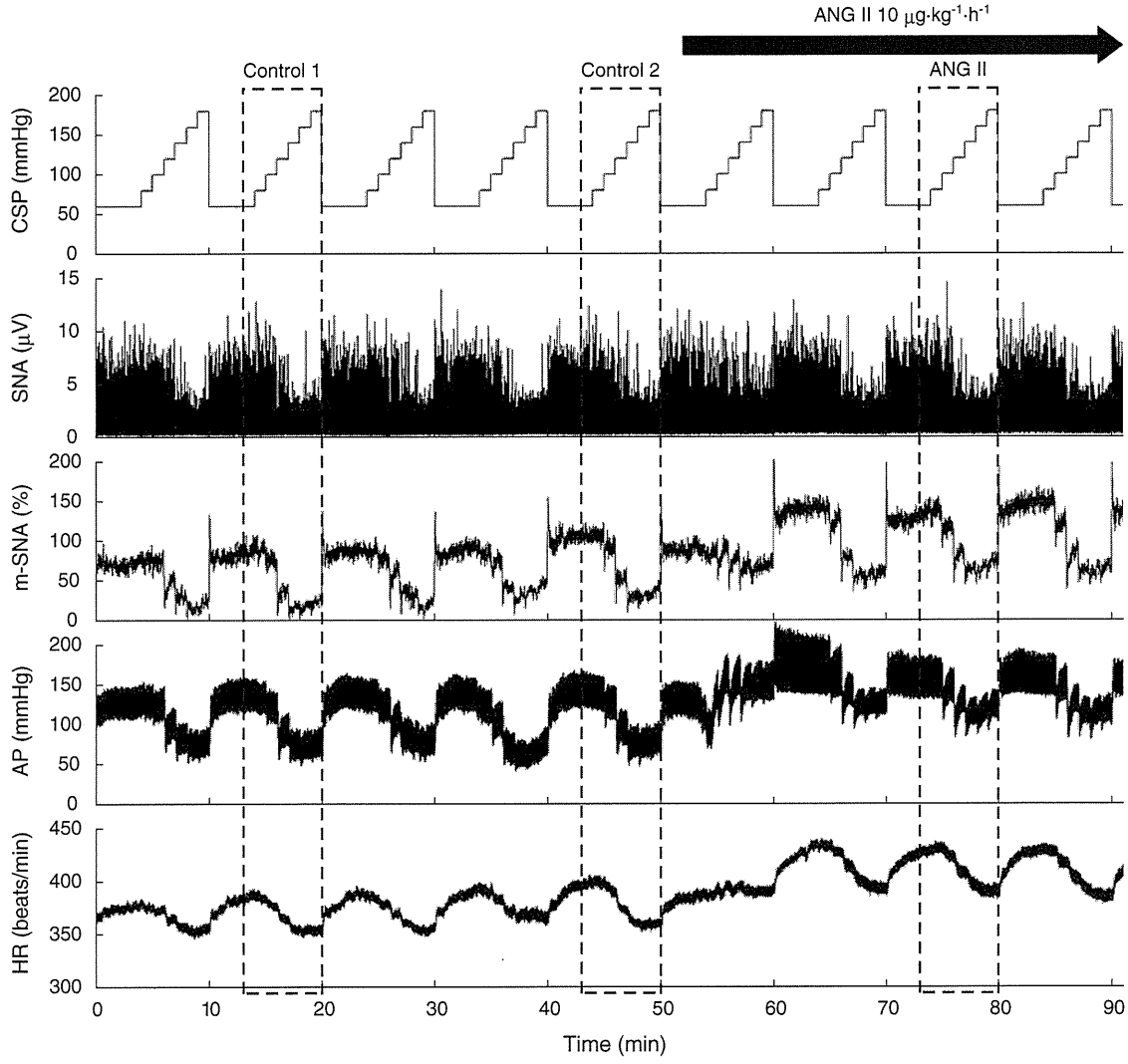

Fig. 1 Typical recordings of carotid sinus pressure (*CSP*), splanchnic sympathetic nerve activity (*SNA*), the 5-s moving-average signal of the percentage of SNA (*m-SNA*), systemic arterial pressure (*AP*) and heart rate (*HR*). CSP was changed stepwise from 60 to 180 mmHg in 20-mmHg increments every minute. Angiotensin II (ANG II) was administered intravenously while the CSP perturbation was continued. ANG II significantly increased SNA, AP and HR. Reflex responses in SNA, AP and HR were not attenuated in the presence of ANG II. *Dashed boxes* indicate the step cycles used for the statistical analysis

regression line, however, was not statistically different among the three conditions.

An equilibrium diagram or a balance diagram was obtained by drawing the neural and peripheral arcs using SNA as the common abscissa and CSP or AP as an ordinate [20–22]. Figure 4 illustrates the equilibrium diagrams under the control 2 (dashed line) and ANG II (solid line) conditions, which were drawn based on the mean parameter values from the logistic function and regression line. Open and filled circles represent the closed-loop operating points under the control 2 and ANG II conditions, respectively. Although AP at the closed-loop operating point was significantly increased by the intravenous ANG II, SNA at the closed-loop operating point was unchanged (Table 1). If ANG II affected the peripheral arc alone, the closed-operating point may have been located at the point depicted by the open triangle. If ANG II affected the neural arc alone, the closed-loop operating point may have been located at the point depicted by the filled triangle.

Discussion

Effects of ANG II on open-loop baroreflex control of SNA

Intravenous ANG II at 167 ng kg^{-1} min^{-1} shifted the open-loop baroreflex control of splanchnic SNA toward higher SNA values without attenuating the size of the response range (Fig. 3a; Table 1). The maximum slope was

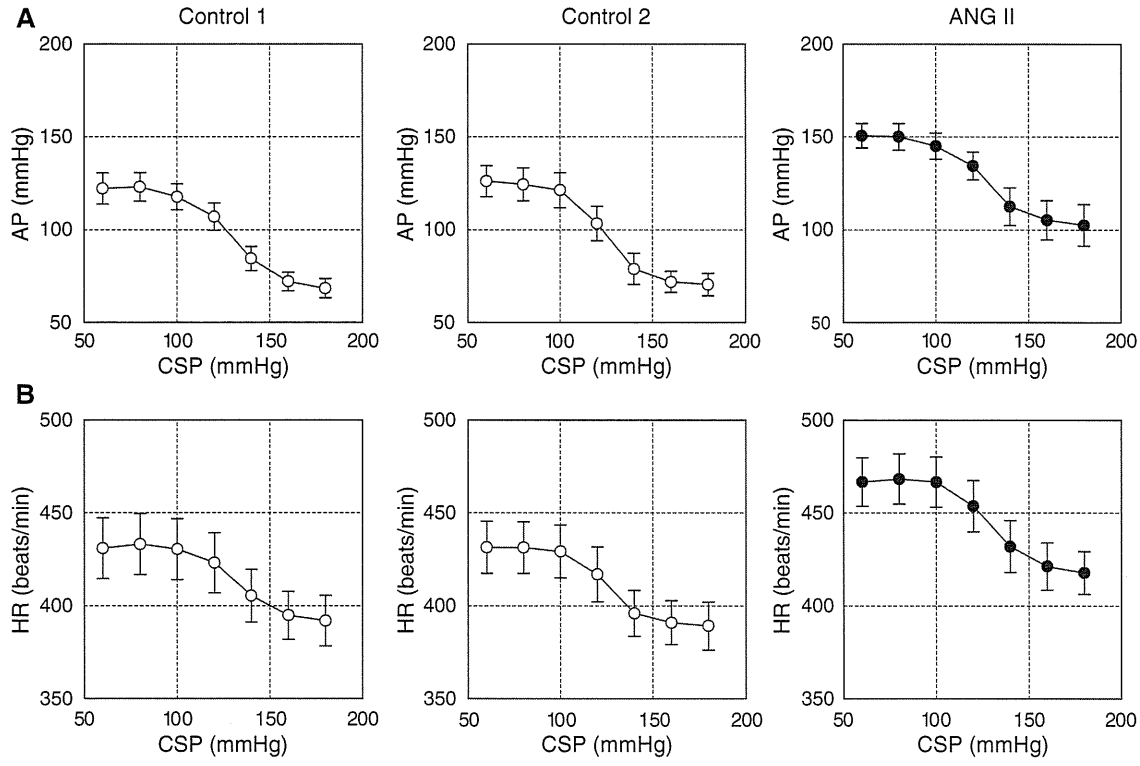

Fig. 2 **a** Averaged input–output relation of the total baroreflex. AP decreased in response to an increase in the CSP. ANG II increased AP, while the range of the AP response was preserved. **b** Averaged input–output relation of the arterial baroreflex control of HR. HR decreased in response to an increase in the CSP. ANG II increased the HR, while the range of the HR response was preserved

unaltered, which agreed with a previous study from our laboratory in which intravenous ANG II at 100 ng kg^{-1} min^{-1} did not change the dynamic gain of the neural arc in anesthetized rabbits [23]. In contrast, Sanderford and Bishop demonstrated that ANG II at 10 or 20 ng kg^{-1} min^{-1} significantly reduced the maximum renal SNA and attenuated the range of baroreflex control of renal SNA in conscious rabbits [9, 24]. On the other hand, Tan et al. [12] demonstrated that intravenous ANG II at 400 ng kg^{-1} min^{-1} did not increase the levels of renal SNA in anesthetized rats. The regional differences in SNA may partly explain the conflicting results, because Fukiyama [25] noted that ANG II infusion (3.5–9.5 ng kg^{-1} min^{-1}) through the vertebral artery resulted in an increase in splanchnic SNA, a transient increase followed by a decrease in renal SNA, and no change in cardiac SNA in anesthetized dogs.

Activation of the renin–angiotensin system contributes to the pathologic sympathoexcitation observed in such cardiovascular diseases as chronic heart failure. In addition to the augmented cardiac sympathetic reflex, impairment of the arterial baroreflex is thought to contribute to sympathoexcitation [13]. The present results indicate that ANG II may increase SNA, but it does not attenuate baroreflex control of SNA such that the magnitude of the SNA response to the input pressure change is preserved (Fig. 3a). ANG II also did not attenuate the gain of the total baroreflex estimated by the magnitude of the AP response to the input pressure change (Fig. 2a). Therefore, the observed weakening of the baroreflex reported in patients with chronic heart failure may not be readily explainable by an acute effect of high circulating levels of ANG II.

Several studies have demonstrated that ANG II-induced hypertension does not decrease SNA via the arterial baroreflex compared to equivalent hypertension induced by phenylephrine [10, 12, 26]. Although those results seem to be consistent with the idea that ANG II blunts the arterial baroreflex, the experimental protocol is confusing, and the interpretation could be wrong as follows. The intersection between the neural and peripheral arcs in the baroreflex equilibrium diagram conforms to the closed-loop operating point [21, 27, 28]. In the present study, ANG II significantly increased AP without significant changes in SNA at the closed-loop operating point (Fig. 4, open vs. filled circles; Table 1). If we calculate the baroreflex control of SNA based on ANG II-induced hypertension, therefore, we would incorrectly conclude that the baroreflex does not control SNA. If we observe the SNA response to changes in

Table 1 Effects of intravenous angiotensin II (ANG II) on the parameters of logistic functions and regression lines of the open-loop baroreflex characteristics

	Control 1	Control 2	ANG II
Total baroreflex, CSP–AP relation			
P_1 (mmHg)	56.2 ± 7.2	56.3 ± 6.4	49.7 ± 6.2
P_2 ($mmHg^{-1}$)	0.116 ± 0.019	0.118 ± 0.015	0.094 ± 0.013
P_3 (mmHg)	129.2 ± 3.5	124.5 ± 2.8	125.7 ± 3.2
P_4 (mmHg)	67.6 ± 4.6	69.7 ± 5.8	101.4 ± 10.9**,††
Maximum gain	1.57 ± 0.28	1.58 ± 0.22	1.20 ± 0.25
Baroreflex control of HR, CSP–HR relation			
P_1(beats/min)	41.7 ± 5.1	43.9 ± 6.2	51.2 ± 3.8
P_2 ($mmHg^{-1}$)	0.123 ± 0.027	0.133 ± 0.018	0.099 ± 0.013
P_3 (mmHg)	131.8 ± 3.8	125.8 ± 3.6	129.1 ± 2.6
P_4 (beats/min)	391.1 ± 13.7	388.0 ± 12.6	417.4 ± 11.5**,††
Maximum slope (beats min^{-1} $mmHg^{-1}$)	1.11 ± 0.12	1.39 ± 0.23	1.28 ± 0.19
Neural arc, CSP–SNA relation			
P_1 (%)	69.6 ± 5.7	66.5 ± 7.4	78.9 ± 9.1
P_2 ($mmHg^{-1}$)	0.110 ± 0.016	0.124 ± 0.015	0.098 ± 0.011
P_3 (mmHg)	133.2 ± 3.8	127.3 ± 3.1	126.0 ± 3.4*
P_4 (%)	33.3 ± 5.4	35.0 ± 6.4	56.5 ± 11.5*,†
Maximum slope (%/mmHg)	1.94 ± 0.34	2.02 ± 0.33	2.04 ± 0.42
Peripheral arc, SNA–AP relation			
Slope, a (mmHg/%)	0.85 ± 0.09	0.86 ± 0.06	0.66 ± 0.10
Intercept, b (mmHg)	37.8 ± 5.2	36.9 ± 5.5	68.0 ± 10.6**,††
AP at 100% SNA (mmHg)	122.7 ± 9.9	122.7 ± 7.0	134.4 ± 4.9
Operating point			
AP (mmHg)	111.4 ± 5.0	110.3 ± 5.1	128.1 ± 4.4**,††
SNA (%)	90.6 ± 7.4	85.8 ± 2.1	94.3 ± 5.9

Data are mean and SE values

CSP Carotid sinus pressure, *AP* arterial pressure, *HR* heart rate, *SNA* sympathetic nerve activity

* $P < 0.05$ and ** $P < 0.01$ from control 1, † $P < 0.05$ and †† $P < 0.01$ from control 2

CSP, however, the baroreflex should be able to control SNA in the presence of ANG II (Fig. 3a). Lumbers et al. [29] pointed out a problem regarding the use of ANG II-induced hypertension as an input perturbation to evaluate the baroreflex.

Effects of ANG II on the baroreflex peripheral arc

The open-loop system characteristics of the baroreflex peripheral arc, assessed using the AP response as a function of SNA, approximated a straight line under both control and ANG II-treated conditions (Fig. 3b), suggesting that the splanchnic SNA may represent changes in systemic SNA that controlled the AP. ANG II significantly increased the intercept of the regression line, reflecting its direct vasoconstrictive effect (Table 1). Because the AP at 100% SNA did not differ among the three conditions, the slope could be shallower in the presence of ANG II. In other words, ANG II appears to elevate the AP to a greater extent for the lower SNA range. Although both the modulation of sympathetic neurotransmission and direct vasoconstriction contribute to the elevation of AP, the fact that ANG II enhances the sympathetic neurotransmission more with a lower stimulation frequency [30, 31] may, in part, account for the greater ANG II-induced increase in AP for the lower SNA range.

Effects of ANG II on the open-loop sympathetic baroreflex control of HR

The baroreflex control of HR showed changes similar to those observed for SNA. Intravenous ANG II increased both the minimum and maximum HR while not significantly affecting the response range of HR or the maximum slope of the response (Fig. 2b; Table 1). The midpoint in CSP was not changed by ANG II. Therefore, the open-loop baroreflex control of HR shifted upward to higher HR values without a concomitant rightward shift to higher CSP values in the present study. In contrast, previous studies reported a rightward shift in the baroreflex control of HR toward higher input pressure values during acute [11, 32] and chronic [33] administration of ANG II in conscious rabbits. Reid and Chou [32] indicated that the inhibition of vagal tone to the heart played a significant role in resetting the baroreflex control of HR in conscious rabbits. It is likely that the rightward shift in the baroreflex control of

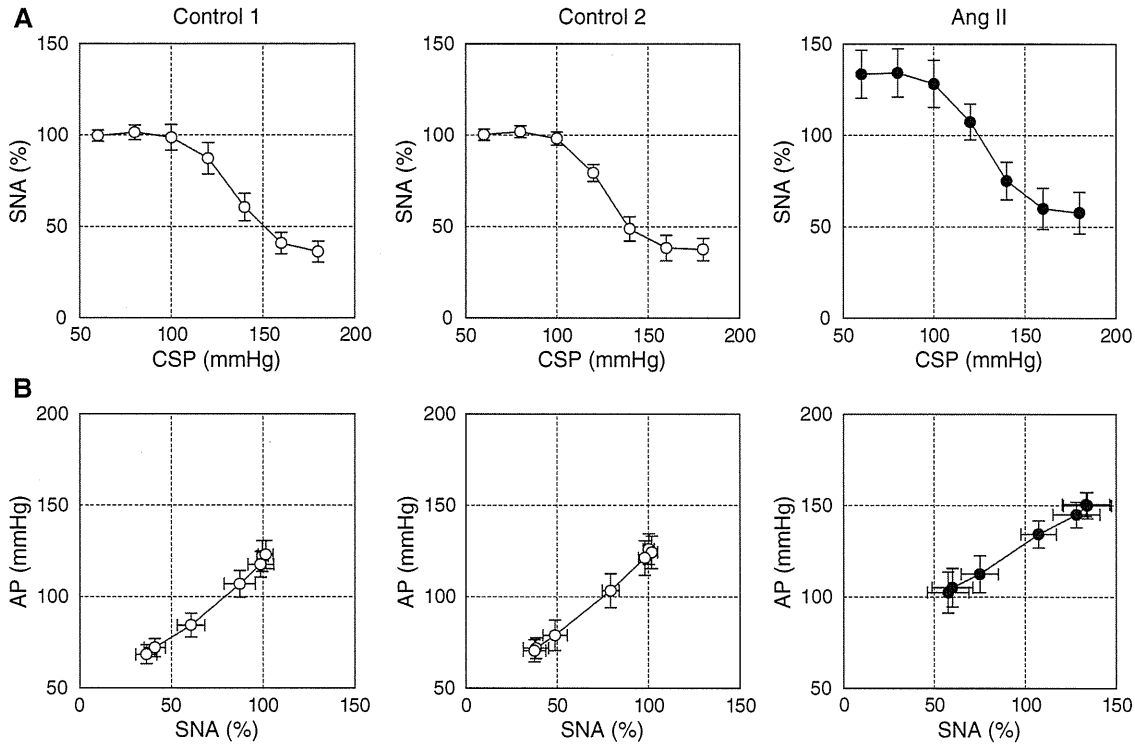

Fig. 3 **a** Averaged input–output relation of the baroreflex neural arc or the arterial baroreflex control of SNA. SNA decreased in response to an increase in the CSP. ANG II increased SNA, while the range of the SNA response was preserved. **b** Averaged input–output relation of the baroreflex peripheral arc. AP increased in response to an increase in SNA. ANG II increased the AP, an effect that was greater for lower SNA

HR by ANG II was not observed in the present study because the vagal nerves were sectioned.

Limitations

First, we performed the experiments in anesthetized animals, and comparisons with results obtained in conscious animals should be made carefully. Circulating levels of ANG II may vary under anesthesia, which could have affected the present results. For instance, reported plasma ANG II concentration in pithed rats is approximately 400 pg/ml [16], which exceeds the plasma ANG II concentration reported in rats with heart failure [34]. Second, although the dose of ANG II used in the present study was within or below those used in previous studies in rats [12, 16, 17], Brown et al. demonstrated that intravenous ANG II at 20 and 270 ng kg^{-1} min^{-1} increased the plasma ANG II concentration from approximately 80 pg/ml to 140 and 2,000 pg/ml, respectively [35]. Based on those data, the plasma ANG II concentration might have been increased beyond a physiologically relevant range to approximately 1,200 pg/ml in the present study. Therefore, the observed effect of ANG II on the arterial baroreflex should be interpreted as pharmacologic. Effects of circulating ANG II can be different when examined in different doses. Third, there was large variation in HR values among the animals (Fig. 2b). Increasing the number of animals would reduce this variation. Nevertheless, data from the eight rats was sufficient to perform statistical analyses and draw reasonable conclusions. Fourth, we occluded the common carotid arteries to isolate the carotid sinuses. Although the vertebral arteries were kept intact and the effects of ANG II were examined using the same preparation, the possibility cannot be ruled out that the carotid occlusion affected the present results. Finally, we cut the vagal nerves to obtain the open-loop condition for the carotid sinus baroreflex. Further studies are needed to clarify the effects of ANG II on the baroreflex control of the cardiovascular system through the vagal system.

Conclusion

The present study indicates that high circulating levels of ANG II significantly increased splanchnic SNA but did not acutely attenuate the range of arterial baroreflex control of SNA. The ranges of the total baroreflex response and the baroreflex control of HR were also preserved during ANG

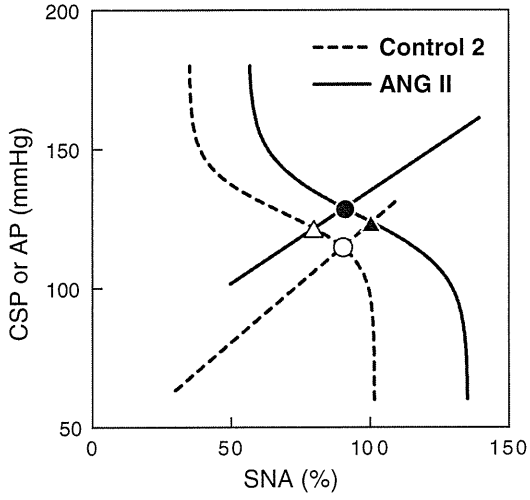

Fig. 4 Equilibrium diagrams between the arterial baroreflex neural and peripheral arcs. The *dashed* and *solid curves* represent the open-loop characteristics of the baroreflex neural arc under the control and ANG II-treated conditions, respectively. The *dashed* and *solid lines* represent the open-loop characteristics of the baroreflex peripheral arc under the control and ANG II-treated conditions, respectively. The *open circle* indicates the closed-loop operating point under the control condition. ANG II causes an upward shift in the peripheral arc. If ANG II does not affect the neural arc, the closed-loop operating point would be at the point depicted by the *open triangle*. In this case, the estimation of baroreflex control of SNA based on the closed-loop operating points (the *open circle* and *open triangle*) approximates the slope of the baroreflex neural arc (*dashed curve*). ANG II, however, causes a rightward shift in the neural arc. Thus, the estimation of the baroreflex control of SNA based on closed-loop operating points (the *open* and *filled circles*) does not match the slope of the neural arc under either the control (*dashed curve*) or ANG II-treated condition (*solid curve*)

II administration. ANG II does modify the arterial baroreflex in that it increases SNA at a given baroreceptor pressure level but does not appear to attenuate the range of arterial baroreflex control of SNA, HR or AP.

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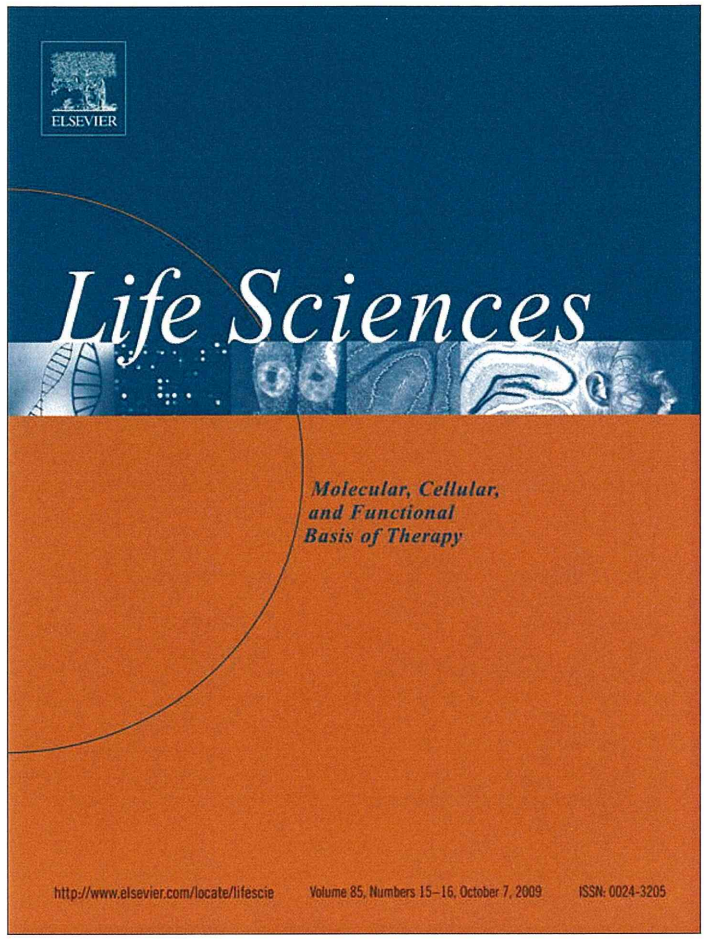

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Detection of endogenous acetylcholine release during brief ischemia in the rabbit ventricle: A possible trigger for ischemic preconditioning

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ABSTRACT

Aims: To examine endogenous acetylcholine (ACh) release in the rabbit left ventricle during acute ischemia, ischemic preconditioning and electrical vagal stimulation.
Main methods: We measured myocardial interstitial ACh levels in the rabbit left ventricle using a cardiac microdialysis technique. In Protocol 1 ($n=6$), the left circumflex coronary artery (LCX) was occluded for 30 min and reperfused for 30 min. In Protocol 2 ($n=5$), the LCX was temporarily occluded for 5 min. Ten minutes later, the LCX was occluded for 30 min and reperfused for 30 min. In Protocol 3 ($n=5$), bilateral efferent vagal nerves were stimulated at 20 Hz and 40 Hz (10 V, 1-ms pulse duration).
Key findings: In Protocol 1, a 30-min coronary occlusion increased the ACh level from 0.39 ± 0.15 to 7.0 ± 2.2 nM (mean ± SE, $P<0.01$). In Protocol 2, a 5-min coronary occlusion increased the ACh level from 0.33 ± 0.07 to 0.75 ± 0.11 nM ($P<0.05$). The ACh level returned to 0.48 ± 0.10 nM during the interval. After that, a 30-min coronary occlusion increased the ACh level to 2.4 ± 0.49 nM ($P<0.01$). In Protocol 3, vagal stimulation at 20 Hz and 40 Hz increased the ACh level from 0.29 ± 0.06 to 1.23 ± 0.48 ($P<0.05$) and 2.44 ± 1.13 nM ($P<0.01$), respectively.
Significance: Acute ischemia significantly increased the ACh levels in the rabbit left ventricle, which appeared to exceed the vagal stimulation-induced ACh release. Brief ischemia as short as 5 min can also increase the ACh level, suggesting that endogenous ACh release can be a trigger for ischemic preconditioning.

Introduction

Although ventricular vagal innervation is sparser than that observed in the atrium, we have previously demonstrated that electrical vagal stimulation and acute myocardial ischemia significantly increased myocardial interstitial acetylcholine (ACh) levels in the feline left ventricle (Kawada et al. 2000, 2001, 2006a,b, 2007). Potential differences between species, however, suggest that data obtained from the feline left ventricle may not be directly extrapolated to ventricular vagal innervation in other species (Brown 1976; Kilbinger and Löffelholz 1976). Compared with the feline heart, the rabbit heart is more frequently analyzed in investigations of myocardial ischemia and ischemic preconditioning. For instance, Qin et al. (2003) used isolated rabbit hearts to demonstrate that ACh and adenosine induce ischemic preconditioning mimetic effects through different signaling pathways. In our previous study, vagal stimulation increased the level of tissue inhibitor of metalloproteinase-1 (TIMP-1) and reduced the level of endogenous active matrix metalloproteinase-9 (MMP-9) during ischemia–reperfusion injury in the rabbit left ventricle (Uemura et al. 2007). Despite its potential cardioprotective effects against myocardial ischemia, the profile of endogenous ACh release in the rabbit left ventricle is poorly understood *in vivo* owing to the difficulty in detecting low levels of myocardial interstitial ACh. Quantification of endogenous ACh release during myocardial ischemia and electrical vagal stimulation would help understand the potential cardioprotective effects of vagal stimulation. In the present study, we examined the effects of acute myocardial ischemia, ischemic preconditioning, and electrical vagal stimulation on myocardial interstitial ACh levels in the rabbit left ventricle *in vivo* using an improved high-performance liquid chromatography (HPLC) system that allowed us to detect low concentrations of ACh (Shimizu et al. 2009).

Materials and methods

Surgical preparation and protocols

Animal care was conducted in accordance with the *Guiding Principles for the Care and Use of Animals in the Field of Physiological Sciences*, which has been approved by the Physiological Society of

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Japan. Japanese white rabbits weighing 2.5 kg to 3.1 kg (2.8 ± 0.1 kg, mean ± SE) were anesthetized via intravenous administration of pentobarbital sodium (30–35 mg/kg) through a marginal ear vein. The animals were ventilated mechanically with room air mixed with oxygen. The anesthetic condition was maintained using a continuous intravenous infusion of urethane (125 mg kg^{-1} h^{-1}) and α-chloralose (20 mg kg^{-1} h^{-1}) through a catheter inserted in the right femoral vein. Mean arterial pressure (AP) was measured using a catheter inserted in the right femoral artery. Heart rate (HR) was measured from an electrocardiogram obtained using a cardiotachometer. The animal was placed in a lateral position, and the left fourth and fifth ribs were partially resected to allow access to the heart. The heart was suspended in a pericardial cradle.

In Protocol 1 ($n = 6$), which was designed to examine the effects of acute myocardial ischemia and reperfusion, a 3-0 silk suture was passed around a branch of the left circumflex coronary artery (LCX); both ends were passed through a polyethylene tube to make a snare to occlude the artery. A dialysis probe was implanted into the anterolateral free wall of the left ventricle perfused by the LCX. After collecting a baseline dialysate sample, the LCX was occluded for 30 min and reperfused for 30 min. After the ischemia–reperfusion protocol was finished, the LCX was occluded again and a 5-ml bolus of 1% methylene blue was injected intravenously to confirm that the dialysis probe had been implanted within the area at risk for myocardial ischemia.

In Protocol 2 ($n = 5$), which was designed to examine the effects of ischemic preconditioning (*i.e.*, a brief ischemic event preceding a major ischemic event), a 3-0 silk suture was passed around a branch of the LCX and both ends were passed through a polyethylene tube to make a snare. Two dialysis probes were implanted into the anterolateral free wall of the left ventricle perfused by the LCX; the probes were separated by at least 5 mm. Combining the dialysate samples obtained from the two dialysis probes increased the time resolution of the ACh measurement. After collecting a baseline dialysate sample, the LCX was temporarily occluded for 5 min which was followed by a 10-min interval. The LCX was then occluded for 30 min and reperfused for 30 min. After the ischemia–reperfusion protocol was completed, the LCX was occluded again and a 5-ml bolus of 1% methylene blue was injected intravenously to confirm that the two dialysis probes had been implanted within the area at risk for myocardial ischemia.

In Protocol 3 ($n = 5$), which was designed to examine the effects of electrical vagal stimulation, the vagus nerves were exposed and sectioned at the neck. Each sectioned vagus nerve was placed on a pair of bipolar platinum electrodes to stimulate the efferent vagus nerve. The nerve and the electrodes were fixed using silicone glue (Kwik-Sil, World Precision Instruments, Sarasota, FL, USA). Two dialysis probes were implanted into the anterolateral free wall of the left ventricle; the probes were separated by at least 5 mm. Dialysate samples obtained from the two dialysis probes were analyzed separately. After collecting baseline dialysate samples, the vagus nerves were stimulated at 20 Hz for 15 min and 40 Hz for 15 min. The stimulation amplitude was 10 V and the pulse duration was 1 ms. The 40-Hz stimulation often caused an initial cardiac arrest for a few seconds and was considered to be the most intensive stimulation in the present experimental settings. The 20-Hz stimulation was arbitrarily selected at a half of the maximum stimulation rate to observe the dependence of the ACh release on the stimulation rate.

At the end of each protocol, the experimental animals were sacrificed with an overdose of intravenous pentobarbital sodium. We performed a postmortem examination and confirmed that the dialysis probe(s) had been implanted within the left ventricular myocardium.

Dialysis technique

We measured dialysate concentrations of ACh as indices of myocardial interstitial ACh levels. The materials and properties of the dialysis probe have been described previously (Akiyama et al. 1994). Briefly, we designed a transverse dialysis probe. A dialysis fiber (length, 8 mm; outer diameter, 310 μm; inner diameter, 200 μm; PAN-1200, 50,000-Da molecular-weight cutoff, Asahi Chemical, Japan) was glued at both ends to polyethylene tubes (length, 25 cm; outer diameter, 500 μm; inner diameter, 200 μm). The dialysis probe was perfused at a rate of 2 μl/min with Ringer's solution containing a cholinesterase inhibitor eserine (100 μM). Dialysate sampling was started from 2 h after probe implantation. In Protocols 1 and 3, one sampling period was set at 15 min, which yielded a sample volume of 30 μl. The actual dialysate sampling lagged behind a given collection period by 5 min owing to the dead space volume between the dialysis membrane and collecting tube. In Protocol 2, one sampling period was set at 5 min to increase the time resolution during the ischemic preconditioning, and dialysate samples from the two dialysis probes were combined to yield a sample volume of 20 μl. The sampling period was changed to 10 min during the main ischemic event to reduce the total number of samples. The amount of ACh in the dialysate was measured using an HPLC system with electrochemical detection (Eicom, Japan) adjusted to measure low levels of ACh (Shimizu et al. 2009). The concentration of ACh was calculated taking the sample volume in account.

Statistical analysis

All data are presented as the mean and SE values. We performed repeated-measures analysis of variance, followed by a Tukey test for all pairwise, multiple comparisons to examine changes in the ACh levels (Glantz 2002). Because the variance of measured ACh levels increased with their mean, statistical analysis was performed after logarithmic conversion of the ACh data (Snedecor and Cochran 1989). The AP and HR data were examined using repeated-measures analysis of variance, followed by a Dunnett's test for multiple comparisons against a single control (Glantz 2002). In Protocols 1 and 3, the baseline value was treated as the single control. In Protocol 2, the value measured just before the main ischemic event was treated as the single control. In all of the statistical analyses, differences were considered significant when $P < 0.05$.

Results

In Protocol 1, the myocardial interstitial ACh levels significantly increased during ischemia compared with the baseline value (Fig. 1). Although the ACh levels declined during reperfusion, they were still significantly higher than the baseline value. Changes in AP and HR are summarized in Table 1. Although AP did not change significantly during ischemia, it decreased significantly throughout the reperfusion period. The HR increased significantly after 30 min of ischemia, and remained high during the reperfusion period with the exception of the last data point.

In Protocol 2, the LCX was occluded for 5 min (ischemic preconditioning) and released for 10 min before the major ischemic event. The brief 5-min occlusion significantly increased the myocardial interstitial ACh level compared with the baseline value (Fig. 2). The ACh levels during the interval between the brief occlusion and the major occlusion did not differ from the baseline value. The ACh levels increased significantly during the major ischemic event compared with the baseline value. Although the ACh levels declined during reperfusion, they were still significantly higher than the baseline value. Changes in AP and HR are summarized in Table 2. Neither AP nor HR changed significantly compared with the respective control values measured after the 10-min middle interval.

In Protocol 3, electrical vagal stimulation significantly increased the myocardial interstitial ACh levels (Fig. 3). The ACh levels returned close to the baseline value just after vagal stimulation was terminated. The AP and HR values were significantly reduced by vagal stimulation (Table 3).

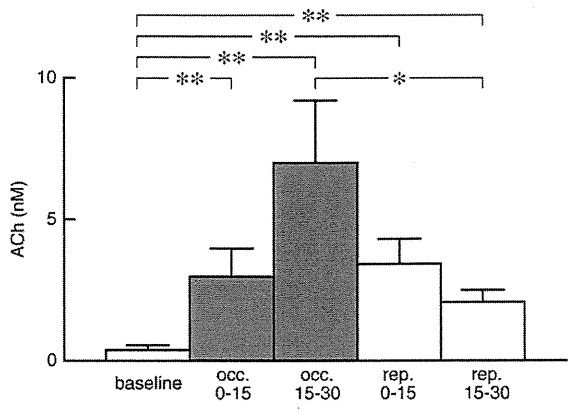

Fig. 1. Changes in the myocardial interstitial ACh levels in Protocol 1. The left circumflex coronary artery was occluded for 30 min and reperfused for 30 min. occ: occlusion; rep: reperfusion. Data are shown as the mean + SE ($n=6$). *$P<0.05$ and **$P<0.01$; Tukey test.

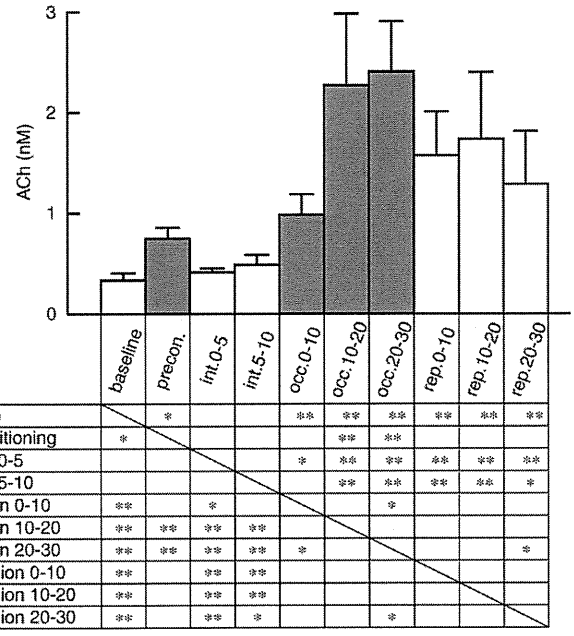

Fig. 2. Changes in the myocardial interstitial ACh levels in Protocol 2. The left circumflex coronary artery was occluded for 5 min. Ten minutes later, the left circumflex coronary artery was occluded for 30 min and reperfused for 30 min. precon: preconditioning; int: interval; occ: occlusion; rep: reperfusion. Data are shown as the mean + SE ($n=5$). *$P<0.05$ and **$P<0.01$; Tukey test.

Discussion

Effects of acute ischemia on myocardial interstitial ACh levels

Acute myocardial ischemia significantly increased myocardial interstitial ACh levels in the ischemic region (Fig. 1). To our knowledge, this is the first report demonstrating ischemia-induced ACh release in the rabbit left ventricle *in vivo*. Because electrical vagal stimulation increased the myocardial interstitial ACh levels (Fig. 3), centrally mediated activation of the efferent vagus nerve could contribute to these effects. LCX occlusion, however, did not decrease the HR significantly (Table 1), suggesting that centrally mediated vagal activation did not have a marked role in the present study. In a previous study, acute myocardial ischemia increased myocardial interstitial ACh levels in vagotomized cats, suggesting an important role of a local release mechanism that is independent of efferent vagal activity (Kawada et al. 2000). Intracellular Ca^{2+} mobilization related to cation-selective stretch-activated channels is thought to be involved in this local release mechanism (Kawada et al. 2000, 2006b). A similar local mechanism may be responsible for ischemia-induced ACh release in the rabbit left ventricle.

In our previous study, topical perfusion of ACh through a dialysis probe increased TIMP-1 levels in the rabbit left ventricle (Uemura et al. 2007). The production of TIMP-1 reduces endogenous levels of active MMP-9, which can limit ventricular remodeling following myocardial ischemia and reperfusion. Whether ischemia-induced ACh release can induce such an anti-remodeling effect remains unanswered, however, because reperfusion reduced the myocardial interstitial ACh levels toward the baseline value. Whether prolonged ischemia for more than 30 min induces sustained elevations of ACh levels is an interesting topic for future studies.

The ACh levels were decreased toward the baseline value upon reperfusion, probably by the washout of ACh from the interstitial fluid. In the case of myocardial interstitial myoglobin levels, the reperfusion further increases the myoglobin levels, suggesting an occurrence of reperfusion injury to the myocardium (Kitagawa et al. 2005). Reoxygenation upon reperfusion rapidly restores the ATP synthesis, which can cause hypercontracture of myofibrils and undesired cytoskeletal lesions (Piper et al. 2004). Because the vagal nerve endings do not have contractile elements, the hypercontracture-induced cell injury does not occur, and the further release of ACh may have been prevented.

Effects of ischemic preconditioning on myocardial interstitial ACh levels

Ischemic preconditioning is a phenomenon in which a brief ischemic event makes the heart resistant to a subsequent ischemic insult (Murry et al. 1986). Acetylcholine, bradykinin, and adenosine are endogenous substances that can induce ischemic preconditioning mimetic effects in the rabbit heart (Liu et al. 1991; Qin et al. 2003; Krieg et al. 2004). In a previous study, we showed that a 5-min ischemic event increased myocardial interstitial ACh levels in the feline ventricle (Kawada et al. 2002). Ischemic preconditioning, however, is not frequently examined in the feline ventricle, making interpretation of these results difficult. In the present study, a 5-min ischemic event caused a significant increase in the ACh level in the rabbit left ventricle (Fig. 2), suggesting that brief ischemia-induced ACh release may serve as a trigger for the ischemic preconditioning. Krieg et al. (2004) demonstrated that ACh triggers preconditioning by sequentially activating Akt and nitric oxide synthase to produce reactive oxygen species. An acetylcholine-induced preconditioning mimetic effect has also been observed in canine (Yao and Gross 1993; Przyklenk and Kloner 1995) and rat (Richard et al. 1995) models.

Table 1
Mean arterial pressure (AP) and heart rate (HR) obtained during Protocol 1 ($n=6$).

	Baseline	Occlusion 5 min	Occlusion 15 min	Occlusion 30 min	Reperfusion 5 min	Reperfusion 15 min	Reperfusion 30 min
AP(mm Hg)	82±4	77±4	72±5	75±5	72±5*	70±4*	70±2**
HR (beats/min)	247±16	264±14	265±13	280±10**	278±9*	277±8*	274±9

Data are shown as the mean±SE. *$P<0.05$ and **$P<0.01$ vs. baseline using Dunnett's test.

Table 2
Mean arterial pressure (AP) and heart rate (HR) obtained during Protocol 2 ($n=5$).

	Baseline	Preconditioning 5 min	Interval 5 min	Interval 10 min	Occlusion 5 min	Occlusion 10 min
AP(mm Hg)	83±5	77±5	78±4	80±4	78±5	78±5
HR(beats/min)	277±7	282±8	282±7	284±5	285±5	286±6
	Occlusion 20 min	Occlusion 30 min	Reperfusion 5 min	Reperfusion 10 min	Reperfusion 20 min	Reperfusion 30 min
AP(mm Hg)	77±4	78±5	77±5	78±5	77±3	79±3
HR(beats/min)	287±5	289±6	290±5	289±5	290±6	293±5

Data are shown as the mean±SE. No significant differences relative to control values (the value 10 min after the preconditioning) were observed based on Dunnett's test.

In a previous study examining the feline ventricle (Kawada et al. 2002), brief ischemia significantly decreased the HR, highlighting the presence of a significant vagal reflex from the heart. Vagotomy abolished the ACh release induced by brief ischemia in that study, suggesting an important role of centrally mediated vagal activation. The vagal reflex from the heart, however, shows regional differences and varies among species (Thames et al. 1978; Kawada et al. 2007). In the present study, brief ischemia did not decrease the HR significantly (Table 2), suggesting that centrally mediated vagal activation was not a major factor for the brief ischemia-induced ACh release in the rabbit heart.

Rabbits exhibit marked effects from ischemic preconditioning, including reduced infarct size (Cohen et al. 1991; Cason et al. 1997). Although whether the ACh release induced by the brief ischemic event exerted cardioprotective effects was not examined in the present study, there was a notable difference in the changes in AP observed with Protocol 1 and Protocol 2. Although AP decreased significantly upon reperfusion in Protocol 1 (Table 1), it did not change significantly during the major ischemic event in Protocol 2 (Table 2), possibly reflecting preserved cardiac function as a result of the ischemic preconditioning.

Effects of electrical vagal stimulation on myocardial interstitial ACh levels

In the feline left ventricle, electrical vagal stimulation at 20 Hz (10 V, 1-ms pulse duration) increases myocardial interstitial ACh levels to approximately 20 nM as measured with a dialysis fiber 13 mm in length (Kawada et al. 2000). In contrast, electrical vagal stimulation at 20 Hz in the rabbit left ventricle (10 V, 1-ms pulse duration) increased the ACh levels to approximately 1.2 nM as measured with a dialysis fiber 8 mm long (Fig. 3). The small increase in the ACh level detected during electrical vagal stimulation may indicate that vagal innervation is much sparser in the rabbit ventricle

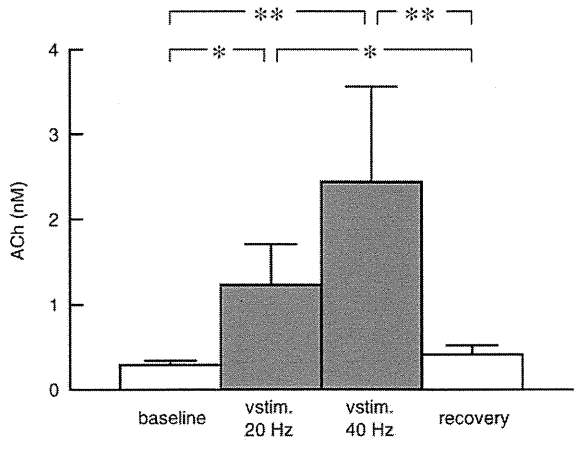

Fig. 3. Changes in the myocardial interstitial ACh levels in Protocol 3. The bilateral efferent vagus nerves were stimulated at 20 Hz for 15 min and 40 Hz for 15 min. Data are shown as the mean + SE ($n=10$, 2 samples from each of the 5 animals). *$P<0.05$ and **$P<0.01$; Tukey test.

than in the feline ventricle. In a previous study that used a dialysis fiber 4 mm in length, right vagal stimulation at 20 Hz increased the dialysate ACh concentration from 0.4±0.2 nM to 0.9±0.3 nM, whereas left vagal stimulation at 20 Hz increased it from 0.3±0.1 nM to 1.0±0.4 nM in the rabbit right ventricle (Shimizu et al. 2009). Considering the bilateral stimulation and fiber length of 8 mm in the present study, the vagal innervation of the left ventricle may be comparable to or slightly sparser than that of the right ventricle.

The dialysis fiber differed in length among studies due to anatomical restrictions related to the fiber implantation procedure (*i.e.*, size of the heart etc.). If we consider diffusive processes alone, the relative recovery (RR) can be expressed as:

$$RR = \frac{C_{inside}}{C_{outside}} = 1 - \exp\left(-k\frac{A}{F}\right) = 1 - \exp\left(-k\frac{mL}{F}\right)$$

where C_{inside} and $C_{outside}$ are the ACh concentrations inside and outside the dialysis fiber; A is the surface area of the dialysis membrane, which can be proportional to the fiber length L with a coefficient m; F is a perfusion flow rate; and k is the mass transfer coefficient (Ståhle 1991). The *in vitro* RR for ACh is approximately 70% with $F=2$ µl/min and $L=13$ mm (Akiyama et al. 1994), which yields $km=0.1852$. Using this value, the *in vitro* RR would be approximately 52% for $L=8$ mm and 31% for $L=4$ mm. Although these values provide some clues to speculate the effects of fiber length on the detected ACh concentrations, they cannot be directly extrapolated to the present results, because k should be different in *in vivo* conditions.

The physiological significance of vagal innervation of the left ventricle is controversial, because fixed-rate atrial pacing abolishes vagally induced inhibition of left ventricular contractility in an experimental setting without significant background sympathetic tone (Matsuura et al. 1997). On the other hand, when the cardiac sympathetic nerve is activated, vagal stimulation can reduce ventricular contractility even under fixed-rate atrial pacing by antagonizing the sympathetic effect (Nakayama et al. 2001). In addition, vagal stimulation suppresses myocardial interstitial myoglobin release during acute myocardial ischemia in anesthetized cats (Kawada et al. 2008). Chronic vagal stimulation improves the survival rate of rat models of chronic heart failure after myocardial infarction (Li et al. 2004). These lines of evidence suggest that vagal innervation of the left ventricle may be of therapeutic significance.

An unresolved question regarding the cardioprotective effects of vagal stimulation is that a large quantity of ACh is released in the ischemic region without vagal stimulation (Fig. 1). In the present

Table 3
Mean arterial pressure (AP) and heart rate (HR) obtained during Protocol 3 ($n=5$).

	Baseline	Vagal stimulation 20 Hz	Vagal stimulation 40 Hz	Recovery
AP (mm Hg)	100±3	59±9**	54±9**	86±5
HR (beats/min)	322±14	126±5**	100±8**	311±8

Data are shown as the mean±SE. **$P<0.01$ vs. baseline based on Dunnett's test.

study, vagal stimulation at 20-Hz lowered the HR by approximately 200 beats/min (to less than 40% of the control value) but the stimulation-induced ACh release did not exceed the ischemia-induced ACh release (Figs. 1 and 3). On the other hand, vagal stimulation that reduced the HR by only 10% produces a significant increase in the survival rate of chronic heart failure rats (Li et al. 2004). Therefore, vagal stimulation probably exerts its beneficial effects not only within the ischemic region but also outside of this region. For instance, vagal stimulation in dogs with a healed myocardial infarction is known to prevent lethal arrhythmia induced by exercise (Vanoli et al. 1991). Afferent vagal activation may also contribute to the cardioprotective effects. Further studies are clearly needed to identify the mechanisms underlying the vagally induced cardioprotective effects against myocardial infarction and chronic heart failure.

Conclusion

The present study demonstrated the presence of vagal innervation in the rabbit left ventricle. Acute myocardial ischemia significantly increased the myocardial interstitial ACh levels. In addition, a brief ischemic event (5 min) caused detectable increases in ACh levels, indicating that endogenous ACh release may provide a trigger for ischemic preconditioning.

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Metformin Prevents Progression of Heart Failure in Dogs: Role of AMP-Activated Protein Kinase

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Metformin Prevents Progression of Heart Failure in Dogs
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Background—Some studies have shown that metformin activates AMP-activated protein kinase (AMPK) and has a potent cardioprotective effect against ischemia/reperfusion injury. Because AMPK also is activated in animal models of heart failure, we investigated whether metformin decreases cardiomyocyte apoptosis and attenuates the progression of heart failure in dogs.

Methods and Results—Treatment with metformin (10 μmol/L) protected cultured cardiomyocytes from cell death during exposure to H_2O_2 (50 μmol/L) via AMPK activation, as shown by the MTT assay, terminal deoxynucleotidyl transferase–mediated dUTP nick-end labeling staining, and flow cytometry. Continuous rapid ventricular pacing (230 bpm for 4 weeks) caused typical heart failure in dogs. Both left ventricular fractional shortening and left ventricular end-diastolic pressure were significantly improved in dogs treated with oral metformin at 100 mg $\cdot$ kg^{-1} $\cdot$ d^{-1} (n=8) (18.6$\pm$1.8% and 11.8$\pm$1.1 mm Hg, respectively) compared with dogs receiving vehicle (n=8) (9.6$\pm$0.7% and 22$\pm$0.9 mm Hg, respectively). Metformin also promoted phosphorylation of both AMPK and endothelial nitric oxide synthase, increased plasma nitric oxide levels, and improved insulin resistance. As a result of these effects, metformin decreased apoptosis and improved cardiac function in failing canine hearts. Interestingly, another AMPK activator (AICAR) had effects equivalent to those of metformin, suggesting the primary role of AMPK activation in reducing apoptosis and preventing heart failure.

Conclusions—Metformin attenuated oxidative stress–induced cardiomyocyte apoptosis and prevented the progression of heart failure in dogs, along with activation of AMPK. Therefore, metformin may be a potential new therapy for heart failure. (***Circulation.* 2009;119:2568-2577.**)

Key Words: AMP-activated protein kinase ■ heart failure ■ metformin ■ nitric oxide

Metformin is widely used as an antidiabetic drug with an insulin-sensitizing effect. A large-scale clinical trial (the UK Prospective Diabetes Study [UKPDS] 34) has shown that metformin therapy decreased the risk of cardiovascular death and the incidence of myocardial infarction associated with diabetes mellitus,[1] suggesting that this drug may be useful for patients who have both cardiovascular disease and diabetes mellitus. Eurich and colleagues[2] recently reported the results of a meta-analysis showing that metformin was the only antidiabetic agent to reduce all-cause mortality without causing any harm in patients who had heart failure and diabetes mellitus. These results suggest that a tight link exists between cardiovascular disease and diabetes mellitus and that metformin has a cardioprotective effect. Metformin is known to activate AMP-activated protein kinase (AMPK),[3–5] which is expressed in various tissues, including the myocardium, and plays a central role in the regulation of energy metabolism under stress conditions.[6] AMPK is activated by ischemia/reperfusion,[7–9] as well as in hearts with pressure overload hypertrophy[10] and subsequent heart failure.[11,12] In addition, Russell et al[9] have demonstrated that isolated hearts of AMPK-deleted mice show increased apoptosis and dysfunction after ischemia/reperfusion. Activation of AMPK by adiponectin also has been reported to protect cardiomyocytes against apoptosis and to attenuate myocardial ischemia/reperfusion injury in mice.[8] Furthermore, metformin has been reported to increase the production of nitric oxide (NO),[13–15] which is known to have various beneficial cardiovascular

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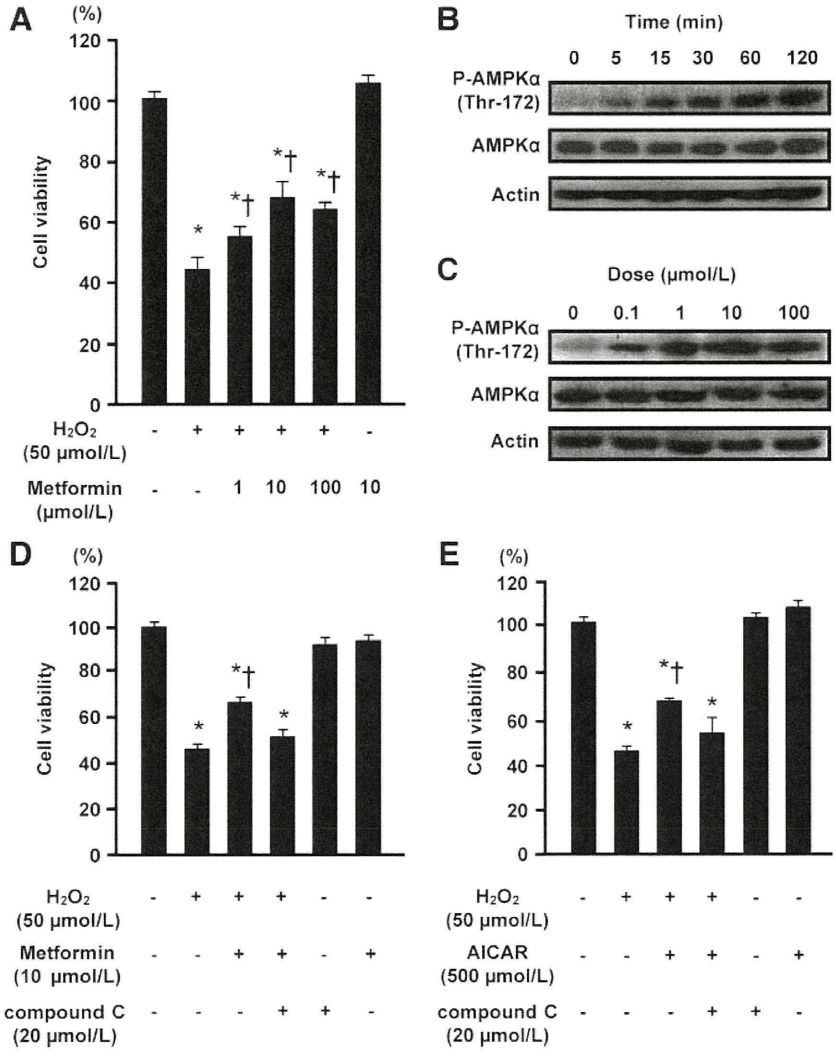

Figure 1. Effect of metformin on oxidative stress–induced cell death via AMPK activation in cultured rat cardiomyocytes. A, Cardiomyocyte viability after treatment with metformin (1, 10, or 100 μmol/L) and exposure to H_2O_2 (50 μmol/L). B, Time (0, 5, 15, 30, 60, 120 minutes) -dependent changes in AMPK phosphorylation in cardiomyocytes after treatment with metformin (10 μmol/L). C, Dose-dependent changes in AMPK phosphorylation in cardiomyocytes after treatment with metformin (0.1, 1, 10, or 100 μmol/L). D, Effect of an AMPK inhibitor (compound C; 20 μmol/L) on cardiomyocyte viability after treatment with metformin (10 μmol/L). E, Effect of an AMPK activator (AICAR; 500 μmol/L) on cardiomyocyte viability after treatment with metformin (10 μmol/L). Values are mean±SEM. P-AMPKα indicates phosphorylation of AMPKα. *$P<0.05$ vs no treatment; †$P<0.05$ vs H_2O_2 (50 μmol/L) treatment.

effects[16] and may alleviate mechanical or neurohormonal stress on the heart.

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These findings led us to hypothesize that activation of AMPK by metformin may exert a cardioprotective effect under stress conditions. Accordingly, metformin might be a potential new treatment for cardiac failure because it activates AMPK and increases NO production. Therefore, we investigated the influence of metformin on apoptosis, an important feature of heart failure, using cultured neonatal cardiomyocytes exposed to H_2O_2 and the effect of metformin on the progression of pacing-induced heart failure in dogs, along with activation of AMPK.

Methods

Experimental procedures are described in the online-only Data Supplement.

Statistical Analysis

Results are expressed as mean±SEM. Comparison of changes between groups over time was performed by 2-way repeated-measures ANOVA. Other data were compared between groups by 1-way fractional ANOVA. The Tukey-Kramer test was used to correct for multiple comparisons. In all analyses, values of $P<0.05$ were considered to indicate statistical significance.

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

Results

Metformin Attenuates Oxidative Stress–Induced Cell Death and Apoptosis in Cultured Cardiomyocytes via AMPK Activation

Cell viability was decreased in the presence of H_2O_2, as shown by the MTT assay, but this change was blunted by treatment with metformin in a dose-dependent manner (Figure 1A). Treatment with metformin (10 μmol/L) stimulated phosphorylation of AMPK in cultured cardiomyocytes in a time- and dose-dependent manner (Figure 1B and 1C). The effect of metformin on cell viability was blunted by cotreatment with compound C, an AMPK inhibitor (20 μmol/L) (Figure 1D). 5-Amino-4-imidazole-1-β-D-carboxamide ribofuranoside (AICAR; another AMPK activator) had an effect similar to metformin on cardiomyocyte viability after exposure to H_2O_2 (Figure 1E). These results suggested that

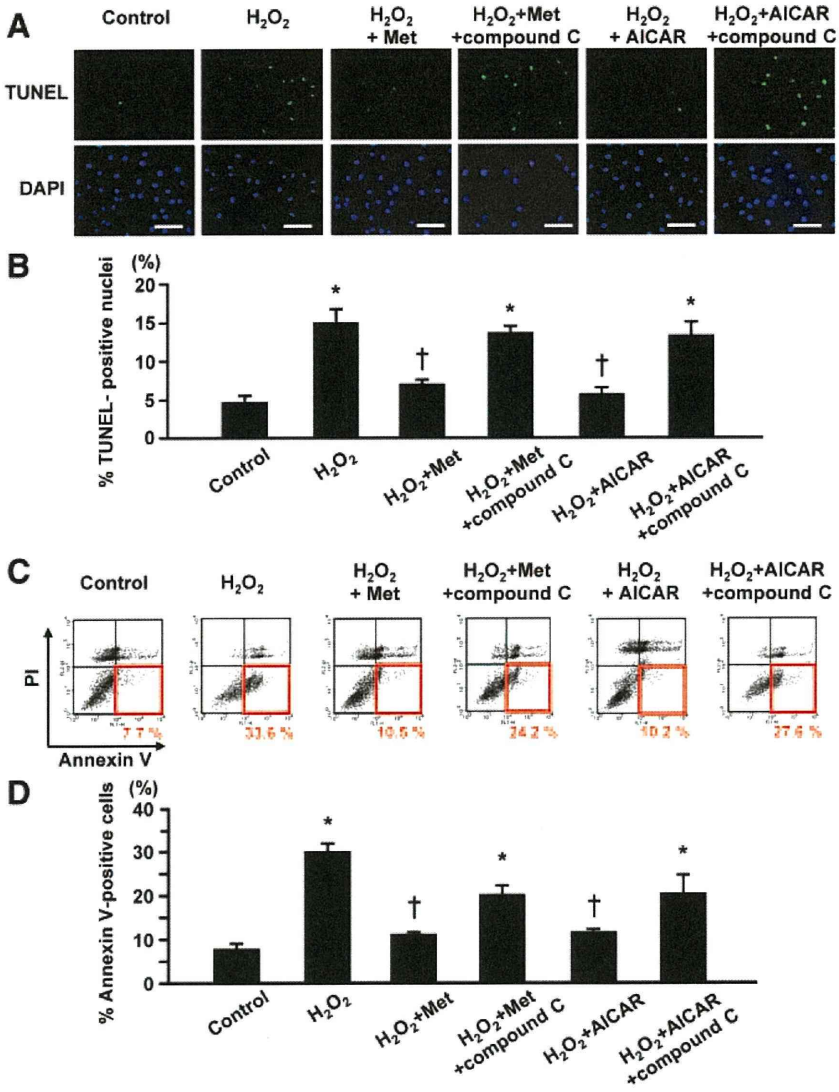

Figure 2. Effect of metformin on oxidative stress–induced apoptosis via AMPK activation in cultured rat cardiomyocytes. Representative (A) and quantitative (B) data on cardiomyocyte apoptosis obtained by TUNEL staining (n=3 in each experiment). Representative (C) and quantitative (D) data on cardiomyocyte apoptosis obtained by flow cytometry (n=3 in each experiment). Values are mean±SEM. PI indicates propidine iodide. *$P<0.05$ vs control; †$P<0.05$ vs H_2O_2 (50 μmol/L) treatment.

activation of AMPK protected cardiomyocytes against damage caused by H_2O_2.

H_2O_2 also increased cardiomyocyte apoptosis, as shown by the terminal deoxynucleotidyl transferase–mediated dUTP nick-end labeling (TUNEL) staining and flow cytometry (annexin V–positive and propidine iodide–negative cells) (Figure 2A through 2D). Metformin pretreatment significantly reduced the extent of cardiomyocyte apoptosis compared with that in untreated control cells (Figure 2A through 2D). Treatment with compound C inhibited the effects of metformin and AICAR (which was similar to that of metformin) on apoptosis in cardiomyocytes exposed to H_2O_2 (Figure 2A through 2D). These results suggested that the activation of AMPK by metformin could prevent apoptosis of cardiomyocytes induced by H_2O_2.

Effect of Metformin on Cardiac Function in Dogs With Pacing-Induced Heart Failure

Cardiac Physiological and Pathophysiological Parameters

Four weeks after the rapid right ventricular (RV) pacing, left ventricular (LV) end-diastolic dimension, LV end-systolic dimension, LV fractional shortening, and LV ejection fraction of the pacing group showed significant deterioration compared with the sham group (Figure 3A and 3B). Treatment with metformin significantly reduced both LV dimensions and increased both LV fractional shortening and LV ejection fraction compared with the pacing group (Figure 3A and 3B). Before RV pacing, both mean aortic pressure and heart rate were similar in all groups, and these parameters did not change throughout the study (Table). Four weeks after the RV pacing, pulmonary capillary wedge pressure, mean pulmonary artery pressure, and LV end-diastolic pressure were all significantly higher in the pacing group compared with the sham group (Figure 4A and 4B). Metformin treatment significantly reduced pulmonary capillary wedge pressure, mean pulmonary artery pressure, and LV end-diastolic pressure compared with the pacing group (Figure 4A and 4B). Furthermore, cardiac output was decreased and systemic vascular resistance was increased in the pacing group compared with the sham group, whereas metformin increased cardiac output and decreased systemic vascular resistance compared with the levels in the pacing group (the Table).

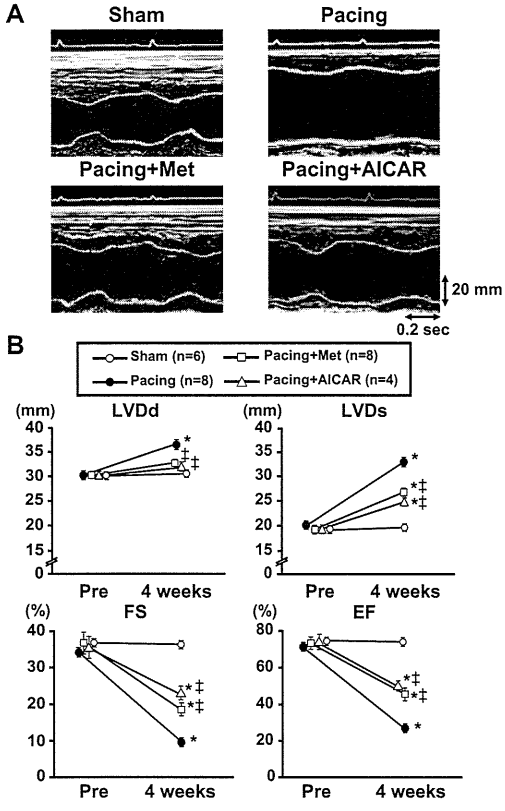

Figure 3. Effect of metformin on echocardiographic parameters. A, Representative M-mode echocardiograms obtained 4 weeks after sham surgery or after RV pacing. B, Echocardiographic parameters before and after sham surgery or after RV pacing in the sham group (n=6), pacing group (n=8), pacing plus metformin group (n=8), and pacing plus AICAR group (n=4). Values are mean±SEM. LVDd indicates LV end-diastolic dimension; LVDs, LV end-systolic dimension; LVFS, LV fractional shortening; and LVEF, LV ejection fraction. *$P<0.01$ vs sham group; ‡$P<0.01$ vs pacing group.

Importantly, the percentage of TUNEL-positive cells to total cells in LV myocardium in the pacing group increased compared with that in the sham group, which was blunted by treatment with either metformin or AICAR (Figure 5A through 5E).

Consistent with previous data,[17] no significant differences were found in body weight, the ratio of LV plus septal weight to body weight, and the ratio of RV weight to body weight among all groups (the Table).

To explore established markers of cardiac failure, we analyzed LV myocardial expression of the atrial natriuretic peptide and brain natriuretic peptide genes, which showed an increase in the pacing group, whereas metformin significantly suppressed this increase (Figure 6A and 6B). Metformin also significantly reduced the levels of angiotensin II and norepinephrine compared with the pacing group (the Table).

Pedometer counts were significantly reduced in the pacing group compared with the sham group, suggesting that heart failure led to reduced physical activities (the Table). Metformin increased the pedometer count compared with that in the pacing group. No differences in body fat were found among all groups (the Table).

Cardiac Molecular Parameters

To assess the molecular basis of the improvement in cardiac performance achieved by metformin administration for 4 weeks, we examined the collagen volume fraction in LV myocardium after staining with Masson's trichrome stain. Metformin reduced the collagen volume fraction compared with the pacing group (Figure 6C and 6D). To further investigate the mechanism of this antifibrotic effect of metformin, we examined the level of transforming growth factor-β1 (TGF-β1) mRNA associated with fibrosis in canine LV myocardium 4 weeks after pacing. Metformin suppressed the increase in TGF-β1 mRNA expression (Figure 6E).

AMPK was phosphorylated in the pacing group, and its phosphorylation was significantly enhanced by administration of metformin (Figure 7A and 7B). Phosphorylation was used as an index of enzymatic activity because AMPK is activated by phosphorylation.[18] This increase in AMPK phosphorylation was accompanied by augmented phosphorylation of acetyl-CoA carboxylase (ACC; a downstream target of AMPK) at Ser-79 (Figure 7A and 7C). Endothelial NO synthase (eNOS) also showed an increase in phosphorylation at Ser-1177 with metformin treatment (Figure 7A and 7D). Furthermore, metformin significantly upregulated eNOS mRNA expression and increased ΔNO (the difference between the plasma NO level before and after 4 weeks of RV pacing) compared with the pacing group (Figure 8A and 8B).

To investigate the level of insulin signaling in the heart, we examined the phosphorylation of Akt in the left ventricles in all groups. Significant increases were found in phosphorylation of Akt at Ser-473 in the pacing group compared with the sham group, and such increases were blunted by either metformin or AICAR treatment (Figure 8C and 8D).

Plasma and Cardiac Metabolic Parameters

To investigate whether activation of AMPK by metformin influenced metabolic parameters in the periphery or the heart, we assessed glucose and lipid metabolism after 4 weeks of pacing. Plasma free fatty acids tended to increase in the pacing group compared with the sham group, although no statistically significant difference was found. Fasting plasma levels of both glucose and lactate were similar among all groups (the Table). Both the fasting plasma insulin level and the homeostasis model assessment–insulin resistance value were significantly increased in the pacing group, whereas metformin reduced both parameters until they were similar to those of the sham group (the Table).

In the heart, both glucose extraction and the arterial–coronary sinus difference were increased in the pacing group compared with the sham group (the Table). In the pacing group, the free fatty acids extraction was not increased, but the arterial–coronary sinus difference tended to increase compared with the sham group (the Table). Lactate extraction and the arterial–coronary sinus difference were similar among all groups (the Table).

AICAR Mimics the Effect of Metformin in This Canine Pacing Model

To further confirm that activation of AMPK contributed to inhibition of the progression of heart failure, we administered