Possible Association of Heart Failure Status With Synthetic Balance Between Aldosterone and Dehydroepiandrosterone in Human Heart

Shota Nakamura, MD; Michihiro Yoshimura, MD, PhD; Masafumi Nakayama, MD, PhD; Teruhiko Ito, MD, PhD; Yuji Mizuno, MD, PhD; Eisaku Harada, MD, PhD; Tomohiro Sakamoto, MD, PhD; Yoshihiko Saito, MD, PhD; Kazuwa Nakao, MD, PhD; Hirofumi Yasue, MD, PhD; Hisao Ogawa, MD, PhD

Background—Aldosterone is produced not only in the adrenal gland but also in the extra-adrenal tissues, including failing human heart. This study examined the production of dehydroepiandrosterone (DHEA) in human heart and elucidated the possible physiological significance.

Method and Results—Using left ventricular tissues obtained at autopsy, reverse transcription–polymerase chain reaction followed by Southern blot analysis revealed the gene expressions of CYP17. By measuring plasma aldosterone and DHEA levels at the coronary sinuses and aortic roots during cardiac catheterization, we found that DHEA but not aldosterone was secreted from control subjects (P < 0.0001 and P = 0.74, respectively), whereas aldosterone but not DHEA was secreted from patients with heart failure (P = 0.0017 and P = 0.67, respectively). To examine the significance of DHEA, we measured myocyte cell sizes and the gene expression of B-type natriuretic peptide (BNP), using a neonatal rat cardiocyte culture system. We found that DHEA (10⁻⁸ mol/L) significantly inhibited the increase in myocyte cell sizes and BNP mRNA levels upregulated by endothelin-1 (P = 0.031 and P < 0.0001, respectively).

Conclusions—CYP17 gene expression and production of DHEA were demonstrated in human control heart. Also, we found that cardiac production of DHEA was suppressed in failing heart. We postulated that DHEA and/or its metabolites exert a cardioprotective action through antihypertrophic effects. (Circulation. 2004;110:1787-1793.)

Key Words: heart failure • hormones • hypertrophy • cardiomyopathy • natriuretic peptides

In addition to the classic adrenal biosynthetic pathway, steroid hormone production has been reported in extra-adrenal tissues,1–4 and it has also been reported that aldosterone is produced in rat heart.3,4 By measuring aldosterone levels in plasma sampled from the anterior interventricular vein, the coronary sinus and the aortic root, we were able to show that aldosterone synthesis is elevated in failing human ventricle.5

The enzymes necessary for the adrenal synthesis of aldosterone include cytochrome P450 cholesterol side-chain cleavage enzyme (CYP11A), 3β-hydroxysteroid dehydrogenase (3β-HSD2), cytochrome P450 21-hydroxylase (CYP21), and cytochrome P450 aldosterone synthase (CYP11B2).6 Kayes-Wandover et al7 recently reported that CYP11A, 3β-HSD2, and CYP21 were expressed in human heart, and Young et al8 demonstrated that CYP11B2 was detected in failing human heart. We have reported that CYP11B2 gene expression was significantly higher in samples of left ventricular tissue from patients with heart failure than in comparable samples from patients free of cardiovascular disease, using modified real-time reverse transcription–polymerase chain reaction (RT-PCR) methods.9

Besides aldosterone, it has been reported that CYP17, the key enzyme for dehydroepiandrosterone (DHEA) and cortisol, is also produced in such extra-adrenal tissues as skin,10 stomach,11,12 liver,13 and brain.14–16 However, the extra-adrenal synthesis of DHEA and cortisol in human heart has not been investigated.

CYP17 has two enzyme activities, cytochrome P450 17α-hydroxylase and 17,20-lyase.17 17α-Hydroxylase hydroxylates pregnenolone and progesterone to 17OH pregnenolone and 17OH progesterone, respectively, and the former is then transformed to DHEA by 17,20-lyase. 17OH progesterone is also hydroxylated by CYP21–11-deoxycortisol, which is in
turn hydroxylated by cytochrome P450 11β-hydroxylase (CYP11B1), becoming cortisol.\(^7\)

DHEA is the most abundantly produced adrenal steroid, and serum concentrations of its sulfate ester, DHEAS, are approximately 20-fold higher than those of any other circulating steroid hormone.\(^18,19\) Plasma levels of DHEA(S) decrease with aging,\(^18,19\) and extensive epidemiological evidence shows that there is an inverse correlation between plasma levels of DHEA(S) and the prevalence of cardiovascular disease.\(^20,21\) Furthermore, plasma levels of DHEA(S) are also decreased in proportion to the severity of heart failure,\(^22\) which suggests that DHEA(S) may play an important physiological role in the prevention of cardiovascular disease. Therefore, a study of a possible extra-adrenal DHEA production is an interesting theme in cardiovascular science.

This study examined the production of DHEA, aldosterone, or cortisol in human heart and elucidated the possible physiological significance of DHEA production.

## Methods

### Protocol 1

**Left Ventricle Samples and Total RNA Extraction**

Samples of left ventricular tissue were obtained at autopsy from 7 cancer patients (patients 1 through 7) for protocols 1 and 2 and 6 patients who died of heart failure (patients 8 through 13) for protocol 2, as shown in Table 1. There was no metastasis to any tissues and no apparent cardiovascular diseases affecting survival. A sample of adrenal glandular tissue as a positive control was obtained at autopsy from patient 2. Total RNA was extracted from frozen tissues with the use of TRIzol reagent (Invitrogen Corp).

**RT-PCR Analysis**

Oligonucleotide primers for human CYP11A, 3β-HSD2, CYP21, CYP11B1, and CYP17 have been reported.\(^7\) Samples (500 ng) of total RNA were reverse-transcribed by means of the SuperScript First-Strand Synthesis System (Invitrogen Corp), using oligo(dT). The amplification protocol consisted of 40 to 50 cycles of 94°C for 30 seconds, 55°C for 30 seconds, and 72°C for 60 seconds. The PCR products were then directly sequenced.

**Southern Blot Analysis**

PCR products of CYP17 and CYP11B1 were transferred overnight to Hybond N nylon membranes; prehybridized in 6×SSPE, 1% SDS, 10×Denhart’s solution, and 100 μg/mL denatured herring sperm DNA at 60°C for 2 hours; and hybridized with \(^32\)P end-labeled oligonucleotides, as previously reported,\(^2\) internal to each amplified segment, at 37°C for 12 hours. Membranes were washed with 6×SSPE and 0.1% SDS twice for 5 minutes at room temperature and twice at 37°C and then exposed to BAS-IP film (Fuji Film) for 3 hours.

### Protocol 2

**Quantitative Real-Time RT-PCR Analysis for Human CYP17, Human CYP11B1, Human BNP, and Rat BNP**

The following primers and fluorescent-tagged probes were used to quantify human CYP17: forward primer; 5'-GCCGTGATCATCACAAATGAGA-3', reverse primer; 5'-CTTACTGACGTTGAAGATGACGT-3', and probe; 5'-FAM-CGGATCAGTTCATGCCTGAGCGTT-TAMRA-3'. Human CYP11B1: forward primer; 5'-CAOCTGCTGCTAGACATCA-3', reverse primer; 5'-ATGCCTGGCCCTCAAATATGAGAAG-3', and probe; 5'-FAM-TGCCACATGTCTGAAACACCTCA-TAMRA-3', human BNP: forward primer; 5'-TTGCACAGAGGAAATGGCTCAGAGACAGC-TAMRA-3', and probe; 5'-FAM-GCGCTGCTCACAATGAGA-3'.

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TABLE 2. Patient Characteristics

<table>
<thead>
<tr>
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<th>Control Subjects (n=48)</th>
<th>Patients With HF (n=26)</th>
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<tbody>
<tr>
<td>Sex, M/F, n</td>
<td>32/16</td>
<td>17/9</td>
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<tr>
<td>Age, y</td>
<td>61.3±1.9</td>
<td>64.1±2.2</td>
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<td>HR, bpm</td>
<td>70.4±3.0</td>
<td>72.3±3.4</td>
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<tr>
<td>Mean BP, mm Hg</td>
<td>102.3±2.6</td>
<td>111.8±7.4</td>
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<tr>
<td>Cl, L/min per m²</td>
<td>3.0±0.1</td>
<td>2.3±0.1</td>
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<tr>
<td>PCWP, mm Hg</td>
<td>9.2±0.6</td>
<td>15.5±1.5</td>
</tr>
<tr>
<td>LVEDP, mm Hg</td>
<td>11.7±0.8</td>
<td>19.5±1.6</td>
</tr>
<tr>
<td>BNP, pg/mL</td>
<td>9.2±1.0</td>
<td>236.4±45.3</td>
</tr>
</tbody>
</table>

HF indicates heart failure; HR, heart rate; BP, blood pressure; Cl, cardiac index; LVEDP, left ventricular end-diastolic pressure; and PCWP, pulmonary capillary wedge pressure. Values are mean±SEM.

Protocol 3

We compared the expression levels of DHEA from patients with heart failure and from control subjects during cardiac catheterization.

Patient Population and the Cardiac Catheterization Study

Blood samples were obtained from 26 patients with heart failure (11 caused by dilated cardiomyopathy, 7 old myocardial infarction, 5 hypertensive heart disease, 2 hypertrophic cardiomyopathy, and 1 mitral regurgitation) and 48 control subjects suspicious for angina pectoris and who underwent cardiac catheterization at our institution. No control subjects had coronary stenosis, left ventricular dysfunction, or left ventricular hypertrophy. Table 2 shows the characteristics of the control subjects and patients with heart failure. All medications including ACE inhibitors, angiotensin II receptor antagonists, aldosterone receptor blockers, nitrates, Ca-antagonists, adrenergic β-antagonists and diuretics were withheld for at least 4 days before the study in all patients.

Hormonal Analysis

Plasma aldosterone concentrations were measured by radioimmunoassay with the use of an SPAC-S aldosterone kit (Duichi RI). Plasma DHEA concentrations were measured by radioimmunoassay (Otsuka Assay). Plasma cortisol concentrations were measured by radioimmunoassay (Immunotech).

Protocol 4

We studied the possible effects of DHEA on cardiac hypertrophy in response to endothelin-1, measuring myocyte cell sizes and the gene expression of BNP in a neonatal rat cardiocyte culture system.

Cell Cultures

In a study conforming to the Guide for the Care and Use of Laboratory Animals published by the US National Institutes of Health, neonatal rat myocytes and nonmyocytes were prepared on Percoll gradient and maintained as previously described. Cells were cultured for a further 12 hours before treatment in serum-free medium containing antibiotics and 0.01% BSA.

Measurement of Myocyte Cell Sizes

Immunocytochemistry for sarcomeric actin was performed to evaluate the morphological changes of the myocytes. Cardiocytes cultured on the culture slide were fixed with 3% formaldehyde for 10 minutes after prepermeabilization with 0.2% Triton X-100. Fixed cells were incubated for 8 hours with anti-rat sarcomeric action antibody α-Sr-1 (DAKO A/S), followed by treatment with a peroxidase-conjugated second antibody for visualization with 3,3′-di-aminobenzidine tetrahydrochloride. Additionally, nuclei of cultured cardiac cells were stained with hematoxylin. The cell sizes of the myocytes were estimated by measuring the area of sarcomeric action-positive cells attached.

Presentation 1

Expression of CYP17 mRNA in Human Cardiac Tissue

As shown in Figure 1A, the expressions of CYP11A, 3β-HSD2, CYP21, and CYP17 mRNA were detected in left ventricular and adrenal tissues obtained at autopsy from patients free of cardiovascular diseases, using RT-PCR analysis (PCR cycles: CYP11A; 40, 3β-HSD2; 40, CYP21; 40, CYP17; 50, CYP11B1; 50), but that of CYP11B1 was not detected in any of the left ventricular tissues. The specificity of the amplified products was confirmed by direct sequencing of gel-purified bands (data not shown). In addition, CYP17 gene expression was confirmed by Southern blot analysis (Figure 1B), although the bands were weak in RT-PCR.

Figure 1. Expression of steroidogenic enzyme mRNA in human heart and adrenal gland. Samples (500 ng) of total RNA were subjected to RT-PCR, after which amplified products were detected by gel electrophoresis on 2% agarose gels (A), followed by Southern blot analysis (B). M indicates φ X Hae III digest; N, cardiac tissue without RT as negative control. Lanes 1 to 7: cardiac tissues from patients numbered 1 to 7, respectively. P indicates adrenal glandular tissue as positive control.

Materials

Endothelin-1 and DHEA were purchased from Sigma Chemical Co.

Statistical Analysis for All the Study Protocols

Statistical analysis was performed with the use of Wilcoxon signed rank test and unpaired t test. Also, 1-way ANOVA followed by the multiple comparison methods of Scheffe was used for statistical analyses. Data were expressed as mean±SEM. Values of P<0.05 were considered significant.

Informed Consent and Animal Care

Written informed consent was obtained for each study protocol from each patient and/or his or her family where appropriate, and the ethics committee at our institution approved the protocol. Also, the institutional committee on animal care at Kumamoto University approved this study.

Results

Protocol 1

Expression of CYP17 mRNA in Human Cardiac Tissue

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Comparison of Hormonal Levels

Cardiac index was significantly lower and left ventricular ejection fraction was significantly higher in the heart failure group than in the control group (Table 2).

Comparison of aldosterone, DHEA, and cortisol levels in plasma samples obtained from aortic root (Ao) and coronary sinus (CS) in control subjects (0) and patients with heart failure (●). Values are mean±SEM. *P<0.05, **P<0.01, †P<0.05, ‡P<0.01.
levels in the two regions (CS; 40.46±2.90×10^-6 mol/L versus Ao; 40.81±3.43×10^-6 mol/L, P=0.82). The value of DHEA/aldosterone in the coronary sinus was significantly lower in patients with heart failure than in control subjects (0.390±0.056 versus 0.637±0.054, P=0.0048).

**Protocol 4**

**Effects of DHEA on Myocyte Cell Sizes and BNP mRNA in Rat Cardiocytes**

To examine the effect of DHEA on rat cardiocytes, cells were incubated in the presence or absence of DHEA added 12 hours before treatment with endothelin-1 for 48 hours.

As shown in Table 3, endothelin-1 (10^-8 mol/L) significantly increased myocyte cell sizes (∆P<0.0001), and DHEA (10^-7 mol/L) significantly inhibited the increase in cell sizes (∆P=0.031, compared with the levels stimulated by endothelin-1 alone) upregulated by endothelin-1.

As shown in Figure 5, endothelin-1 (10^-7 mol/L) significantly increased BNP mRNA levels (1.51±0.11-fold; ∆P=0.0016, compared with control), and DHEA (10^-8 and 10^-6 mol/L) significantly inhibited BNP mRNA levels (∆P<0.0001 and ∆P<0.0001 respectively, compared with the levels stimulated by endothelin-1 alone) upregulated by endothelin-1.

**Discussion**

In protocol 1, using left ventricular tissue samples collected from autopsies, we examined gene expressions for the synthesis of DHEA and cortisol. CYP11A, 3β-HSD2, CYP21, CYP11B1, and CYP17 are required to produce DHEA and cortisol.6 The expression of CYP11A, 3β-HSD2, and CYP21 were clearly demonstrated in all left ventricular tissue samples. This result is in agreement with those of previous reports.7,8 As for CYP17, we were able to demonstrate its expression, although the bands were weak compared with those of the other three enzymes. However, direct sequencing and Southern blot analysis reinforced the expression in left ventricular tissues.

Because we obtained positive data for gene expression of CYP17 from human hearts, we then compared the expression levels of CYP17 mRNA from human heart between patients who died of heart failure (heart failure group) and those who were free of cardiovascular disease (non–heart failure group) in protocol 2. In the analysis, we succeeded in detecting the gene expression of CYP17 by real time RT-PCR in both heart failure and non–heart failure groups. The amount of CYP17 mRNA expressed in left ventricle was found to be ≈2×10^5 times lower than in adrenal gland. However, because the heart is 30- to 50-fold larger than the adrenal gland,24 the total mass of CYP17 mRNA in the heart is probably at least 0.01% of that in the adrenal gland. However, we could not detect a difference in degree of gene expression between the heart failure and non–heart failure groups. Nonetheless, we still hypothesized a possible decrease in DHEA production in heart failure and then proceeded to protocol 3. Interestingly, we were able to obtain a significant difference in secretion of DHEA between the heart failure and control groups, as shown in Figure 4; we demonstrated cardiac DHEA production in control heart, whereas its production was decreased in failing heart. Even in the control group, the amount of DHEA synthesized by the heart may be too small to serve any endocrine function, and it may act as an autocrine/paracrine manner within healthy heart.25

The results of protocol 2 and 3 seem not to agree; we did not find any difference in CYP17 gene expression between the heart failure and non–heart failure groups in protocol 2, but we found a significant difference in secretion of DHEA between the heart failure and control groups in protocol 3. At present, we cannot clearly explain the reason, but we hypothesize as follows. Cardiac DHEA production could depend on not only CYP17 mRNA level but also the stability of CYP17 mRNA and 17,20-lyase activity. CYP17 has two enzyme activities, 17α-hydroxylase and 17,20-lyase; 17α-hydroxylase reaction leads to cortisol, and the subsequent 17,20-lyase reaction leads to DHEA.17 These are regulated by redox partners such as cytochrome P450 reductase and cytochrome b5.26 Cytochrome P450 reductase activity significantly decreases in aged adrenal glands; however, the cytochrome b5 contents do not change between young and aged...
adrenal glands. The decrease in P450 reductase activity causes a specific decrease in 17,20-lyase activity without affecting 17α-hydroxylase activity. It is thus possible that 17α-hydroxylase activity would be suppressed in failing heart. Many neurohormonal factors including angiotensin II and aldosterone are activated in heart failure and aldosterone production is upregulated in turn. The pattern of aldosterone secretion is in agreement with our earlier report. Although this phenomenon is considered to be a result of heart failure or oxidative status, it may be one factor that further advances heart failure. Indeed, in this study, we found an antihypertrophic effect of DHEA by measuring not only myocyte cell sizes but also the gene expression of BNP, a sensitive marker of cardiac hypertrophy and heart failure. Endothelin-1 is known to stimulate cardiac hypertrophy in cultured rat cardiocytes. DHEA significantly inhibited BNP mRNA levels upregulated by endothelin-1 in a dose-dependent manner from 10^{-8} to 10^{-6} mol/L. It should be noted that the concentration of 10^{-8} mol/L was at a level similar to the circulating hormonal levels of DHEA shown in this study. These results suggested that a small dose of DHEA produced in the heart could act as a cardioprotective agent against neurohormonal factors stimulating cardiac hypertrophy in an autocrine/paracrine manner.

Because an intracellular steroid hormone receptor for DHEA has not been identified, the molecular mechanisms of DHEA are still to be clearly described, despite evidence suggesting beneficial cardiovascular effects. However, recent reports have shown that there are specific DHEA-binding sites in cardiovascular tissues and that this putative receptor is present in rat heart. DHEA probably is converted to testosterone or 17β-estradiol in the heart, and furthermore, specific receptors for testosterone and 17β-estradiol are present in the heart. Thus, it is unclear whether DHEA directly exerts its effects or if it acts after conversion to these hormones. Also, our preliminary data showed that testosterone or 17β-estradiol each significantly inhibited mRNA expression of BNP upregulated by endothelin-1, suggesting that the effect of DHEA may depend on, at least in part, its metabolites, testosterone or 17β-estradiol (data not shown). Aromatase, which metabolizes testosterone to 17β-estradiol, is reported to be present in rat cardiocytes. Even in the presence of an aromatase inhibitor, DHEA still significantly inhibited mRNA expression of BNP, indicating that the effect of DHEA does not depend entirely on conversion to 17β-estradiol. However, it is unclear whether DHEA or testosterone has the stronger antihypertrophic effect. At present, we can conclude that DHEA and/or its metabolites directly exert an effect on the heart; the effect of the conversion from DHEA to testosterone or 17β-estradiol in the heart might be involved in antihypertrophic effects. Also, the direct intracellular signaling cascade of DHEA has been unconfirmed as yet; thus, investigation is required.

Cortisol is released from the zona fasciculata of adrenal glands and plays an important role in the stress response. The plasma levels of cortisol increase with aging, contrasting with those of DHEA. It is still unclear whether cortisol or CYP11B1, the key enzyme catalyzing the final step in the synthesis of cortisol, is expressed in human heart. In the present analysis, we could not detect the expression of CYP11B1 by using RT-PCR followed by Southern blot analysis and real-time RT-PCR in human ventricles. We also could not detect any significant increase at the coronary sinus as compared with that at the aortic root. We thus concluded that neither cortisol nor CYP11B1 was expressed in the heart. These results are in agreement with previous reports. However, the examination of whether there is any exception for cardiac cortisol production is required.

In this study, we were able to demonstrate CYP17 expression in human heart, even though others have reported that CYP17 is not expressed in heart. In the present study, the bands of CYP17, which were subjected to 50 cycles of RT-PCR, were very weak but were detectable; however, we were able to confirm them by direct sequencing and Southern blot analysis. Furthermore, the levels of CYP17 mRNA were quantified by real-time RT-PCR, which is more sensitive than conventional RT-PCR and other methods of detecting mRNA. It may seem difficult to assess the relative significance or contribution of in situ production of DHEA or in situ expression of CYP17 in human heart compared with larger amounts in systemic circulation because of low levels of CYP17 expression. At present, we do not have a complete answer; however, a similar discussion with regard to aldosterone has been carried out. Although the expression of aldosterone synthase gene CYP11B2 is very small in human failing heart, we certainly detected it by modified real-time PCR. Interestingly, there also is a report that the tissue levels of aldosterone were 17 times as high as circulating levels. Several explanations for this cardiac concentration effect are possible. For instance, aldosterone degradation may be slower in cardiac tissue than in plasma or may be segregated intracellularly once produced and/or locally delivered into the extracellular space instead of being released into plasma. This in situ synthesis of a biologically active hormone might thus result in a far greater concentration within tissue than that which could be achieved via the blood stream; supporting a putative physiological role. Possibly, the same situation as this might be applicable to DHEA, although this is only speculation on our part.

It would also be of interest to know the effect of DHEA on myocardial and vascular inflammation because perivascular inflammation has been shown to precede aldosterone-induced myocardial fibrosis. Although this study is important to clarify the pathogenesis of myocardial inflammation and fibrosis, we have no data about it at present. This kind of study should be undertaken in the future.

In summary, DHEA, secreted from the heart, might directly or after conversion to its metabolites exert a cardioprotective action. Also, it may be possible that reduced cardiac
DHEA production causes a worsening of status during heart failure. The cardiac steroid-genesis of small quantity would be important; however, its significance needs to be continuously discussed in detail in the future.

Acknowledgments

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References

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