Effects of Spironolactone and Eprosartan on Cardiac Remodeling and Angiotensin Converting Enzyme Isoforms in Rats with Experimental Heart Failure

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Abstract: Angiotensin converting enzyme–2 (ACE-2) is a newly described enzyme, with antagonistic effects to those of the classical ACE (ACE-1). Both angiotensin II (AngII) and aldosterone play an important role in the pathophysiology of congestive heart failure (CHF), and in the adverse cardiac remodeling during its development. In this study, we examined the effects of experimental CHF induced by an aortocaval fistula (ACF), and of its treatment with AngII and aldosterone inhibitors, on the relative levels of ACE-1 and ACE-2. We also compared the effects of spironolactone, an aldosterone antagonist, and eprosartan, an AngII receptor antagonist, on heart hypertrophy and fibrosis in rats with ACF. Spironolactone (15mg/Kg/d ip, via minipump) or eprosartan (5mg/Kg/d ip via minipump) were administered into rats with ACF for 14 and 28 days. Specific antibodies were used to determine the protein levels of myocardial ACE-1 and ACE-2. ACF increased the cardiac levels of ACE-1 and decreased those of ACE-2. Heart-to-body weight ratio (HW/BW) significantly increased from 0.30±0.004% in sham controls to 0.50±0.018% and 0.56±0.044%, (p<0.001) in rats with ACF, 2 and 4 weeks following surgery, respectively, in association with increased plasma levels of aldosterone. The area occupied by collagen increased from 2.33±0.27% to 6.85±0.65% and 8.03±0.93% (p<0.01) 2 and 4 weeks following ACF, respectively. Both spironolactone and eprosartan decreased cardiac mass and collagen content, and reversed the shift in ACE isoforms. ACF alters the ratio between ACE isoforms, in a manner that increases local AngII and aldosterone levels. Early treatment with both AngII and aldosterone antagonists is effective in reducing this effect. Thus, ACE isoform shift may represent an important component of the development of cardiac remodeling in response to hemodynamic overload, and its correction may contribute to the beneficial therapeutic effects of renin angiotensin aldosterone system (RAAS) inhibitors.
Keywords: Aldosterone antagonist, Angiotensin antagonist, ACE-2, Heart failure.

**Introduction**

The involvement of vasoconstrictor neuro-hormonal systems in the pathogenesis of congestive heart failure (CHF), has been increasingly recognized (14;12;27). Numerous studies in patients and in experimental models of CHF have established the important role of the renin-angiotensin-aldosterone system (RAAS) in the progression of cardiovascular and renal dysfunction in CHF. It is now accepted that excessive neuro-humoral activation may adversely affect cardiac function and the hemodynamic condition by enhancement of systemic vasoconstriction and promoting salt and water retention by the kidney. In addition, prolonged activation of the RAAS may have direct deleterious actions on the myocardium, independent of their systemic hemodynamic effects (27). Specifically, angiotensin II (Ang II) has been shown to stimulate myocyte hypertrophy and to enhance fibrosis and apoptosis, leading ultimately to progressive remodeling and further deterioration in cardiac performance (23).

The concept that CHF is also a "neurohormonal disorder" has led to the use of angiotensin converting enzyme (ACE) inhibitors, and ang II receptor antagonists aldosterone antagonists, as well as β-blockers, that are now central to the treatment of CHF (22;23;27). Yet, Ang II comprises only one of the two major components of the RAAS (14). The role of the other component, namely, aldosterone in cardiac remodeling has emerged in the last few years. It is widely accepted that structural remodeling of the interstitial collagen matrix is regulated by both angII and aldosterone (5;38;40). These effects have been attributed to both the elevated circulatory and local cardiac levels of these two active components of the RAAS, activated in both experimental and clinical severe CHF (33). Recently, Mizuno et al. (25) showed that cardiac aldosterone production is increased in patients with CHF, especially when caused by systolic dysfunction. Convincing evidence for the local production of aldosterone was
provided by the finding that CYP11B2 mRNA (aldosterone synthase) is expressed in cultured neonatal rat cardiac myocytes (21). The adverse contribution of aldosterone to the functional and structural alterations of the failing heart was elegantly demonstrated by Suzuki et al. (36). These authors showed that eplerenone, a specific aldosterone antagonist, prevented progressive LV systolic and diastolic dysfunction in association with reducing interstitial fibrosis, cardiomyocyte hypertrophy and LV chamber sphericity in dogs with CHF. Similarly, Delyani et al (9) reported that eplerenone, attenuated the development of ventricular remodeling and reactive but not reparative fibrosis after myocardial infarction in rats. These findings are in agreement with the results observed in clinical trials. Randomized Aldactone Evaluation Study (RALES), therapy with spironolactone reduced overall mortality in patients with advanced heart failure by 30% compared with placebo (30). Recently, the EPHESUS study showed that addition of eplerenone to optimal medical therapy reduces morbidity and mortality among patients with acute myocardial infarction complicated by left ventricular dysfunction and heart failure (29).

It has recently been discovered, that the local levels of AngII and aldosterone depend not only on renin activity, but also on the ratio between two isoforms of ACE. The classic ACE converts AngI into AngII, and is the target of ACE inhibitors. Its inhibition exerts well established beneficial effects in various cardiovascular disorders, including CHF. In contrast, angiotensin converting enzyme-2 (ACE-2), an enzyme recently identified, was shown to possess a different biochemical activity (8). It converts Ang-I into [Ang(1-9)] and Ang-II into [Ang(1-7)], therefore antagonizing ACE activity. In addition, the resulting [Ang(1-7)] possesses opposite effects to those of Ang-II including vasodilatation, antihypertrophy and diuresis (10). The role of aldosterone in the pathophysiology of heart failure was shown to involve amplification of tissue ACE expression (17) and spironolactone treatment reduced ACE activity (13). Similarly, AngII receptor blockers (ARBs) have also been an effective treatment for CHF. The relative contribution of AngII and
aldosterone to myocardial hypertrophy and fibrosis in CHF has not been comparatively investigated.

Therefore, the present study was designed to examine the changes in ACE and ACE2 during the development of CHF and the effects of early treatment with either eprosartan (an ARB) or spironolactone (an aldosterone antagonist) on these changes, as well as on the cardiac hypertrophy and fibrosis. We used the animal model of CHF induced by an aortocaval fistula (ACF), a well established and thoroughly characterized model of volume overload in rats.

**Methods**

**The Experimental Model:** Experiments were performed on male Wistar rats weighing about 300 g and maintained on standard diet and water *ad libitum*. An aorto-caval fistula (ACF, side-to-side, 1.2 mm O.D.) was surgically created between the inferior vena cava and abdominal aorta according to the methodology that was described by Stumpe et al. (34) and adapted by our laboratory (41;1). Sham operated rats served as controls. Following the surgical procedure the animals were allowed to recover and then transferred into individual metabolic cages for daily monitoring of sodium excretion and urinary output. Previously, we have demonstrated that rats with a surgically created ACF develop within seven days a syndrome mimicking the hemodynamic and neurohormonal alterations observed in patients with severe heart failure (41;1;7). Most notably, the creation of ACF was associated with activation of RAAS and increased heart weight to body weight ratio, an index of cardiac hypertrophy.

**In Vivo Experiments**

**Effects of treatment with either spironolactone or eprosartan on rats with ACF:** This protocol was designed to evaluate the effects of long-term administration (14 and 28 days) of either spironolactone or eprosartan through osmotic minipumps: ALZET model 2ML2 for 14 days of treatment, ALZET model 2ML4, ALZA for 28 days of treatment; (Alza, Palo Alto, CA) on the
changes in the cardiac ACE/ACE2 immunoreactivity, as well as on the development of cardiac hypertension and fibrosis in rats with ACF (n=6-30). Sham operated rats (n=6-23) or untreated ACF animals (n=6-20) served as controls. Spironolactone (Sigma) was dissolved in polyethylene glycol 400 (35 mg/ml) and was adjusted to a final concentration sufficient to deliver 15 mg/kg/d for either 14 or 28 days, according to the manufacturer's specifications. Eprosartan (Merck & Co) was dissolved in NaHCO₃ (20 mg/ml) and was adjusted to a final concentration sufficient to deliver 5 mg/kg/d for either 14 or 28 days. The osmotic minipumps containing either spironolactone, eprosartan or vehicles were implanted into the peritoneal cavity during the creation of the ACF. After the operation the animals were transferred into metabolic cages, and daily measurements of urinary sodium and potassium excretion were performed for either 14 or 28 days. After completion of spironolactone or eprosartan treatment, animals were sacrificed and their blood was collected in precooled tubes, their chest opened, and the heart was removed immediately, placed on absorbent paper to remove excess blood, weighed, and halved. Half of the cardiac tissue was frozen for immunoblot analysis, and half was embedded in paraffin for histological analysis.

**In Vitro**

**Morphological analysis:** Fixed blocks of the myocardial tissue were embedded in paraffin, and 4-5 μm-thick sections were cut from the blocks of the different experimental groups. The sections placed in Harris Hematoxylin for 5 minutes, and washed 3 times with distilled water. Sections were stained with Trichrome solution for 10 minutes and washed 3 times with 0.2% acetic acid as described by Masson (24). The sections were dehydrated in 2 changes of 95% ethanol followed by 2 changes of 100% ethanol, and cleared in 4 changes of xylol. Collagen volume was determined by measuring the area of stained tissue within a given field and expressed as the proportion of the total area under observation by using ImageProPlus, version 4.5, resolution 760x590 pixels (MediaCybernetics, USA).
Western blot: Western blot analysis was performed on heart tissue stored at -70°C. 100 micrograms of total ventricular homogenate were resolved in a polyacrylamide gel (4-20%, Bio Rad). Proteins were transferred onto nitrocellulose membranes (Optitran; Schleicher & Schuell, Keene, NH) using a semidry transfer apparatus (Bio-Rad). After blocking in three percent non-fat milk, membranes were incubated with specific antibodies (anti-ACE and ACE-2, Santa Cruze) for 2h, and with secondary antibody for 1h at 24 °C. After each incubation, three 10 min TBS-Tween washes were performed. Blots were developed with an enhanced chemiluminescence detection kit (ECL; Amersham, Amersham, UK). The corresponding bands were quantified by densitometric scan (Bioprofil Imaging, Wilber Lourmat, France).

Determination of ACE activity
Cardiac homogenates were analyzed for their ACE activity using a commercial kit (Buhlmann, Swiss). The kinetics of ACE-mediated cleavage of the synthetic substrate furyl-acryloyl-phenylalanyl-glycyl-glycine to furyl-acryloyl-phenylalanine and glycine is measured by reduced absorbance at 340 nm (31). The absorbance kinetic was measured in a UV microplate reader (PowerWave, Biotech) and standardized to a known calibrator activity.

ACE2 activity assay
ACE2 activity determination is a modification of the method described by Huang et al (19). Briefly, ACE2 cleaves the leucine at the C-terminal of the decapeptide Angiotensin I - Asp\(^1\) Arg\(^2\) Val\(^3\) Tyr\(^4\) Ile\(^5\) His\(^6\) Pro\(^7\) Phe\(^8\) His\(^9\) Leu\(^10\) - and the assay is based on measurement of free leucine released. With the addition of β-Nicotinamide adenine dinucleotide (NAD) and leucine dehydrogenase (LeuDH) (Sigma), NADH is formed and the latter is coupled to diaphorase mediated conversion of resazurine to resorufin which is fluorescent (ex 565nm, em 585nm). Fluorescence kinetic is measured for one hour at room temperature in the Fluostar Galaxy plate reader (BMG Labtechnologies, Germany).
The assay was adapted to measure ACE2 in myocardial homogenate. LeuDH and diaphorase concentrations were increased five-fold (0.5U/ml) to minimize rate limiting kinetics. With the addition of angiotensin I (7.7nmole) to the homogenate, an increase of fluorescence was measured. This increase is dependent upon presence of leucine dehydrogenase and external supply of NAD, indicating the specific measurement of free leucine released. Angiotensin II alone was unable to induce increase of fluorescence. Pre-incubation of homogenate with a specific antibody directed against the ectopic domain of ACE2 (R&D systems, Minneapolis) completely abolished the AngI-induced increase of fluorescence, indicating the association of the AngI degradation activity with ACE2. Activity results are expressed as fmol leucine formation per min and normalized to mg tissue protein.

**Chemical analysis:** Sodium and potassium concentrations in plasma and urine were determined by flame photometry (model IL 943, Instrumentation Laboratories).

**Statistical Analysis:** Data are presented as mean values ± SEM. One way analysis of variance was used when multiple comparisons are made followed by Dunnett test. For comparison of the graphs representing control and experimental groups, two-way ANOVA was used. A value of p< 0.05 was considered statistically significant.

**Results**

**Effects of spironolactone or eprosartan on rats with ACF:** Figure 1 depicts that plasma levels of aldosterone significantly increased after 2 and 4 weeks from the placement of ACF, compared with sham controls, in line with our previous observation in rats with ACF for one week (1;7;41). Aldosterone levels were further elevated following treatment spironolactone for 2 and 4 weeks. In agreement with its inhibitory effects on AngII-induced aldosterone production, eprosartan significantly attenuated the elevation of aldosterone levels in rats with ACF. Administration of the vehicles did not affect plasma levels of aldosterone (data not shown). These findings demonstrate
that chronic administration of either spironolactone or eprosartan through osmotic minipumps appears to be an effective and reliable approach for the experimental blockade of aldosterone or angiotensin II, respectively.

Rats with ACF for 2 and 4 weeks display a moderate elevation in plasma concentrations of K+ (5.54±0.47 and 5.67±0.39 µEq/L, compared with sham 4.38±0.17 µEq/L, p<0.05) and normal Na+ levels (143.2±1.11 and 142.9±0.79 µEq/L, compared with sham controls, 141.1±1.79 µEq/L, P=NS). Spironolactone slightly, but significantly decreased plasma Na+ levels, to 138.4±0.97 µEq/L (p=0.007), and increased circulating K+ to 6.69±0.43 µEq/L (p<0.11), after 4 weeks of treatment. These effects of spironolactone are well known in patients, and further support our conclusion regarding the validity of the drug administration via osmotic minipumps.

Fig 2A shows that rats with ACF have lower urinary potassium excretion compared with sham operated rats, and spironolactone treatment has a further potassium sparing effect, contributing to the hyperkalemic effect of this agent. The decrease in U_kV by spironolactone was significant after the fifth day of treatment (p<0.05 by ANOVA 2). This dose of the aldosterone antagonist did not significantly affect U_NaV (data not shown). AngII blockade by eprosartan in rats with ACF for 2 or 4 weeks did not affect Na+, and K+ plasma levels, but significantly (p<0.05, ANOVA 2) improved natriuresis in ACF rats (Fig. 2B).

The effect of spironolactone on cardiac hypertrophy in rats with ACF is depicted in Figure 3. Rats with ACF display significant increase in HW/BW after 2 (0.502 ± 0.018%, p<0.001) and 4 weeks (0.56±0.044%, p<0.001) from the creation of the fistula compared with sham controls (0.3±0.004%). Administration of spironolactone for 2 and 4 weeks partially but significantly attenuated the development of cardiac hypertrophy (HW/BW decreased to 0.409±0.012% p<0.05, and 0.485±0.0035%, p=NS, respectively). Similar to spironolactone, administration of eprosartan for 2 or 4 weeks reduced cardiac mass in rats with ACF to 0.4053±0.022 (p<0.01) and 0.454±0.035, respectively (p<0.05), (Fig. 3).
Figure 4 quantitatively summarizes the effects of either spironolactone or eprosartan on the interstitial fibrosis in cardiac ventricular tissue (combined right and left). The myocardial collagen volume fraction in rats with ACF for two (6.85±0.65%) and four weeks (8.03±0.93 %) was significantly (p<0.01) higher compared with sham operated rats (2.33±0.27%), indicating that fibrosis is a characteristic of the ACF model. Administration of spironolactone for 2 weeks and 4 weeks significantly reduced myocardial collagen volume fraction in rats with ACF fistula (5.05±0.41 %, p<0.5 and 3.10+0.39%, P<0.01 respectively.). Administration of eprosartan for 2 and 4 weeks produced an even more profound reduction in myocardial collagen volume fraction in rats with ACF (2.87±0.24 % and 1.86+0.26%, respectively, p<0. 01) (Fig. 4).

Changes in ACE and ACE2 immunoreactivity in untreated and treated rats with ACF: Fig. 5 shows an increase in the level of ACE, and a decrease in the level of ACE2, 2 and 4 weeks after the placement of ACF. Treatment with both spironolactone and eprosartan restored the immunoreactive levels of ACE and ACE2, to comparable levels of sham operated controls. The increase in ACE2 in response to eprosartan was greater than that in response to spironolactone. Densitometric analysis of ACE-2 in the various experimental groups is presented in figure 6.

Effect of the spironolactone and eprosartan on cardiac ACE and ACE2 activities in rats with CHF

To determine whether the effects of spironolactone or eprosartane on ACE and ACE-2 immunoreactive levels are associated with similar trend in activities, the ACE and ACE-2 activities were determined in the different experimental groups.

ACE activity in ventricular homogenate derived from rats with CHF for 2 weeks, increased by 15 % (P=NS). Treatment of CHF animals with spironolactone and eprosartan reduced ACE activity by 41% (p=0.086) and 8% (p=0.766) compared with untreated CHF (Figure 7).
In contrast to ACE, ACE-2 activity decreased by 14% (p=0.63) in the myocardium of rats with CHF for 2 weeks. Both spironolactone and eprosartan increased ACE-2 activity by 42% (p=0.067) and 100.5% (p=0.042), respectively in rats with ACF compared with untreated animals (Figure 7).

**Discussion**

Cardiac remodeling occurs in response to a wide variety of prolonged hyperfunction stimuli. It consists of biochemical and structural-morphological changes. Furthermore, it serves as an adaptive mechanism in the short term, but is a major pathophysiological component of decompensation and the development of severe cardiac dysfunction in the long run, with the evolvement of heart failure, major arrhythmias and ischemia (34;36;15). Previously, we have shown that rats with ACF, an experimental model of cardiac hypertrophy, display neurohormonal, renal, and cardiac characteristics that closely mimic those observed in patients with clinical CHF. These include increased activity of the RAAS, sympathetic nervous system, and arginine vasopressin, and a marked decrease in renal function in association with sodium and water retention (2). In addition, rats with ACF develop proportionate cardiac hypertrophy to the severity of the cardiac dysfunction (28). The present study demonstrates that early treatment with either spironolactone or eprosartan for either 2 or 4 weeks partially and comparably reduced the increase in cardiac mass in rats with ACF. Both drugs remarkably diminished the interstitial cardiac fibrosis, though eprosartan was more effective than spironolactone in this respect.

This study demonstrated, to the best of our knowledge for the first time, that cardiac hyperfunction due to volume overload affects the local angiotensin levels by modulating the ratio between ACE and ACE-2: Rats with heart failure not only express high levels of cardiac ACE, but also exhibit reduced levels of cardiac ACE2. Thus, higher levels of Ang II are formed by ACE, given the reduced competition of ACE2 as demonstrated by activity determination tests. Furthermore, Ang II
is not metabolized into Ang[1-7], which further augments AngII levels. Moreover, both spironolactone and eprosartan treatment in rats with ACF restores the ratio between cardiac ACE and ACE-2 immunoreactivity, by down-regulating cellular ACE and up-regulating ACE-2 in association of similar alterations in the activity of these enzymes. These effects were associated with a significant lowering in the cardiac hypertrophy and fibrosis.

Studies performed on myocytes and fibroblast cultures taken from rat hearts showed that Ang II, and to a lesser extent aldosterone, induced collagen synthesis in a dose dependent manner, and decreased the activity of matrix metalloproteinases, key enzymes in interstitial collagen degradation (6;32;43). Likewise, in vivo studies have demonstrated that aldosterone and angiotensin II can stimulate the accumulation of collagen within the cardiac interstitium, and therefore lead to LV diastolic dysfunction and ultimately systolic dysfunction. Brilla et al (4) demonstrated that spironolactone prevents the development of interstitial fibrosis in hypertensive and normotensive rats given intravenous aldosterone. Similarly, the prognosis of CHF patients correlates with plasma procollagen, a collagen synthesis marker. Procollagen also served as a marker for the responsiveness to spironolactone therapy: patients with high levels of plasma procollagen showed decreased morbidity and morbidity in response to the aldosterone antagonist. These results suggest that reducing the excessive extracellular matrix turnover may be one of the various extra-renal mechanisms contributing to the beneficial effect of spironolactone in patients with CHF (42). Our finding that spironolactone modulates the ratio between ACE and ACE2 offers an additional mechanistic explanation for the beneficial effects of aldosterone inhibition. This finding is in agreement with reports that aldosterone upregulates tissue ACE expression in cardiomyocytes, indicating that this hormone increases local production of Ang-II (17). In the current study, spironolactone therapy lowered cardiac ACE immunoreactivity in rats with ACF, which could lead to the blockade of the Ang II-induced aldosterone production, and eventually to the reduction in hypertrophy and fibrosis of the heart in our experimental model of heart failure.
The significance of ACE2 in physiological and pathophysiological processes in the heart is starting to be studied, and there are contradictory reports on the potential consequences of high expression of this protein. On one hand, Crackower et al. (8) found that ACE2 null-mice exhibited a severe impairment in myocardial contractility in association with increased angiotensin II levels. Moreover, genetic ablation of ACE in the ACE2 null mice rescued the cardiac phenotype (26). In contrast to these findings, ACE2 transgenic mice have high incidence of sudden death that correlates with transgenic expression levels (11). However, the relative roles of ACE and ACE2 should be studied at physiological levels, in conditions mimicking common human pathological disorders such as hypertension, CHF and cardiac ischemia.

Our results are somewhat contradictory to those reported by Zisman et al (44) who demonstrated that failing human hearts display high cardiac levels of Ang 1-7, an evidence of upregulation of ACE2. Likewise, Goulter et al (16) showed that cardiac ACE-2 is up-regulated in patients with both idiopathic and ischemic cardiopathy. However, it should be emphasized that these patients received different conventional pharmacological therapies, including ACE inhibitors, aldosterone and Ang II antagonists, which, according to our study may significantly contribute to their finding. To summarize, the yin-yang regulation of ACE and ACE2 observed in this study could be a central key for the understanding of mechanisms affecting Ang-II production and its pathophysiological consequences. ACE-2 may be an important therapeutic target, and drugs that specifically influence its activity may have considerable clinical value. Therefore, determination of ACE-2 levels and activity in the cardiac tissue could represent an important marker for the assessment of the pathophysiological status and of the effect of therapeutic agents.

The reduction in cardiac fibrosis associated with spironolactone or eprosartan treatment in the ACF model exceeded the extent reported by similar studies in other models. For instance, Suzuki et al. (35;36) showed that in dogs with moderate CHF, long term aldosterone receptor blockade with eplerenone prevented the progressive LV systolic and diastolic dysfunction and attenuated the
interstitial fibrosis, cardiomyocyte hypertrophy, to a lesser extent than our results: Compared with controls, eplerenone treatment was associated with a 37% reduction of volume fraction of reactive interstitial fibrosis, and a 34% reduction of volume fraction of replacement fibrosis. Eplerenone did not alter body weight, electrolytes, BUN or creatinine, which suggests that regulation of fluid volume did not play a primary role in cardioprotective actions.

Treatment with aldosterone antagonists has become widespread in different cardiac disorders. Hayashi (18) has recently recommended that an aldosterone blocker should be maintained indefinitely in patients with severe chronic CHF due to systolic left ventricular dysfunction, as should be an ACE inhibitor and a β-adrenergic blocker. Moreover, mineralocorticoid receptor antagonist combined with ACE inhibitor can prevent post-infarct LV remodeling better than ACE inhibitor alone in association with the suppression of a marker of collagen synthesis (29;42). Moreover, Farquharson (13) demonstrated that spironolactone improves endothelial dysfunction in patients CHF class II-III, by increasing NO bioreactivity, and inhibiting AngI/AngII conversion, suggesting novel mechanisms for this agent beneficial effect on cardiovascular mortality.

Using a different model than ours, the group of Ishiyama (20) found recently that both losartan and olmesartan completely reversed the reduction in cardiac angiotensin II type-1 receptors mRNA observed after coronary artery ligation while augmenting ACE 2 mRNA by approximately 3-fold. The latter correlated significantly with angiotensin II, angiotensin-(1-7), and angiotensin I levels. This group suggested that the effect of angiotensin II blockade on cardiac ACE 2 may be due to direct blockade of AT1a receptors or a modulatory effect of increased angiotensin-(1-7).

In conclusion, treatment with both spironolactone antagonist and ARB was associated with reduction in cardiac hypertrophy and fibrosis in rats with experimental heart failure. We propose a novel mechanism for the beneficial effects of these agents in CHF, which involves down regulation of cardiac ACE and up regulation of ACE2.
References


33) Silvestre JS, Robert V, Heymes C, Aupetit-Faisant B, Mouas C, Moalic JM, Swynghedauw B, Delcayre C. Myocardial production of aldosterone and


40) Wilke A, Funck R, Rupp H, Brilla CG. Effect of the renin-angiotensin-aldosterone


Figure Legends

Figure 1: Plasma levels of aldosterone in rats with A-V fistula before and after spironolactone or eprosartan administration via osmotic mini pumps for 2 and 4 weeks. Sham operated rats served as controls. * P<0.05 vs. sham-operated rats; #P<0.05 vs. appropriate untreated rats with A-V fistula. Values are means±SEM.

Figure 2: Chronic effects of spironolactone on daily urinary potassium (A) and eprosartan on daily sodium excretion (B) in rats with A-V fistula compared to untreated animals. Sham operated animals (n=8) served as controls. Spironolactone was administered at a dose of 15 mg/kg/day via osmotic minipumps implanted into the peritoneal cavity during the creation of the A-V fistula.

Figure 3: Effects of early chronic administration of spironolactone or eprosartan for 2 and 4 weeks on heart weight/body weight ratio (HW/BW%) in rats with A-V fistula. * P<0.05 vs. sham-operated rats; #P<0.05 vs. untreated appropriate rats with A-V fistula. Values are means±SEM.

Figure 4: Effect of spironolactone or eprosartan treatments for 2 and 4 weeks on collagen volume fraction in rats with A-V fistula. Sham controls and untreated rats with A-V fistula served as controls. * P<0.05 vs. sham-operated rats; #P<0.05 vs. untreated appropriate rats with A-V fistula. Values are means±SEM.

Figure 5: A representative western blot analysis of ACE and ACE-2 in cardiac tissue of control rats and rats with CHF, before and after treatment with spironolactone or eprosartan. Bands at ~ 150 kDa represent ACE, and at ~100 kDa ACE-2 immunoreactive proteins.
**Figure 6:** Densitometric analysis of bands at ~100 kDa corresponding ACE-2 immunoreactive proteins in cardiac tissue of control rats and rats with CHF, before and after treatment with spironolactone or eprosartan. * P<0.05 vs. sham-operated rats; #P<0.05 vs. untreated appropriate rats with A-V fistula. Values are means±SEM.

**Figure 7:** ACE and ACE2 activities in the cardiac tissues of control rats and rats with CHF, before and after treatment with spironolactone or eprosartan. A) ACE activity expressed in units. B) Activity of ACE2 (Ang I-induced ACE2-mediated release of leucine) expressed in pmole per minute and. Each bar represents means±SEM (n=5-6, *p<0.05 vs. untreated rats with CHF).
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