Association of arginine vasopressin with low atrial natriuretic peptide levels, left ventricular remodelling, and outcomes in adults with and without heart failure

Julio A. Chirinos
University of Pennsylvania

Mayank Sardana
University of Massachusetts Medical School

Garrett Oldland
University of Pennsylvania

See next page for additional authors

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Association of arginine vasopressin with low atrial natriuretic peptide levels, left ventricular remodelling, and outcomes in adults with and without heart failure

Julio A. Chirinos¹,²,³*, Mayank Sardana⁴†, Garrett Oldland¹,², Bilal Ansari³, Jonathan Lee², Anila Hussain³, Anique Mustafa³, Scott R. Akers¹, Wen Wei⁵, Edward G. Lakatta⁵ and Olga V. Fedorova⁵

¹Corporal Michael J. Crescenz VAMC, Philadelphia, PA, USA; ²University of Pennsylvania Perelman School of Medicine, Philadelphia, PA, USA; ³Hospital of the University of Pennsylvania, Philadelphia, PA, USA; ⁴University of Massachusetts Medical School, Worcester, MA, USA; ⁵National Institute of Aging, Baltimore, MD, USA

Abstract

Aims The arginine vasopressin (AVP) pathway has been extensively studied in heart failure (HF) with reduced ejection fraction (HFrEF), but less is known about AVP in HF with preserved EF (HFpEF). Furthermore, the association between AVP and atrial natriuretic peptide (ANP, a well-known inhibitor of AVP secretion) in HF is unknown.

Methods and results We studied subjects with HFpEF (n = 28) and HFrEF (n = 25) and without HF (n = 71). Left ventricular (LV) mass and left atrial (LA) volumes were measured with cardiac magnetic resonance imaging. Arginine vasopressin and ANP were measured with enzyme-linked immunosorbent assay. Arginine vasopressin levels were significantly greater in HFpEF [0.96 pg/mL; 95% confidence interval (CI) = 0.83–1.1 pg/mL] compared with subjects without HF (0.69 pg/mL; 95% CI = 0.6–0.77 pg/mL; P = 0.0002). Heart failure with preserved ejection fraction (but not HFrEF) was a significant predictor of higher AVP after adjustment for potential confounders. Arginine vasopressin levels were independently associated with a greater LA volume and also paradoxically, with lower ANP levels. Key independent correlates of higher AVP were the presence of HFpEF (standardized β = 0.32; 95% CI = 0.09–0.56; P = 0.0073) and the ANP/LA volume ratio (standardized β = −0.23; 95% CI = −0.42 to −0.04; P = 0.0196). Arginine vasopressin levels were independently associated with LV mass (β = 0.26; 95% CI = 0.09–0.43; P = 0.003) and with an increased risk of death or HF admissions during follow-up (hazard ratio = 1.61; 95% CI = 1.13–2.29; P = 0.008).

Conclusions Arginine vasopressin is increased in HFpEF and is associated with LV hypertrophy and poor outcomes. Higher AVP is associated with the combination of LA enlargement and paradoxically low ANP levels. These findings may indicate that a relative deficiency of ANP (an inhibitor of AVP secretion) in the setting of chronically increased LA pressure may contribute to AVP excess.

Keywords Arginine vasopressin; Heart failure with preserved ejection fraction; Left ventricular hypertrophy; Left atrium; Atrial natriuretic peptide

Introduction

The arginine vasopressin (AVP) pathway is important in the regulation of sodium and water metabolism, as well as vascular homeostasis.¹ Arginine vasopressin exerts a wide variety of effects on the heart, vascular smooth muscle, vascular endothelium, platelets, and kidneys. V1a receptors mediate vasoconstriction, platelet aggregation, myocardial hypertrophy, and fibrosis, whereas activation of V2 receptors in renal collecting ducts mediates the antidiuretic effects of AVP.² Excessive activation of the AVP pathway has been considered a maladaptive response to heart failure (HF), contributing to volume retention.¹ Circulating levels of AVP have been
studied in HF with reduced ejection fraction (HFrEF)\(^3\) and shown to correlate with the severity of left ventricular (LV) dysfunction\(^4\) and with clinical outcomes.\(^5\) However, little data are available regarding the role of AVP in HF with preserved ejection fraction (HFpEF). Recent studies demonstrated increased circulating copeptin levels (a surrogate for AVP release) in subjects with HFpEF.\(^6,7\) However, the correlates of increased AVP levels in HFpEF are not well understood. In particular, whether increased AVP levels are associated with LV remodelling in HFpEF and HFrEF is unknown. Similarly, little is known about the association between AVP levels and atrial natriuretic peptide (ANP) levels, which are released in response to increased atrial stretch and inhibit AVP release.\(^8\)

In this study, we aimed to (i) compare levels of plasma AVP between subjects with HFpEF and HFrEF and subjects without HF; (ii) assess the association between AVP, ANP levels, and LV remodelling in HFpEF and HFrEF; (iii) assess the association between AVP and LV remodelling; and (iv) assess the association between AVP and the risk of incident cardiovascular death or HF admission.

**Methods**

We prospectively enrolled a convenience sample of patients referred for a cardiac magnetic resonance imaging (MRI) study at the Corporal Michael J. Crescenz VA Medical Center. The protocol was approved by the Philadelphia VA Medical Center Institutional Review Board, and all subjects provided written informed consent.

Heart failure with reduced ejection fraction was defined as a symptomatic HF in the presence of an LV ejection fraction (LVEF) < 50%. Heart failure with preserved ejection fraction was defined as (i) New York Heart Association Class II–IV symptoms consistent with HF, in the absence of significant aortic or mitral stenosis; (ii) LVEF > 50%; and (iii) a mitral E wave to annular e’ ratio > 14,\(^9\) or at least two of the following: (a) a mitral E wave to annular e’ ratio > 8; (b) treatment with a loop diuretic for control of HF symptoms; (c) LA volume index > 34 mL/m\(^2\) of body surface area; (d) N-terminal pro B-type natriuretic peptide level > 200 pg/mL; and (e) LV mass index > 149 g/m\(^2\) in men and 122 g/m\(^2\) in women (measured by cardiac MRI). Subjects without HF had an LVEF > 50%, no significant valvular disease, and no symptoms and signs consistent with HF.

Key exclusion criteria were as follows: (i) claustrophobia; (ii) presence of metallic objects or implanted medical devices in body; (iii) conditions that could make the interpretation of MRI less accurate and/or unreliable (i.e. arrhythmia such as atrial fibrillation affecting cardiac gating and inability to hold breath for the cardiac MRI acquisitions); and (iv) known infiltrative or hypertrophic cardiomyopathy, or extra-cardiac amyloidosis or sarcoidosis.

**Measurement of serum arginine vasopressin and atrial natriuretic peptide**

Venous plasma samples were obtained at the time of enrollment and stored at −80°C for batch analysis. Arginine vasopressin and ANP were measured with enzyme-linked immunosorbent assay technique (Cayman Chemical, Ann Arbor, MI, USA).

**Measurement of central blood pressure**

We measured central blood pressure via carotid arterial tonometry performed in the supine position immediately after the MRI, using a high-fidelity Millar applanation tonometer (SPT-301; Millar Instruments, Houston, TX, USA) and a dedicated acquisition platform (Sphygmocor device; Atcor Medical, Sydney, Australia). This approach does not require the use of a generalized transfer function, because the carotid pressure waveform is a direct surrogate of aortic pressure.

**Cardiac magnetic resonance imaging**

We measured LV mass and volume and LA volume, using a 1.5 Tesla whole-body MRI scanner (Avanto or Espree; Siemens, Malvern, PA, USA) equipped with a phase-array cardiac coil.

Left ventricular volumes (end-diastolic and end-systolic volumes) and function (ejection fraction) were measured using steady-state free-precession cine imaging. Typical acquisition parameters were repetition time (TR) = 30.6 ms; echo time (TE) = 1.3 ms; slice thickness = 8 mm; phases = 30; parallel image (IPAT) factor = 2; and matrix size = 192 × 192. CMR42 software (Circle CVI, Calgary, AB, Canada) was utilized to manually trace the LV short-axis cine images at end of diastole and systole. Left ventricular mass was calculated as the difference between epicardial and endocardial volumes, multiplied by the myocardial density. Left ventricular mass was normalized for body height raised to the allometric power of 1.7.\(^10\) Left atrial volume was calculated by averaging the volumes measured end-systole by manually tracing the LA endocardial border in the apical two-chamber and four-chamber views.

**Statistical methods**

Continuous and categorical variables were compared between the groups using analysis of variance and chi-squared

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tests, respectively. Multivariable linear regression models were utilized to assess HFrEF and HFrEF as predictors of AVP levels, with and without adjusting for potential confounders. When required, Box–Cox transformation was applied to normalize regression model residuals. A second set of multivariable linear regression models were utilized to assess the association between ANP and AVP. Multivariable linear regression was also utilized to assess whether AVP was associated with LV mass index. We present standardized regression coefficients for easier comparison of the magnitude of the effect of various predictors on the dependent variable in regression models. The association between AVP levels and the risk of a composite endpoint of incident hospitalized HF or cardiovascular death was assessed with proportional hazards (Cox) regression. All tests were two-tailed. Statistical significance was defined as a P-value ≤ 0.05. We used SPSS v24 for Mac (IBM, Chicago, IL, USA) and Matlab v2016b (The Mathworks; Natick, MA, USA) to perform statistical analyses.

Association of arginine vasopressin and heart failure with preserved ejection fraction

Figure 1 shows mean AVP levels in patients without HF, HFrEF, and HFrEF. There were significant between-group differences in AVP levels (analysis of variance P = 0.0002). Arginine vasopressin levels were significantly greater in HFrEF [0.96 pg/mL; 95% confidence interval (CI) = 0.83–1.1 pg/mL] compared with controls (0.69 pg/mL; 95% CI = 0.6–0.77 pg/mL; P for pairwise comparison = 0.0003). In post hoc pairwise comparisons, AVP levels among subjects with HFrEF (0.73 pg/mL; 95% CI = 0.67–0.80 pg/mL) were significantly higher than those in controls (P = 0.0001). In addition, AVP levels were significantly higher in HFrEF compared to both controls (P = 0.0001) and HFrEF (P = 0.0002). AVP levels were significantly higher in HFrEF compared to both controls (P = 0.0001) and HFrEF (P = 0.0002).

Table 1 General characteristics of study participants

<table>
<thead>
<tr>
<th></th>
<th>No HF (n = 71)</th>
<th>HFrEF (n = 25)</th>
<th>HFrEF (n = 28)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Male</td>
<td></td>
<td></td>
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<tr>
<td>Race/ethnicity</td>
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<tr>
<td>White</td>
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<td></td>
</tr>
<tr>
<td>African American</td>
<td></td>
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<tr>
<td>Other</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>30.3 (28.84 to 31.77)</td>
<td>29.53 (27.07 to 32)</td>
<td>35.7 (33.36 to 38.03)</td>
<td>0.0003</td>
</tr>
<tr>
<td>Hypertension</td>
<td>59 (83.10%)</td>
<td>24 (96.00%)</td>
<td>24 (85.71%)</td>
<td>0.45</td>
</tr>
<tr>
<td>Coronary artery disease</td>
<td>19 (26.76%)</td>
<td>21 (84.00%)</td>
<td>10 (35.71%)</td>
<td>0.0001</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>40 (56.34%)</td>
<td>14 (56.00%)</td>
<td>22 (78.57%)</td>
<td>0.11</td>
</tr>
<tr>
<td>History of atrial fibrillation</td>
<td>2 (2.82%)</td>
<td>1 (4.00%)</td>
<td>1 (3.57%)</td>
<td>0.95</td>
</tr>
<tr>
<td>History of CVA or TIA</td>
<td>10 (14.06%)</td>
<td>7 (28.00%)</td>
<td>4 (14.29%)</td>
<td>0.26</td>
</tr>
<tr>
<td>Peripheral vascular disease</td>
<td>6 (8.45%)</td>
<td>4 (16.00%)</td>
<td>7 (25.00%)</td>
<td>0.09</td>
</tr>
<tr>
<td>Current smoker</td>
<td>15 (21.13%)</td>
<td>8 (32.00%)</td>
<td>5 (17.86%)</td>
<td>0.42</td>
</tr>
<tr>
<td>Beta-blocker use</td>
<td>29 (40.85%)</td>
<td>22 (88.00%)</td>
<td>16 (57.14%)</td>
<td>0.0001</td>
</tr>
<tr>
<td>ACE inhibitor use</td>
<td>36 (50.70%)</td>
<td>18 (72.00%)</td>
<td>17 (60.71%)</td>
<td>0.17</td>
</tr>
<tr>
<td>ARB use</td>
<td>5 (7.04%)</td>
<td>2 (8.00%)</td>
<td>6 (21.43%)</td>
<td>0.10</td>
</tr>
<tr>
<td>Furosemide use</td>
<td>2 (2.82%)</td>
<td>14 (56.00%)</td>
<td>1 (3.57%)</td>
<td>0.0001</td>
</tr>
<tr>
<td>Calcium channel blocker use</td>
<td>25 (35.21%)</td>
<td>6 (24.00%)</td>
<td>11 (39.29%)</td>
<td>0.47</td>
</tr>
<tr>
<td>Thiazide use</td>
<td>19 (26.76%)</td>
<td>7 (28.00%)</td>
<td>10 (35.71%)</td>
<td>0.67</td>
</tr>
<tr>
<td>eGFR (mL/m²)</td>
<td>83.88 (78.04 to 89.73)</td>
<td>79.76 (69.91 to 89.61)</td>
<td>79.32 (70.02 to 88.63)</td>
<td>0.63</td>
</tr>
<tr>
<td>Systolic BP (mmHg)</td>
<td>144.5 (140 to 149.1)</td>
<td>141 (133.3 to 148.7)</td>
<td>154.5 (147.2 to 161.8)</td>
<td>0.029</td>
</tr>
<tr>
<td>Diastolic BP (mmHg)</td>
<td>83.61 (81 to 86.3)</td>
<td>80.2 (75.8 to 84.7)</td>
<td>87.5 (83.3 to 91.7)</td>
<td>0.069</td>
</tr>
<tr>
<td>Central systolic BP (mmHg)</td>
<td>136.7 (131.29 to 142.1)</td>
<td>136.6 (127.7 to 145.6)</td>
<td>150.8 (141.8 to 159.8)</td>
<td>0.026</td>
</tr>
<tr>
<td>NYHA Class III–IV</td>
<td>0 (4.17%)</td>
<td>1 (3.57%)</td>
<td>1 (3.57%)</td>
<td>0.25</td>
</tr>
<tr>
<td>LV EDV (mL)</td>
<td>145 (132.8 to 157.2)</td>
<td>231.9 (211.4 to 252.5)</td>
<td>170.3 (150.8 to 189.7)</td>
<td>0.0001</td>
</tr>
<tr>
<td>LV mass (g)</td>
<td>145.8 (135.2 to 156.4)</td>
<td>186.6 (167.8 to 204.5)</td>
<td>182 (165.0 to 198.9)</td>
<td>0.0001</td>
</tr>
<tr>
<td>LVF (%)</td>
<td>60.07 (57.79 to 62.34)</td>
<td>35.48 (31.65 to 39.32)</td>
<td>63.31 (59.69 to 66.93)</td>
<td>0.0001</td>
</tr>
<tr>
<td>LV mass index (g/m³)</td>
<td>56.29 (52.23 to 60.36)</td>
<td>70.82 (63.96 to 77.68)</td>
<td>71.46 (64.98 to 77.94)</td>
<td>0.0001</td>
</tr>
<tr>
<td>LVEDV index (mL/m²)</td>
<td>48.81 (44.8 to 52.83)</td>
<td>77.14 (70.37 to 83.91)</td>
<td>57.81 (51.42 to 64.21)</td>
<td>0.0001</td>
</tr>
<tr>
<td>LA volume (mL)</td>
<td>59.9 (52.8 to 67)</td>
<td>79.1 (61.9 to 96.3)</td>
<td>77 (62.3 to 91.6)</td>
<td>0.013</td>
</tr>
<tr>
<td>LA volume index (mL/m²)</td>
<td>28.3 (25 to 31.7)</td>
<td>36.8 (28.9 to 44.6)</td>
<td>33.9 (27.6 to 40.3)</td>
<td>0.041</td>
</tr>
</tbody>
</table>

ACE, angiotensin convertase enzyme; ARB, angiotensin receptor blocker; BP, blood pressure; CVA, cerebrovascular accident; E/e', mitral inflow to mitral annular tissue velocity ratio; eGFR, estimated glomerular filtration rate; HF, heart failure; HFrEF, heart failure with preserved ejection fraction; HFrEF, heart failure with reduced ejection fraction; LA, left atrial; LV, left ventricular; LVEDV, left ventricular end-diastolic volume; LVEF, left ventricular ejection fraction; NYHA, New York Heart Association; TIA, transient ischaemic attack.
Figure 1. Comparison of arginine vasopressin (AVP) levels between subjects without heart failure (HF), subjects with heart failure with reduced ejection fraction (HFrEF), and heart failure with preserved ejection fraction (HfPEF).

![Graph showing AVP levels between groups](image)

**ANOVA P=0.00352**

**P=0.00254**

Cl = 0.59–0.88 pg/mL did not significantly differ from any of the other two groups.

We also assessed the presence of HfPEF or HFrEF as predictors of AVP levels in unadjusted and adjusted linear regression models. In unadjusted analyses, the presence of HfPEF (standardized \( \beta = 0.31; 95\% \text{ CI} = 0.13–0.48; P = 0.0001 \)) was associated with higher AVP levels. In a multivariable linear regression model adjusted for age, sex, race, systolic blood pressure, diabetes mellitus, the use of angiotensin convertase enzyme inhibitors, angiotensin receptor blockers, furosemide, estimated glomerular filtration rate, and New York Heart Association Class III–IV (Table 2), the two independent correlates of a higher AVP were the presence of HfPEF (standardized \( \beta = 0.32; 95\% \text{ CI} = 0.09–0.56; P = 0.0073 \)) and the ANP/LA volume ratio (standardized \( \beta = -0.23; 95\% \text{ CI} = -0.42 \) to \(-0.04; P = 0.0196 \)).

**Association of arginine vasopressin levels and left ventricular hypertrophy**

In unadjusted analyses, AVP levels were directly associated with LV mass (standardized \( \beta = 0.29; 95\% \text{ CI} = 0.12–0.46; P = 0.001, Figure 3, upper panel). In a model that adjusted for HF status, age, sex, race, glomerular filtration rate, and central systolic blood pressure (Figure 3, lower panel), AVP was a significant independent predictor of LV mass (standardized \( \beta = 0.24; 95\% \text{ CI} = 0.07–0.40; P = 0.005 \)). Similarly, after further adjustment for the use of angiotensin convertase enzyme inhibitors, angiotensin receptor blockers, furosemide, spironolactone, thiazide diuretics, calcium channel blockers, beta-blockers, and estimated glomerular filtration rate, the presence of HfPEF was independently associated with higher AVP levels (standardized \( \beta = 0.27; 95\% \text{ CI} = 0.04–0.5; P = 0.025 \)).

**Arginine vasopressin as a predictor of outcomes**

During a median follow-up of 1507 days (~4.12 years), 15 subjects had an HF admission, and 10 died of cardiovascular causes. Figure 4 shows the Kaplan–Meier event-free survival curves for subjects stratified by the median value of AVP. Survival was significantly lower in subjects with higher AVP. In a proportional hazards regression model, AVP was a significant predictor of an increased risk of incident cardiovascular death or HF admission [standardized hazard ratio (HR) = 1.61; 95% CI = 1.13–2.29; \( P = 0.008 \)]. Similarly, AVP predicted the endpoint after adjustment for age, gender, and HF group membership (standardized HR = 1.65; 95% CI = 1.10–2.49; \( P = 0.016 \)). The association between AVP and incident cardiovascular death or hospitalized HF was also independent of LA volume index, LV mass, and ANP (standardized HR = 1.82; 95% CI = 1.12–2.96; \( P = 0.015 \)). In an analysis that included only subjects with HF (HfPEF or HFrEF), AVP predicted
incident cardiovascular death or HF admissions (standardized HR = 1.72; 95% CI = 1.09–2.72; P = 0.021).

**Discussion**

In this study, we report that HFpEF is associated with increased plasma AVP, even after adjustment for potential confounders. We report, for the first time, that AVP levels are independently associated with the combination of greater LA volume and paradoxically low ANP levels. This finding is consistent with the physiological regulation of AVP by ANP demonstrated in animal models and raise the hypothesis that atrial natriuretic peptide deficiency in the setting of increased LA pressure is related to AVP excess, which should be tested in future studies. We demonstrate that AVP independently correlates with LV hypertrophy measured by MRI. Finally, we show that greater AVP levels are associated with an increased risk of adverse outcomes, independent of ANP, LA volume, and LV mass. Our findings contribute to
Arginine vasopressin is a nonapeptide synthesized by the hypothalamus, and it is released into the circulation from the neurohypophysis in response to various osmotic and non-osmotic stimuli (intravascular hypovolaemia).2 Initial studies in patients with HFrEF and asymptomatic LV dysfunction reported that AVP levels are inappropriately elevated in these conditions (in response to non-osmotic stimuli).3,4,11 Secretion of AVP can lead to deleterious effects in HF through its vasoconstrictive (V1a receptors) and free water retaining properties (V2 receptors), as well as through its hypertrophy and fibrosis promoting effects on the myocardium (V1a receptors) leading to adverse cardiac remodelling.1 Whereas great attention has been placed on V2-related effects on hyponatraemia in advanced HF, much less is known about the role of vascular and myocardial V1a effects. Finally, little is known about the relationship between ANP and AVP levels, despite its well-known physiological cross-regulation.8 To the best of our knowledge, no prior study has reported the comparative association of plasma AVP with HFpEF vs. HFrEF. We observed that in adjusted models, mean levels of AVP were significantly higher in HFpEF as compared with HFrEF and the control group. Of note, average AVP levels in our participants with HFrEF were lower than those previously reported in the older studies,3,4 However, more recent studies have reported similar results as ours.5 In the Efficacy of Vasopressin Antagonism in Heart Failure Outcome Study with Tolvaptan (EVEREST), 59% of the participants had AVP levels below the lower detection limit of the assay, and another 19% had levels within normal range.5 This difference might be related to (i) increased utilization of guideline directed medial therapy in recent studies12 and (ii) differences in assay sensitivity.13 Copeptin is the C-terminal peptide of the precursor protein to AVP and is secreted in equimolar amounts as AVP in the circulation.14 Mainly due to the short half-life of AVP, copeptin has been utilized as a surrogate marker of AVP activity in recent investigations.6,7 Data from these investigations suggest that higher copeptin levels are associated with an increased risk of adverse outcomes in both unselected HF5,7 and selected samples with HFpEF.15 Contrary to our findings (higher AVP in HFpEF compared with HFrEF), Loncar et al.16 reported that copeptin levels were significantly higher in HFrEF compared with HFpEF. However, their study enrolled participants with recent HF exacerbation, which might have led to a higher degree of
neurohormonal activation (and AVP levels) when compared with the participants with chronic HF enrolled in our study.

Arginine vasopressin excess and left ventricular mass

Prior studies in animal models have demonstrated that the activation of V1a receptors by AVP leads to structural changes in cardiac myocytes and fibroblasts leading to an increase in myocardial mass (LV hypertrophy).\(^{17,18}\) Tozawa et al.\(^{19}\) reported that in spontaneously hypertensive rats treated with an angiotensin convertase enzyme inhibitor (delapril), there was a positive direct association between LV mass and AVP levels. In a cross-sectional analysis of 706 middle-aged participants without cardiovascular comorbidities, Bhandari et al.\(^{20}\) reported a weak direct correlation of copeptin levels with indexed LV mass. In a prospective investigation of middle-aged participants, Strand et al.\(^{21}\) demonstrated that higher baseline AVP levels predicted the development of LV hypertrophy at 20 years of follow-up in 17 participants who were diagnosed with hypertension in interim. We hereby report a direct independent association between AVP levels and LV mass determined with cardiac MRI, independent of the presence or absence of HF and multiple potential confounders, including renal function and central systolic blood pressure. Taken together, available animal studies and human data support a role for AVP in the development of LV hypertrophy, an important cardiovascular phenotype involved in the pathogenesis of HF.\(^{22}\)

Arginine vasopressin, atrial natriuretic peptide, and left atrial volume

Despite the importance of AVP and its role in hyponatraemia in advanced HF, little is known about the non-osmotic triggers for its release in humans with and without HF. A role for baroreceptor desensitization has been proposed as a cause for dysregulated AVP release.\(^{23}\) However, human studies assessing the association between the ANP axis and AVP levels are scarce. Atrial natriuretic peptide, a member of the natriuretic peptide family, is released in response to atrial stretch and exerts a variety of biological effects such as natriuresis, vasodilation, and inhibition of renin–angiotensin–aldosterone pathway.\(^{24}\) Animal models have also established an inhibitory role for ANP on AVP release.\(^{25}\) Vascular and intracerebral administration of ANP inhibits the release of AVP,\(^{26}\) and ANP binding sites after systemic administration of ANP have been identified in the posterior pituitary.\(^{27}\) Interestingly, in our study, LA enlargement with paradoxically low ANP levels was associated with increased AVP levels. Although physiological considerations from animal models suggest that a deficient ANP axis may causally contribute to such excess, further studies are required to establish this mechanism in human HF and to determine whether strategies aimed at enhancing natriuretic peptide activity blunt AVP excess and its deleterious consequences. Our findings are consistent with the recently proposed paradigm that a deficiency of ANP and/or increased target organ resistance to ANP actions contribute to LV remodelling\(^{26}\) and HF.\(^{27}\)

Our study also demonstrates that increased AVP levels are associated with an increased risk of incident cardiovascular death or hospitalized HF. This association was highly significant and was independent of ANP levels, LV mass, and LV enlargement measured by cardiac MRI, supporting the clinical importance of AVP.

Our study should be interpreted in context of its strengths and limitations. We utilized cardiac MRI, which provides highly accurate measurements of chamber volumes and function. However, we acknowledge that our study has limitations. Our findings are observational in nature, and this cannot prove causal associations. Although most analyses were based on well-established quantitative traits, our sample size and the number of prospective events during follow-up was relatively small, and thus, only limited adjustments were possible to avoid overfitting of proportional hazards models; the low number of events also precluded stratified analyses by HF subtype. Residual confounding could still be present, and larger future studies should study this further. Lastly, we utilized convenience sampling of subjects referred for a cardiac MRI study at a Veteran Affairs Medical Center. Thus, the majority of the participants were male and may not be representative of AVP levels seen in unselected HF populations. We also applied various exclusion criteria. An important exclusion criterion was atrial fibrillation (because atrial fibrillation complicates measurements of LV mass by segmented cine MRI). Therefore, extrapolation of our findings to patients with advanced atrial disease and/or atrial arrhythmia cannot be made. We did not assess the potential role of the sympathetic nervous system, which is physiologically linked to AVP secretion and subject to inhibition by ANP. The interactions between AVP, ANP, and the sympathetic nervous system in HF (particularly HFPEF) should be the focus of future research. Our population exhibited relatively favourable outcomes, and our results may not extrapolate to patients with more advanced disease.

Conclusions

Increased plasma AVP is seen in subjects with HfPEF, even after adjustment for potential confounders. Arginine vasopressin levels are independently associated with a greater LA volume and also paradoxically, with lower ANP levels. These findings are consistent with the known inhibitory effect of

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AnP on AVP secretion. High plasma AVP was independently associated with LV mass measured by cardiac MRI. High AVP was predictive of an increased risk of cardiovascular death and HF admissions, independently of LV mass, LA volume, and ANP levels. Our findings demonstrate the clinical importance of AVP in HFpEF and suggest that a relative deficiency of ANP in the setting of increased LA pressure is associated with AVP excess. Further studies are required to establish whether this association is causal and to assess whether strategies aimed at potentiating the ANP axis may ameliorate AVP excess and its deleterious effects.

Conflict of interest

J.A.C. has received consulting honoraria from Bristol-Myers Squibb, OPKO Healthcare, Fukuda Denshi, Microsoft, Sanifit, Pfizer, Ironwood Pharmaceuticals, Vital Labs, and Merck. He received research grants from the National Institutes of Health, American College of Radiology Network, Fukuda Denshi, Bristol-Myers Squibb, Microsoft, and CVRx Inc. and device loans from AtCor Medical. J.A.C. is named as inventor in a University of Pennsylvania patent application for the use of inorganic nitrates/nitrates for the treatment of heart failure and preserved ejection fraction.

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