The Effect of Renal Function and Hemodialysis Treatment on Plasma Vasopressin and Copeptin Levels

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Introduction: Copeptin is increasingly used in epidemiological studies as a substitute for vasopressin. The effect of renal function per se on copeptin and vasopressin concentrations as well as their ratio have, however, not been well described.

Methods: Copeptin and vasopressin levels were measured in 127 patients with various stages of chronic kidney disease, including 42 hemodialysis patients and 16 healthy participants in this observational study. Linear (segmental) regression analyses were performed to assess the association between renal function and copeptin, vasopressin and the C/V ratio. In addition, clearance of copeptin and vasopressin by hemodialysis was calculated.

Results: Both copeptin and vasopressin levels were higher when renal function was lower, and both showed associations with plasma osmolality. The C/V ratio was stable across renal function in subjects with an eGFR > 28 ml/min per 1.73 m2. In contrast, the C/V ratio increased with worsening renal function in patients with eGFR ≤28 ml/min per 1.73 m2. During hemodialysis, the initial decrease in vasopressin levels was greater compared with copeptin and, consequently, the C/V ratio increased. This was, at least in part, explained by a greater dialytic clearance of vasopressin compared with copeptin.

Discussion: Our data indicate that copeptin is a reliable substitute for vasopressin in subjects with an eGFR > 28 ml/min per 1.73 m2, whereas at an eGFR ≤28 ml/min per 1.73 m2, that is, CKD stages 4 and 5, a correction for renal function is required in epidemiological studies that use copeptin as a marker for vasopressin. Intradialytic copeptin levels do not adequately reflect vasopressin levels because vasopressin clearance by hemodialysis is higher than that of copeptin.

KEYWORDS: chronic kidney disease; copeptin; hemodialysis; kidney function; vasopressin
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changes in fluid status and plasma osmolality.6,14,15
Given the recent interest in the effects of vasopressin
on kidney health, measurement of copeptin in epide-
miological studies gains popularity.16,17
Vasopressin as well as copeptin are small-sized
molecules (1 and 5 kDa, respectively).5,18 and both
are therefore theoretically subjected to renal clearance.
As yet, it is not clear whether renal function affects
both analytes to the same extent and therefore whether
copeptin can be used as marker for vasopressin in pa-
tients with impaired renal function. Several studies
found an inverse association between copeptin and
renal function.10,19–23 However, concurrent measure-
ment of vasopressin is pivotal to understand whether
increased copeptin levels accurately reflect vasopressin
levels in patients with chronic kidney disease (CKD).24
In case copeptin and vasopressin are cleared similarly,
the copeptin-to-vasopressin ratio (C/V ratio) is expected
to be stable across the full range of kidney function.
In hemodialysis patients, differential extracorporal
clearance could also result in divergent plasma copep-
tin and vasopressin levels, because copeptin is larger
than vasopressin and may therefore be cleared less by
the artificial kidney. However, copeptin removal by
hemodialysis has not yet been studied.
Because copeptin is used as a surrogate for vaso-
pressin in patients with decreased renal function while
it is unknown whether renal function affects copeptin
and vasopressin concentrations in a similar fashion, we
investigated in the present study the association of
copeptin and vasopressin in subjects over a broad
range of renal function as well as the kinetics of these
analytes during hemodialysis.

METHODS
Participants and Study Protocol
For this study, samples were used of subjects that
participated in 4 studies performed at the Nephrology
Department of the University Medical Center Gronin-
gen between March 1, 2010 and March 1, 2016.24 The
cohort was established from patients with either auto-
somal dominant polycystic kidney disease or IgA neph-
rophathy with normal and impaired renal function
from whom plasma vasopressin and copeptin levels
were available and in hemodialysis patients partici-
-pating in a study on vasopressin. In these studies,
blood samples were drawn according to a strict pro-
tocol to allow reliable measurement of plasma copeptin
and vasopressin levels after completion. Blood was
collected in chilled ethylenediamine tetraacetic acid
tubes, immediately centrifuged in a cooled centrifuge
at 4 °C, and the plasma supernatant was stored frozen
at −80 °C in plastic 2 ml aliquots until measurement
that took place within 1 year of storage. Samples were
available of healthy subjects (n = 15), CKD patients
with either autosomal dominant polycystic kidney
disease (n = 54) or IgA nephropathy (n = 16), and
hemodialysis patients (n = 42). All participants gave
written informed consent. The studies were performed
in accordance with the principles of the Declaration of
Helsinki and approved by the Medical Ethical Com-
mittee of the University Medical Center Groningen.

Outcome and Measurements
The primary outcome in the present study is the C/V ratio
across different stages of renal function and its associa-
tion with estimated glomerular filtration rate (eGFR).
Vasopressin was measured by radioimmunoassay (DRG
International Inc., Springfield, NJ) with a lower limit of
detection of 0.25 pmol/l and a functional assay sensi-
tivity of 0.5 pmol/l with 2.0 ml of plasma. The interassay
and intraassay coefficients of variation were both <7%
in the low and high concentration range (i.e., around 4
and 20 pmol/l, respectively). Copeptin was measured by
an automated sandwich immunofluorescent assay (CT-
proAVP; Thermo Fisher Scientific, B.R.A.H.M.S GmbH,
Hennigsdorf, Germany) with a lower limit of detection
of 0.9 pmol/l and a functional assay sensitivity of 2 pmol/l.
The interassay and intraassay coefficients of variation for
copeptin concentrations >15 pmol/l were <5% and 4%
respectively.
In healthy subjects and in patients with CKD, GFR was
estimated from plasma creatinine concentration,
age, and sex with the Chronic Kidney Disease Epide-
miology Collaboration equation that expresses GFR
indexed for 1.73 m2 body surface area.25 In hemodial-
ysis patients, residual renal function was assumed to be
present when diuresis was ≥200 ml/day and GFR was
estimated as 0.5 × (24-hour urea clearance + 24-hour
creatinine clearance) and similarly expressed per 1.73 m2
body surface area.26 A 24-hour urine sample
was used to estimate residual renal function, this urine
sample is collected every 4 months after the longest
interdialytic interval preceding the first dialysis session
of the week (i.e., Monday or Tuesday).
Plasma and urine creatinine was measured with the
Roche enzymatic creatinine assay. Plasma and urine
urea were measured with the colorimetric method on a
Roche Modular analyzer. Plasma sodium was measured
with the indirect method of ion-selective electrode
(Roche Modular, Mannheim, Germany) and plasma
osmolality was measured by freezing-point depression
(Osmo Station Osmometer, Kyoto, Japan).
In hemodialysis patients, blood samples for mea-
urement of plasma copeptin and vasopressin were
collected from the arterial line at the initiation of
hemodialysis and at 30 minutes on dialysis. Clearance of copeptin and vasopressin by hemodialysis was calculated as described previously\textsuperscript{27} using simultaneously collected efferent dialysate and predialyzer blood. A detailed description is provided as Supplementary Item S1. At the same time, copeptin and vasopressin were also measured in postdialyzer blood samples to evaluate the possible change in plasma concentration over the dialyzer.

Hemodialysis was conducted in a 3-times weekly 4-hour schedule with a low-flux polysulphone dialyzer (F8 or F10, Fresenius Medical Care, Bad Hamburg, Germany). The ultrafiltration volume was set to achieve dry weight at the completion of the hemodialysis session. Specifications of the dialysis treatment are provided as Supplementary Item S2. In a subgroup of 27 hemodialysis patients, blood samples were also collected during dialysis at 60, 120, 180, and 240 minutes (just before the end of the treatment) intradialysis. Intradialytic copeptin and vasopressin concentrations were corrected for hemoconcentration,\textsuperscript{28} as described in Supplementary Item S3.

**Statistical Analysis**

Normally distributed variables are presented as means ± SDs, and variables with a skewed distribution as medians and interquartile ranges (IQRs). Categorical data are given as numbers and percentages. For comparison of baseline characteristics, the participants were subdivided into 4 subgroups according to kidney function: group 1: eGFR ≥90 ml/min per 1.73 m\(^2\) (n = 16); group 2: eGFR between 45 and 89 ml/min per 1.73 m\(^2\) (n = 33); group 3: eGFR < 45 ml/min per 1.73 m\(^2\) not on hemodialysis (n = 36); group 4: eGFR <15 ml/min per 1.73 m\(^2\) on hemodialysis (n = 42). Differences among the 4 study groups were tested for statistical significance with a chi-square test, or 1-way analysis of variance or Kruskal-Wallis test with post hoc testing for multiple comparisons. Univariate and multivariate regression analyses were used to assess associations. Nonnormally distributed variables (i.e., copeptin, vasopressin, and osmolality) were log transformed to fulfill the requirements of normal distribution of the residuals for regression analysis. In the regression analyses, eGFR is used as a continuous variable to be able to perform break-point analyses. Segmented linear regression analysis was used to determine possible breakpoints in the association of renal function with the C/V ratio. Differences in copeptin, vasopressin, and the C/V ratio between hemodialysis patients with and without residual renal function were analyzed using the Wilcoxon signed rank test. This same test was used to analyze copeptin and vasopressin during hemodialysis, with Bonferroni correction for multiple testing, and to study differences in hemodialysis clearance characteristics of copeptin and vasopressin. Spearman correlation was used to assess correlations between copeptin, vasopressin, the C/V ratio, and dialysis vintage. Analyses were performed with SPSS version 22.0 and GraphPad Prism version 5.0 (GraphPad Software, San Diego, CA). P values of < 0.05 (2-tailed) were considered statistically significant.

**RESULTS**

**Participant Characteristics**

Table 1 shows the characteristics of the entire study group and the subgroups stratified according to renal function. Age, plasma osmolality, blood pressure, use of antihypertensive medication, and plasma vasopressin and copeptin levels were progressively higher in subgroups with lower renal function (Table 1).

**Copeptin and Vasopressin**

Average plasma copeptin and vasopressin concentration in the overall group of participants was 25.9 pmol/l and 2.2 pmol/l, respectively. As shown in Table 1, plasma copeptin and vasopressin levels were significantly higher in subjects with an eGFR <45 compared with subjects with eGFR ≥90 ml/min per 1.73 m\(^2\) (P < 0.05) and in patients on dialysis compared with participants not on dialysis (P < 0.001). The C/V ratio in patients on dialysis was significantly higher than for the other 3 groups (P < 0.001), whereas no significant differences were observed among the 3 nondialysis subgroups.

Overall, a strong association was found between copeptin and vasopressin (\(\beta = 0.77; P < 0.001\)). The association between copeptin and vasopressin differed between nondialysis and dialysis patients. “Dialysis treatment” was, therefore, added to the linear regression model, which had indeed a significant effect (\(\beta = 0.58; P < 0.001\)). Therefore, the hemodialysis patient group was analyzed separately. Copeptin and vasopressin remained strongly associated in the nondialysis subjects, including healthy individuals and CKD patients (\(n = 85, \beta = 0.75; P < 0.001\)), as well as in the hemodialysis patients (\(n = 42, \beta = 0.84; P < 0.001\)) (Figure 1).

**Effect of Renal Function on Copeptin and Vasopressin and Their Ratio in Nondialysis Subjects**

In nondialysis subjects, a significant inverse association between renal function and copeptin was found (Table 2 and Figure 2a). Associations were also observed between renal function and plasma osmolality (\(\beta = -0.78; P < 0.001\)), and between plasma osmolality...
and copeptin (β = 0.70; P < 0.001) (Figure 3a). To investigate the association of copeptin with renal function per se, this association was therefore stepwise adjusted for plasma osmolality and for other potential confounders (age, sex, and blood pressure). The final multivariate model shows that, after adjustment for these covariates, the association between copeptin and eGFR remained significant (Table 2). Besides eGFR and plasma osmolality, sex also contributed significantly to copeptin concentration (with women having significantly lower values), whereas age and blood pressure did not.

In univariate analysis, vasopressin was also significantly inversely associated with renal function (Figure 2b) and also an association between plasma osmolality and vasopressin was found (β = 0.45; P < 0.001) (Figure 3b). In contrast to copeptin, the association between vasopressin and renal function was attenuated after adjustment for plasma osmolality, and additional adjustment for age, sex, and blood pressure (Table 3).

As sensitivity analyses, we also added etiology (i.e., autosomal dominant polycystic kidney disease or IgA nephropathy) to the univariate analyses, but did not find an effect of etiology on the association between eGFR and copeptin (β = −0.06; P = 0.41) or on the association between eGFR and vasopressin (β = −0.12; P = 0.24). We also added diuretic use separately to the multivariate analyses because diuretic use might affect vasopressin and copeptin levels independent of an

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**Table 1. Characteristics of the overall group of participants and for participants stratified according to renal function**

<table>
<thead>
<tr>
<th>eGFR (ml/min per 1.73 m²)</th>
<th>≥90 (n = 16)</th>
<th>45-89 (n = 33)</th>
<th>&lt;45 non-HD (n = 36)</th>
<th>HD (n = 42)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>28 ± 10</td>
<td>47 ± 10</td>
<td>51 ± 8</td>
<td>63 ± 18</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Males</td>
<td>8 (50)</td>
<td>17 (52)</td>
<td>19 (53)</td>
<td>30 (71)</td>
<td>0.21</td>
</tr>
<tr>
<td>eGFR (ml/min per 1.73 m²)</td>
<td>103 ± 9</td>
<td>64 ± 15</td>
<td>25 ± 9</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Plasma osmolality (mOsm/kg)</td>
<td>—</td>
<td>—</td>
<td>0.4 (0.0-2.2)</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Plasma vasopressin (pmol/l)</td>
<td>0.7 (0.3-1.5)</td>
<td>1.2 (0.8-2.6)</td>
<td>2.0 (1.2-3.2)</td>
<td>5.0 (3.3-6.8)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Plasma copeptin (pmol/l)</td>
<td>6.1 (2.7-8.3)</td>
<td>9.0 (6.6-18.2)</td>
<td>25.8 (9.4-36.7)</td>
<td>170.0 (102.6-280.5)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Copeptin-vasopressin ratio</td>
<td>5.3 (3.5-8.2)</td>
<td>7.1 (5.1-10.2)</td>
<td>11.4 (6.7-17.5)</td>
<td>42.6 (31.3-57.4)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Volume 24-hour urine (ml)</td>
<td>2195 ± 936</td>
<td>2166 ± 705</td>
<td>2489 ± 942</td>
<td>336 ± 423</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SBP (mm Hg)</td>
<td>128 ± 10</td>
<td>130 ± 14</td>
<td>132 ± 12</td>
<td>143 ± 25</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>DBP (mm Hg)</td>
<td>78 ± 9</td>
<td>84 ± 19</td>
<td>82 ± 9</td>
<td>72 ± 13</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

**Medication**

<table>
<thead>
<tr>
<th>ACEI or ARB</th>
<th>Beta-blocker</th>
<th>CCB</th>
<th>Diuretic</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (25)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>19 (58)</td>
<td>3 (9)</td>
<td>3 (9)</td>
<td>2 (6)</td>
</tr>
<tr>
<td>33 (92)</td>
<td>11 (31)</td>
<td>12 (33)</td>
<td>12 (33)</td>
</tr>
<tr>
<td>8 (19)</td>
<td>29 (69)</td>
<td>13 (31)</td>
<td>10 (24)</td>
</tr>
<tr>
<td>P value</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

ACEI, angiotensin-converting enzyme inhibitor; ARB, angiotensin receptor blocker; CCB, calcium channel blocker; DBP, diastolic blood pressure; eGFR, estimated glomerular filtration rate; HD, hemodialysis; NA, not applicable; RRF, residual renal function; SBP, systolic blood pressure.

Variables are presented as mean ± SD, n (%), or median and interquartile range.

*Analysis of variance with post hoc Bonferroni: age differed among all 4 groups (P < 0.01) except between patients with an eGFR < 45 and 45 to 89 ml/min per 1.73 m². Volume of 24-hour urine was lower in HD patients compared with the other 3 groups (P < 0.001). SBP was higher in HD patients compared with the 3 other groups (P < 0.05). DBP was lower in HD patients compared with patients with an eGFR between < 45 and 45 to 89 (P < 0.05).

*Kruskal-Wallis with post hoc test for multiple comparisons: osmolality differed among all 4 groups (P < 0.001), except for participants with an eGFR between 45 to 89 and ≥ 90 and between patients with an eGFR < 45 and on HD. Vasopressin and copeptin levels were higher in HD patients compared with the 3 other groups (P < 0.01) and in the group with an eGFR < 45 compared with ≥ 90 (P < 0.05). The copeptin-vasopressin ratio was higher in HD patients compared with the 3 other groups (P < 0.001).
effect on blood pressure and found that it was not significantly associated with copeptin ($\beta = -0.15; P = 0.07$) or vasopressin ($\beta = -0.16; P = 0.13$).

The C/V ratio was inversely associated with renal function ($\beta = -0.36; P = 0.001$), indicating that copeptin levels rose to a greater extent compared with vasopressin levels when renal function declined. Breakpoint analysis of the association between eGFR and the C/V ratio in nondialysis subjects indicated a change in slope at an eGFR of 28 ml/min per 1.73 m$^2$ (Figure 4). Therefore, the association between renal function and C/V ratio was analyzed separately for subjects with an eGFR above and below this threshold. In subjects with an eGFR above 28 ml/min per 1.73 m$^2$ ($n = 60$), the association between eGFR and C/V ratio was not significant ($\beta = -0.10; P = 0.46$). In contrast, in subjects with an eGFR below 28 ml/min per 1.73 m$^2$ and not on dialysis ($n = 25$), eGFR was inversely associated with the C/V ratio ($\beta = -0.46; P = 0.024$). To investigate the separate associations between renal function and copeptin and vasopressin in patients with an eGFR $>28$ and $\leq 28$ ml/min per 1.73 m$^2$, similar multivariate analyses as performed for the overall group, were also performed for the 2 subgroups identified by breakpoint analysis (Supplementary Tables S1 and S2). Remarkably, no associations were found between vasopressin and renal function or vasopressin and plasma osmolality in patients with an eGFR $\leq 28$ ml/min per 1.73 m$^2$ ($\beta = 0.14; P = 0.52$, and $\beta = 0.14; P = 0.50$, respectively). In contrast, in subjects with an eGFR $>28$ ml/min per 1.73 m$^2$ renal function and plasma osmolality were significantly associated with vasopressin ($\beta = -0.46; P < 0.001$, and $\beta = 0.54; P < 0.001$, respectively) and also with

### Table 2. Associations between plasma copeptin and eGFR in healthy participants and CKD patients not on dialysis

<table>
<thead>
<tr>
<th></th>
<th>Univariate</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$\beta$</td>
<td>$P$</td>
<td>$\beta$</td>
<td>$P$</td>
</tr>
<tr>
<td>eGFR (ml/min per 1.73 m$^2$)</td>
<td>$-0.67$</td>
<td>$&lt;0.001$</td>
<td>$-0.32$</td>
<td>$0.01$</td>
</tr>
<tr>
<td>Plasma osmolality (mOsm/kg)</td>
<td>$0.70$</td>
<td>$&lt;0.001$</td>
<td>$0.45$</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>$0.48$</td>
<td>$&lt;0.001$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sex $^a$</td>
<td>$-0.32$</td>
<td>$&lt;0.01$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBP (mm Hg)</td>
<td>$0.13$</td>
<td>$0.24$</td>
<td></td>
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</tbody>
</table>

CKD, chronic kidney disease; eGFR, estimated glomerular filtration rate; SBP, systolic blood pressure.

Model 1: adjustment for plasma osmolality. Model 2: as model 1 + adjustment for age and sex. Model 3: as model 2 + adjustment for systolic blood pressure.

$^a$Men are considered the reference group.

Figure 2. Associations of renal function with (a) copeptin and (b) vasopressin. Gray symbols indicate healthy participants and chronic kidney disease patients not on dialysis. Black symbols indicate hemodialysis (HD) patients. eGFR, estimated glomerular filtration rate.
copeptin ($\beta = -0.57; P < 0.001$, and $\beta = 0.57; P < 0.001$, respectively). In subjects with an eGFR $\leq 28$ ml/min per 1.73 m$^2$, copeptin, in contrast to vasopressin, was associated with renal function and plasma osmolality ($\beta = -0.56; P = 0.004$, and $\beta = 0.60; P < 0.001$, respectively).

**Hemodialysis Patients**

The mean total ultrafiltration volume was $2.65 \pm 0.67$ L. Twenty of the 42 hemodialysis dialysis patients (48%) had residual renal function. There was no difference in age, sex, plasma osmolality, or systolic blood pressure between patients with and without residual renal function, but patients without residual renal function had a significantly longer dialysis vintage compared with those with residual renal function (Table 4). Patients with residual renal function had significantly lower copeptin and vasopressin levels compared with patients without residual renal function, but the pretreatment C/V ratio did not differ between both groups (Table 4). Of note, there was no significant association between dialysis vintage and plasma copeptin ($\beta = 0.13; P = 0.40$), plasma vasopressin ($\beta = 0.07; P = 0.66$) or the C/V ratio ($\beta = 0.07; P = 0.66$). There was also no correlation between the total ultrafiltration volume and the C/V ratio ($r = -0.14, P = 0.38$).

**Effect of Hemodialysis on Copeptin, Vasopressin, and the C/V Ratio**

During hemodialysis, copeptin decreased slightly from $211.0$ pmol/l (IQR, 102.4–304.3) to $209.1$ pmol/l (IQR, 113.0–312.4) during the first half of the dialysis session ($P < 0.01$) and increased again during the second half to $247.3$ pmol/l (IQR, 87.2–312.0), that was not

![Figure 3. Associations of plasma osmolality with (a) copeptin and (b) vasopressin. Gray symbols indicate healthy participants and chronic kidney disease patients not on dialysis. Black symbols indicate hemodialysis (HD) patients. eGFR, estimated glomerular filtration rate.](image)

**Table 3.** Associations between plasma vasopressin and eGFR in healthy participants and CKD patients not on dialysis

<table>
<thead>
<tr>
<th></th>
<th>Univariate</th>
<th>Multivariate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\beta$</td>
<td>$P$ value</td>
</tr>
<tr>
<td>eGFR (ml/min per 1.73 m$^2$)</td>
<td>$-0.45$</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>Plasma osmolality (mOsm/kg)</td>
<td>$0.45$</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>$0.27$</td>
<td>$0.01$</td>
</tr>
<tr>
<td>Sex$^*$</td>
<td>$-0.16$</td>
<td>$0.14$</td>
</tr>
<tr>
<td>SBP (mm Hg)</td>
<td>$0.24$</td>
<td>$0.03$</td>
</tr>
</tbody>
</table>

CKD, chronic kidney disease; eGFR, estimated glomerular filtration rate; SBP, systolic blood pressure.

Model 1: adjustment for plasma osmolality. Model 2: as model 1 + adjustment for age and sex. Model 3: as model 2 + adjustment for systolic blood pressure.

$^*$Men are considered the reference group.
significantly different compared with predialysis ($P = 0.53$). Vasopressin followed a similar but more outspoken pattern, with a decrease during the first hours on dialysis (from 4.9 pmol/l [IQR, 2.5–7.3] to 2.5 pmol/l [IQR, 1.6–3.7], $P < 0.01$), also followed by an increase to reach a value of 3.1 pmol/l [IQR, 1.1–5.6], that was significantly different when compared with predialysis ($P = 0.04$). Consequently, the C/V ratio increased significantly during the first two hours on hemodialysis and remained higher during the remainder of the dialysis session.

Plasma vasopressin levels decreased significantly while passing through the dialyzer from 3.9 pmol/l [IQR, 2.0–5.3] predialyzer to 3.2 pmol/l [IQR, 1.9–4.3] postdialyzer ($P < 0.01$), whereas copeptin levels increased significantly from 171.7 pmol/l [IQR, 112.5–296.4] predialyzer to 176.6 pmol/l [IQR, 121.7–352.8] postdialyzer ($P < 0.01$), presumably as a result of ultrafiltration-induced hemoconcentration. Dialysate concentrations of vasopressin and copeptin were 0.44 pmol/l [IQR, 0.33–0.59; $n = 42$] and 1.03 pmol/l [IQR, 0.89–1.31; $n = 23$], respectively. The clearance of vasopressin was significantly higher than that of copeptin ($P < 0.001$).

**Figure 4.** Association of renal function with copeptin-vasopressin ratio in healthy participants and in chronic kidney disease patients not on dialysis. The dotted line indicates the break-point at an estimated glomerular filtration rate (eGFR) of 28 ml/min per 1.73 m$^2$. CI, confidence interval.

| Table 4. Characteristics of hemodialysis patients with and without residual renal function |
|-----------------|-----------------|-----------------|-----------------|
|                 | HD patients     | HD patients     | $P$ value       |
|                 | with RRF ($n = 20$) | without RRF ($n = 22$) |               |
| Age (yr)        | 67 ± 18         | 60 ± 18         | 0.22            |
| Male            | 17 (85)         | 13 (59)         | 0.09            |
| Dialysis vintage (mo) | 17.5 (8.3–27.5) | 37.5 (21.3–65.5) | 0.003           |
| Plasma vasopressin (pmol/l) | 4.2 (1.5–6.1) | 6.0 (4.6–8.2) | <0.01          |
| Plasma copeptin (pmol/l) | 115.9 (65.1–215.7) | 221.7 (148.6–313.8) | 0.01           |
| Copeptin-vasopressin ratio | 47.7 (30.1–59.3) | 40.4 (31.5–57.4) | 0.99           |
| Plasma osmolality (mOsm/kg) | 305 (295–307) | 307 (299–315) | 0.20            |
| SBP (mm Hg)     | 145 ± 25        | 142 ± 27        | 0.64            |

HD, hemodialysis; RRF, residual renal function; SBP, systolic blood pressure. Variables are presented as mean ± SD, n (%), or median and (interquartile range).

**DISCUSSION**

In this study we investigated the effect of renal function and hemodialysis on the association between copeptin and vasopressin levels. We showed that copeptin and vasopressin were strongly associated in the overall cohort of participants, including predialysis subjects. With declining renal function, the C/V ratio remained constant until an eGFR of 28 ml/min per 1.73 m$^2$, after which this ratio progressively

$\quad n = 22$, respectively. The clearance of vasopressin was significantly higher than that of copeptin ($P < 0.001$).

**Figure 5.** Copeptin and vasopressin concentrations in blood leaving the dialyzer and in the dialysate compared to the predialyzer concentration (median and interquartile range).
In hemodialysis patients, the C/V ratio was higher than for nondialysis patients and healthy individuals, with no difference between subjects with and without residual renal function. The C/V ratio rose during a hemodialysis session, because vasopressin was cleared by dialysis to a greater extent than copeptin.

One of the 2 aims of the present study was to assess whether the C/V ratio remained stable throughout the full range of renal function to delineate whether copeptin can be used as a substitute for vasopressin in patients with impaired renal function. The ratio between copeptin and vasopressin was investigated once before in 83 CKD patients with an eGFR ranging from 7 to 61 ml/min per 1.73 m² by Roussel et al. In that study, it was observed that both copeptin and vasopressin levels were higher in patients with a lower eGFR. The C/V ratio increased across quintiles of decreasing renal function and the investigators suggested a greater decrease in renal clearance rate of copeptin compared with vasopressin when renal function declines. In our study we investigated the association between renal function and C/V ratio more closely using break-point analysis. We add that an association between renal function and C/V ratio is only found when renal function is severely impaired (i.e., eGFR ≤28 ml/min per 1.73 m²). Furthermore, we also studied copeptin and vasopressin and their ratio in hemodialysis patients pretreatment and during hemodialysis. Another difference with our study is that samples were stored frozen during prolonged periods of time (up to 20 years vs. maximally 1 year in our study), which may have affected the concentrations of copeptin and especially vasopressin, as acknowledged by Roussel et al.

Copeptin and vasopressin are assumed to be produced in equimolar amounts. Therefore, we expect copeptin and vasopressin and their ratio to behave similarly to changes in volume status. Still, in subjects with completely normal renal function, that is, an eGFR >90 ml/min per 1.73 m², plasma concentration of copeptin is more than 5-fold higher than that of plasma vasopressin. This may, at least in part, be caused by a difference in apparent distribution volume. Vasopressin binds to the V1 and V2 receptors, and bound vasopressin will be sequestered from plasma. In addition, vasopressin binds to platelets that are removed by centrifugation during the preanalytic handling of samples for vasopressin measurement. In contrast, copeptin is presumably not bound to platelets and, to our knowledge, no copeptin receptor is known. Another explanation for lower vasopressin concentration may be that the half-life of vasopressin is shorter than that of copeptin. These 3 mechanisms may explain why even in healthy subjects with normal renal function, the C/V ratio is >1.

When renal function declines, both copeptin and vasopressin increased. This does not necessarily imply that these analytes are subject to renal clearance. It is shown that patients with lower renal function have impaired urine concentrating capacity. Such subjects tend to have higher plasma osmolality and, consequently, will also have higher vasopressin (and copeptin) concentration. Indeed we found significant associations between eGFR and plasma osmolality, and between plasma osmolality and copeptin and vasopressin. In a previous study we found no association between copeptin and renal function in 134 healthy kidney donors predonation and postdonation. Copeptin levels remained unchanged after kidney donation, despite a decrease in iothalamate-measured GFR of ~40% (from 105 to 66 ml/min per 1.73 m²). These data suggest that not renal clearance per se but renal disease-induced kidney damage modulates vasopressin and copeptin levels.

Importantly, when eGFR decreases progressively below 28 ml/min per 1.73 m², copeptin levels increased to a greater extent than vasopressin levels, and consequently the C/V ratio increased. On one hand, this could be explained by a decreased clearance of copeptin compared with vasopressin. The more marked copeptin increase in severe renal insufficiency indeed suggests a renal component in the total body clearance of copeptin. Partial renal clearance of copeptin has been suggested before, as copeptin has been found in urine. Renal clearance, however, will presumably not be the predominant factor in the degradation of copeptin because a fast decrease in copeptin levels has been observed within minutes after the start of water loading that is more rapid than one would expect from renal clearance alone. On the other hand, no associations between renal function and vasopressin and between plasma osmolality and vasopressin were observed in patients with an eGFR ≤28 ml/min per 1.73 m². The relatively low vasopressin levels in this group may, therefore, be attributable to increased extrarenal clearance of vasopressin. This could also result in an increase of the C/V ratio in severely impaired renal function. Vasopressin metabolism has been studied more extensively, and it has been found that indeed only 5% to 27% of the total body clearance is accounted for by the kidneys. Hepatic vasopressinases and endopeptidases and aminopeptidases seem to play a more important role in vasopressin clearance. One might also speculate that accumulation of uremic toxins in severe renal failure may lead to differences in copeptin and vasopressin distribution and metabolism. A study on the kinetics of...
copeptin and vasopressin (i.e., exact route of elimination, total body clearance and renal clearance, volume of distribution) and potential physiological effects of copeptin could clarify this. We want to emphasize that investigating the exact metabolic fate of copeptin and vasopressin is beyond the scope of the present clinical study, as this will necessitate a specific experimental design.

The second aim of the present study was to investigate the kinetics of copeptin and vasopressin during hemodialysis. The highest C/V ratio was found in hemodialysis patients. During hemodialysis, the ratio increased further, indicating that vasopressin was removed to a greater extent than was copeptin. The higher dialyzer clearance rate of vasopressin in comparison to copeptin is in line with these findings. Due to the lower clearance rate of copeptin, accumulation may occur in the interdialytic interval, provided that the half-life of copeptin that is associated with extra-renal clearance mechanisms is long enough. This could, at least in part, explain the greater increase of copeptin relative to vasopressin levels in hemodialysis patients.

This study has 2 limitations that need to be acknowledged. First, copeptin and vasopressin were measured in samples taken from different studies. However, in these studies samples were collected according to the same strict protocol to ensure optimal preanalytic sample handling, and copeptin and vasopressin measurements were performed using the same assays. Inclusion of patients from different studies explains that the number of participants differed somewhat between the study groups, that is, healthy individuals, IgA nephropathy, autosomal dominant polycystic kidney disease, and hemodialysis patients. Second, hematocrit levels in the postdialyzer bloodline was not measured. Therefore, we could not correct the postdialyzer copeptin and vasopressin levels for hemoconcentration over the dialyzer, but this does not affect the measurement of copeptin and vasopressin clearance by hemodialysis, which was the primary aim of this part of our study. Strengths of this study are that we investigated the associations among renal function, copeptin, vasopressin and their ratio in detail, and that this study is the first to investigate kinetics of copeptin in relation to vasopressin during dialysis.

In conclusion, the C/V ratio was stable across the range of renal function in patients with an eGFR above 28 ml/min per 1.73 m². Thus, elevated copeptin levels observed in this eGFR range seem to accurately reflect vasopressin concentration. Consequently, copeptin seems a suitable marker for vasopressin in healthy subjects and patients with CKD stages 1 to 3. However, in studies that include patients with CKD stages 4 and 5, it is necessary to adjust for eGFR when studying copeptin as a marker for vasopressin. This is important for future studies in which copeptin is used as a surrogate marker for vasopressin in patients with CKD. We found no effect of etiology of renal disease on the association between eGFR and copeptin and vasopressin, which implies that our results might be generalizable for patients with CKD. In hemodialysis patients, predialysis copeptin and vasopressin showed a tight correlation. Copeptin may therefore be used as surrogate for vasopressin when assessed in blood samples drawn before dialysis. During a dialysis session, however, copeptin and vasopressin show a different kinetic profile, implying that copeptin does not adequately reflect vasopressin levels during dialysis.

DISCLOSURE
All the authors declared no competing interests. For this research no specific grants were obtained from funding agencies in the public, commercial, or not-for-profit sector.

SUPPLEMENTARY MATERIAL
Item S1. Calculation of clearance.
Item S2. Specifications of the hemodialysis treatments.
Item S3. Hemoconcentration.
Item S4. STROBE statement.
Table S1. Associations between plasma copeptin and estimated glomerular filtration rate (eGFR) in healthy participants and chronic kidney disease patients not on dialysis, stratified for eGFR above or below 28 ml/min per 1.73 m².
Table S2. Associations between plasma vasopressin and estimated glomerular filtration rate (eGFR) in healthy participants and chronic kidney disease patients not on dialysis, stratified for eGFR above or below 28 ml/min per 1.73 m².
Supplementary material is linked to the online version of the paper at www.kireports.org.

REFERENCES


