Endothelial Dysfunction and Damage in Congestive Heart Failure
Relation of Flow-Mediated Dilation to Circulating Endothelial Cells, Plasma Indexes of Endothelial Damage, and Brain Natriuretic Peptide

Aun Yeong Chong, MRCP; Andrew D. Blann, PhD; Jeetesh Patel, PhD; Bethan Freestone, MRCP; Elizabeth Hughes, MD; Gregory Y.H. Lip, MD

Background—Congestive heart failure (CHF) is associated with endothelial perturbation (as defined by flow-mediated endothelial-dependent vasodilation [FMD, an index of endothelial dysfunction], circulating endothelial cells [CECs, an index of endothelial damage], or plasma indexes of endothelial damage/dysfunction [eg, von Willebrand factor (vWf) and soluble thrombomodulin (sTM)]) and raised plasma levels of brain natriuretic peptide (BNP, a peptide hormone associated with left ventricular systolic dysfunction and prognosis). However, the relations between these parameters are unclear.

Methods and Results—To test the hypothesis that there is a relation between endothelial perturbation (defined by FMD, CECs, vWf, and sTM) and BNP in CHF, we studied these indexes in 30 patients with CHF who were compared with 20 age-matched control subjects. FMD, CECs, plasma vWf, and BNP levels (but not sTM) were all abnormal in patients with CHF. There were significant inverse correlations between FMD and vWf ($P<0.001$), CECs ($P<0.002$) and BNP ($P<0.006$) as well as a positive correlation between CECs and vWf ($P=0.032$). In multivariate analysis, BNP ($P<0.001$) and FMD ($P<0.001$) were both independently associated with CHF.

Conclusions—Ample evidence of endothelial cell damage/dysfunction in CHF cannot be fully explained by the variance in plasma BNP per se. Therefore, the routes by which these indexes influence the pathophysiology of CHF as well as predict adverse outcomes may be independent. (Circulation. 2004;110:1794-1798.)

Key Words: heart failure ■ endothelium ■ von Willebrand factor ■ endothelium-derived factors ■ natriuretic peptides
TABLE 1. Baseline Characteristics of Study Population

<table>
<thead>
<tr>
<th>Variable</th>
<th>Chronic CHF (n=30)</th>
<th>Control Subjects (n=20)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>65±12</td>
<td>64±9</td>
<td>0.640</td>
</tr>
<tr>
<td>Sex, M:F, n</td>
<td>19:11</td>
<td>6:14</td>
<td>0.021</td>
</tr>
<tr>
<td>LVEF, %*</td>
<td>31 (29–35)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>NYHA class, n</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>I–II</td>
<td>19</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>III–IV</td>
<td>11</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Comorbidity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IHD</td>
<td>23 (76.7)</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>HT</td>
<td>12 (40.0)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DM</td>
<td>12 (40.0)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cholesterol, mmol/L</td>
<td>4.4±1.3</td>
<td>5.9±0.9</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Current smoking</td>
<td>5 (16.7)</td>
<td>1 (5)</td>
<td>0.214</td>
</tr>
<tr>
<td>Treatment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACEI/ARB</td>
<td>29 (96.7)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Spironolactone</td>
<td>6 (20.0)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>β-Blocker</td>
<td>12 (40.0)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Antiplatelet</td>
<td>24 (80.0)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Warfarin</td>
<td>1 (3.3)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Statin</td>
<td>18 (60.0)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nitrate</td>
<td>13 (43.3)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Data expressed as mean±1 SD, median (IQR) or n (%) unless stated; ... not estimated. NYHA indicates New York Heart Association classification (I, asymptomatic; II, symptoms at rest or minimal exertion; III, moderate to severe symptoms. Patients were compared with 20 age-matched, healthy control subjects. Clinical characteristics of patients and healthy control subjects are summarized in Table 1. Exclusion criteria were concomitant atrial fibrillation, acute coronary syndromes, infection or pyrexial illness, recent (<3 months) myocardial infarction or stroke, chronic and systemic illnesses (including renal failure, hepatic impairment, cancer, inflammatory connective tissue disease, inflammatory bowel disease, chronic obstructive airways disease), history of thromboembolism and the use of nonsteroidal antiinflammatory drugs (NSAIDs, except aspirin which was considered unethical to withdraw), oral steroids, and hormone replacement therapy. Heart failure primarily caused by valvular disease or pulmonary disease was also excluded. Healthy control subjects were recruited from among healthy hospital staff, spouses of patients, and subjects attending hospital for hernia repairs, varicose vein procedures, or other relatively minor operations. All healthy control subjects had no clinical evidence of vascular, metabolic, neoplastic, diabetic, or inflammatory disease on careful history, examination, and routine laboratory tests. The West Birmingham Research Ethics Committee approved the study protocol, and all patients gave written informed consent to the study.

FMD and Echocardiography

High-resolution ultrasound was used to assess changes in the diameter of the brachial artery, as previously described.13,14 Measurements were taken after the patient had rested in a supine position for 20 minutes in a quiet room. High-quality images were obtained by a single dedicated operator using a 10-MHz vascular ultrasound probe (GE Vingmed Ultrasound, System V). A longitudinal section of the brachial artery was scanned 5 to 10 cm above the antecubital fossa. The transducer remained in a fixed position relative to the patient’s arm throughout the procedure. Vessel diameter was assessed at end-diastole, demarcated by the onset of the R wave on the ECG trace, with 5 measurements over a short segment of the artery from leading edge to leading edge and averaged. After a baseline scan, a pneumatic cuff was placed at the level of the mid forearm and inflated to 250 to 300 mm Hg for 4.5 minutes. The second scan was performed 60 to 90 seconds after cuff release (peak changes during reactive hyperemia), and 15 minutes was allowed for vessel recovery. Subsequent scans of the brachial artery were done before and again at 4.5 minutes after the administration of sublingual glyceryl trinitrate (GTN; 400 μg spray) to assess endothelium-independent vasodilation. The repeat baseline scan is to take into account the possibility of a change in the resting tone so that the final change in vessel diameter is purely due to the effect of GTN.13 Scans were recorded on optical discs for later analysis by an independent investigator blinded to patient group. Interobserver and intraobserver variation was <10%. FMD and GTN-induced (endothelium-independent) dilation were estimated percent change in diameter relative to their respective baseline measurements.

Laboratory

Citrated and EDTA plasma was obtained from venous blood by centrifugation at 3000 rpm (1000g) for 20 minutes at 4°C. Aliquots of plasma were then stored at −70°C to allow batch analysis. vWF was measured by an established ELISA (Dako). ST2 was measured with commercially available ELISA kits (Diagnostica Stago). BNP was measured with a fully automated, 2-site sandwich immunoassay by direct chemiluminescent on EDTA plasma, using the ADVIA Centaur analyser (Bayer Diagnostics Ltd). The intra-assay coefficient of assays was <5%; interassay variation was <10%.

Four milliliters of blood for CECs was collected in a sodium fluoride tube and prepared for immunomagnetic separation within 1 hour and counted by a single observer under epifluorescence microscopy (Zeiss). Blood collection for CECs was collected last (after approximately 20 mL blood was collected for other analyses) to avoid the possibility of collecting endothelial cells dislodged as a consequence of venepuncture. The detailed methodology for capturing CECs and criteria for counting CECs in our unit has been previously described.9 Intra-assay (n=40) and interassay (n=20) coefficients of variation were <5% and <10%, respectively; the interobserver and intraobserver variations of the method in our laboratory were <5%.9 All laboratory work was performed in blinded fashion with regard to the identity of the samples.

Power Calculations

We have previously reported increased CECs in the plasma of 26 subjects with acute myocardial infarction and 33 with unstable angina compared with 13 with stable angina and 14 healthy control

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subjects with an overall $F$ statistic of 16, giving a probability value of $<0.001$. We have also demonstrated a 3-fold increase in CECs in 20 patients with critical limb ischemia compared with 20 with intermittent claudication and 20 healthy control subjects ($P<0.001$). Consequently, we hypothesized similar levels and distribution in chronic CHF versus control subjects. Thus, with two groups, our power calculation required 20 subjects with CHF to have 3-fold higher CECs than the control group, generating a value of $P<0.01$. This target number of subjects ($n=40$) provides the power to detect a correlation coefficient of 0.3 at $P<0.05$ and $\beta=0.80$. However, for additional confidence, we recruited 30 consecutive patients with CHF.

### Statistical Analysis

Data were analyzed by the Shapiro-Wilk test to determine distribution. Normally distributed data are expressed as mean±SD. Data for LVEF, FMD, BNP, EID, sTM, and CECs were not normally distributed and therefore are expressed as median (interquartile range, IQR). Baseline cross-sectional data between chronic CHF and healthy control subjects were analyzed by $t$ test or Mann-Whitney test as appropriate. Correlations were performed by using Spearman’s rank correlation method. A 2-tailed probability value of $<0.05$ was considered statistically significant. Stepwise multiple regression analyses were used to determine the following: (1) which of vWF, sTM, CECs, and BNP were independently associated with FMD; and (2) which of these indexes were most closely associated with CHF.

### Results

Results are presented in Table 2. In patients with CHF, there were (3-fold) higher levels of CECs ($P<0.0001$) but no difference in sTM compared with control subjects. As expected, there was raised BNP (approximately 5-fold, $P<0.0001$), poorer FMD (approximately 6-fold, $P<0.0001$), and raised vWF (approximately 1 SD, $P=0.005$). There was no significant difference in equivalent endothelium-independent (GTN-mediated) vasodilation. In the entire cohort of 50 subjects, there were modest inverse correlations between FMD and vWF (Spearman, $r=-0.461$, $P=0.001$), CECs (Spearman, $r=-0.423$, $P=0.002$) and BNP (Spearman, $r=-0.419$, $P=0.006$), as well as an expected (but weak) positive correlation between CECs and vWF (Spearman, $r=0.29$, $P=0.032$) (Figures 1 through 3). Within the CHF group alone, only the correlation between FMD and vWF was significant (Spearman, $r=-0.457$, $P=0.011$). Acknowledging the likely confounder of diabetes, we performed analyses for this risk factor. FMD was significantly lower in the 12 patients with CHF with diabetes (mean±SD, −0.1±3.1%) compared with the 18 CHF patients free of diabetes (3.2±3.4, $P=0.01$). Even excluding the diabetic subgroup, FMD was significantly lower in patients with CHF without diabetes compared with control subjects ($P<0.0001$).

### Multivariate Analysis

To determine those factors associated with FMD (as that index most abnormal in CHF compared with health), we entered indexes significantly different in univariate analysis (ie, vWF, CECs, BNP) into multivariate stepwise logistic and regression analyses. Here, vWF ($P=0.320$) and BNP ($P=0.074$) dropped out, leaving CECs ($P=0.021$) as the only significant independent predictor of FMD. Together, these 3 variables accounted for

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**Table 2.** FMD, vWF, STM, and CECs in Subjects With CHF and Control Subjects

<table>
<thead>
<tr>
<th>Variable</th>
<th>Chronic CHF</th>
<th>Control Subjects</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNP, pmol/L</td>
<td>28.8 (18.9–118.8)</td>
<td>5.3 (1.6–13.5)</td>
<td>$&lt;0.0001$</td>
</tr>
<tr>
<td>FMD, %</td>
<td>1.5 (0.0–3.5)</td>
<td>9.1 (5.3–15.2)</td>
<td>$&lt;0.0001$</td>
</tr>
<tr>
<td>EID, %</td>
<td>13.3 (5.0–21.0)</td>
<td>13.3 (9.5–22.9)</td>
<td>0.337</td>
</tr>
<tr>
<td>vWF, IU/dL</td>
<td>197±93</td>
<td>123±67</td>
<td>0.005</td>
</tr>
<tr>
<td>sTM, ng/mL</td>
<td>45.0 (16.8–80.1)</td>
<td>37.5 (25.0–47.5)</td>
<td>0.286</td>
</tr>
<tr>
<td>CECs, cells/mL</td>
<td>11.8 (4.6–18.4)</td>
<td>3.7 (1.3–7.2)</td>
<td>$&lt;0.0001$</td>
</tr>
</tbody>
</table>

EID indicates endothelium-independent (GTN-mediated) dilation. vWF expressed as mean±SD; FMD, EID, sTM, and CECs expressed as median (IQR).
FMD together accounted for 66.1% of the variance. FMD alone accounted for 31.3% in the variability; BNP and significantly, accounting for 49.2% of the variability of CHF/health. 

This plethysmography, it has been reported that the impairment of fore an indirect measure of eNOS activity. Using strain-gauge dependent vasodilation in response to shear stress and there-

raised levels previously reported in CHF. Since then, FMD has been developed as a more "physiological" method of assessing the endothelium, centering on endothelium-dependent vasodilation in response to shear stress and therefore an indirect measure of eNOS activity. Using strain-gauge plethysmography, it has been reported that the impairment of endothelium-dependent vasodilation was near maximum even in mild CHF. This "plateau effect" could explain the lack of relation between FMD and the severity of CHF. Indeed, impaired endothelium-dependent vasodilation may explain the abnormal vasoconstriction that is a hallmark of CHF, and the detrimental effect of NSAI

This coupled with raised vWF that facilitates platelet adhesion to other platelets and the endothelium further exacerbates the problem in CHF.

The other inverse relation between plasma BNP and FMD is interesting, as neither BNP nor FMD correlated with LVEF or NYHA class in our study, possibly because of the small number of subjects. However, both were independently selected in multivariate analysis of factors linked to CHF, providing approximately 49% and 31% variability, respectively. The two markers seem likely to have some interrelation, as together they provide 66% of the variability in CHF and have a respectably significant correlation. Thus far, there is only conflicting evidence from a few studies of such a possible relation, some showing upregulation of eNOS and iNOS by ANP and BNP and others downregulation of tumor necrosis factor-α (TNF-α) and, indirectly, iNOS by ANP. Although strictly speaking, the latter studies were performed using ANP, both ANP and BNP appear to have identical functions. Therefore, whereas upregulation of eNOS and iNOS should improve FMD as shown by exogenous administration of BNP, albeit in healthy individuals, 11,12 downregulation of TNF-α and consequently iNOS may impair FMD further. Indeed, in patients with CHF, iNOS has been shown to play a significant role in resistance vessel tone and endotheli-

protein C (VWF) in CHF is generalized. To be able to explain the significant relations between FMD, vWF, and CECs, we have to accept that FMD measured in only a very short segment of the brachial artery is representative of the endothelium in its entirety. Indeed, the endothelium should be recognized as an organ in its own right and in this respect, targeted specifically as a therapeutic measure. Endothelial denudation also exposes the underlying prothrombotic collagen that forms the subendothelial layer, and the resultant activation of the coagulation system may explain the excess risk of thromboembolism associated with CHF. 

As such, not only is the endothelial monolayer dysfunctional, but some parts may in fact be denuded of vascular endothelial cells. Akin to early in vitro observations of the effect of endothelium denudation on endothelium-dependent vasodilation, we suggest that our data provide indirect in vivo proof of that concept in humans. Furthermore, this suggests that endothelial damage in CHF is generalized. To be able to explain the significant relations between FMD, vWF, and CECs, we have to accept that FMD measured in only a very short segment of the brachial artery is representative of the endothelium in its entirety. Indeed, the endothelium should be recognized as an organ in its own right and in this respect, targeted specifically as a therapeutic measure. Endothelial denudation also exposes the underlying prothrombotic collagen that forms the subendothelial layer, and the resultant activation of the coagulation system may explain the excess risk of thromboembolism associated with CHF.

### Discussion

Endothelial integrity can be assessed by a number of techniques, the longest established being release of vWF, with raised levels previously reported in CHF. Since then, FMD has been developed as a more "physiological" method of assessing the endothelium, centering on endothelium-dependent vasodilation in response to shear stress and therefore an indirect measure of eNOS activity. Using strain-gauge plethysmography, it has been reported that the impairment of endothelium-dependent vasodilation was near maximum even in mild CHF. This "plateau effect" could explain the lack of relation between FMD and the severity of CHF. Indeed, impaired endothelium-dependent vasodilation may explain the abnormal vasoconstriction that is a hallmark of CHF, and the detrimental effect of NSAI

The inverse correlation between FMD and vWF in the present study of patients with CHF is mirrored in a substudy of hypertensive patients in the Anglo-Scandinavian Cardiac Outcomes Trial (ASCOT) and also in type 2 diabetic patients with treated hypertension. This is consistent with current views on the function of the endothelial monolayer in mediating vasodila-

plasminogen activator (tPA) which, in turn, endogenously limits the coagulation system and prevents fibrin deposition. Moreover, atherosclerosis poses a threat to the integrity of the endothelium and its resistance to shear stress. In a pathological setting, as in CHF, an imbalance exists between vasodilator and vasoconstrictor substances, which may be related to the presence of vWF. 

With the use of indomethacin, a selective cyclooxygenase inhibitor, vasodilation was impaired, with a resultant increase in vWF secretion. Furthermore, the current observed (respectable) inverse relation between FMD and CECs lends further support to our viewpoint that CECs are desquamated, damaged, or dysfunctional endothelial cells. An increased number of CECs raises the possibility that not only is the endothelial monolayer dysfunctional, but some parts may in fact be denuded of vascular endothelial cells. Akin to early in vitro observations of the effect of endothelium denudation on endothelium-dependent vasodilation, we suggest that our data provide indirect in vivo proof of that concept in humans. Furthermore, this suggests that endothelial damage in CHF is generalized. To be able to explain the significant relations between FMD, vWF, and CECs, we have to accept that FMD measured in only a very short segment of the brachial artery is representative of the endothelium in its entirety. Indeed, the endothelium should be recognized as an organ in its own right and in this respect, targeted specifically as a therapeutic measure. Endothelial denudation also exposes the underlying prothrombotic collagen that forms the subendothelial layer, and the resultant activation of the coagulation system may explain the excess risk of thromboembolism associated with CHF. 

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tinue low-dose aspirin because the majority of the patients with CHF either had coronary artery disease or were at significantly high risk of a cardiovascular event. Even if we assume that aspirin did attenuate some of our research indexes, we would expect an even greater difference between patients with CHF and control subjects.

Conclusions
In conclusion, we have confirmed raised vWF, raised BNP, and impaired FMD in CHF. Notably, all 3 of these endothelial assessments significantly intercorrelated. Our first novel finding is of raised CECs but no change in sTM in this disease. The second contribution of our data is a correlation between BNP and FMD, but both remained as significant independent (statistical) predictors of the presence of CHF. This implies to us that the factors responsible for the increase in BNP in CHF may be independent of those responsible for endothelial damage/dysfunction. Therefore, the routes by which these indexes influence the pathophysiology of CHF as well as predict adverse outcomes may be independent.

Acknowledgments
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References
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