PATHOPHYSIOLOGY AND NATURAL HISTORY
CONGESTIVE HEART FAILURE

Relationship between central hemodynamics and regional blood flow in normal subjects and in patients with congestive heart failure

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ABSTRACT Central and regional (hepatic, renal, and limb) hemodynamic data are presented for a normal population (n = 16) and for a group of patients with congestive heart failure (n = 64). The patient population represented a wide spectrum of severity of congestive heart failure. Various relationships between central and regional hemodynamics were analyzed. The results indicate that in congestive heart failure blood flow to hepatic, renal, and limb regions is significantly decreased, and that this decrease is proportional and linearly related to the reduction in cardiac output. The vascular resistances of these regions correlated directly with systemic vascular resistance. Changes in renal vascular resistance and renal blood flow became attenuated as the severity of the heart failure advanced from moderate to severe and at higher levels of systemic vascular resistance. There was little to no correlation between systemic blood pressure and liver, kidney, and limb blood flow for the range of systemic pressures studied.

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HEART FAILURE is accompanied by a variety of compensatory mechanisms (e.g., sympathetic nervous system activation and mechanisms of the renin-angiotensin-aldosterone and vasopressin systems) affecting regional, as well as central, hemodynamics. In general, studies in animals and humans suggest that, in congestive heart failure, there is a redistribution of regional blood flow away from vascular beds sensitive to sympathetic nervous system stimulation (e.g., splanchnic, renal), with a relative increase in the proportion of cardiac output to the more autoregulated vascular beds such as the coronary and cerebral circulations.

Regional blood flow measurements in previous human studies have generally been restricted to one organ system. Current methods of bedside cardiac catheterization and techniques that determine blood flow to multiple vascular beds have provided the opportunity to study, in a large population of patients with congestive heart failure, the central and regional hemodynamics in each subject. This investigation was performed to examine the relationships between central hemo-

dynamics and regional blood flow in patients with congestive heart failure and in an age- and sex-matched normal control population.

Methods

Patient population. The congestive heart failure population consisted of 64 patients (54 men and 10 women) with a mean age of 54 ± 12 years (range 19 to 69). A wide spectrum of mild-to-severe congestive heart failure as defined by clinical and hemodynamic data was represented by this population. Twenty-four patients were classified as functional class IV, 28 as functional class III, and 12 as functional class II (New York Heart Association). Fifty-six patients underwent diagnostic cardiac catheterization within 1 year of being studied. After clinical and laboratory evaluation, 40 patients had congestive heart failure secondary to idiopathic dilated cardiomyopathy, 13 had ischemic cardiomyopathy, five had congestive heart failure after valve replacement for longstanding rheumatic valvular disease, three were judged to have alcoholic cardiomyopathy, and the remaining three patients had hypertensive, peripartal, or doxorubicin-induced cardiomyopathy.

Forty-nine patients were receiving an oral digitalis preparation daily (0.25 mg digoxin in 38 patients and 0.125 mg in eight patients; 0.05 to 0.1 mg digitoxin in three patients). Forty-six patients were receiving 20 to 300 mg oral furosemide daily, eight patients 600 to 1600 mg quinidine sulfate daily, five patients 1500 to 4500 mg oral propranolol daily, two patients 300 to 340 mg oral disopyramide daily, nine patients 20 to 80 mg oral isosorbide dinitrate daily, and four patients were receiving 15 to 30 mg topical nitroglycerin ointment daily. Digitalis and antiarrhythmics were continued throughout the study while furosemide and nitrates were discontinued at least 24 hr before the study.
Normal subjects. The normal group consisted of 16 subjects (12 men and four women) with a mean age of 51 ± 16 years (range 24 to 79). These individuals had an unremarkable history and physical examination, a normal chest roentgenogram, electrocardiogram, and echocardiogram, and normal systolic time intervals.

Written informed consent was obtained from each subject before the study.

Procedures and measurements. All studies were performed while patients were in a 20 to 30 degree recumbent position and postabsorptive state and between 8:00 A.M. and 12 noon.

Central hemodynamic data for the patients with congestive heart failure were obtained with a flow-directed triple-lumen catheter; this catheter was placed in the pulmonary artery 1 day before the study to achieve adequate equilibration. Cardiac output, obtained in triplicate and averaged for each patient, was measured by the thermodilution technique with an Instrumentation Laboratory 601 computer and 602 recorder.

In the normal subjects, cardiac output was measured in duplicate by the precordial radioisotope-dilution curve technique. An indwelling catheter was placed in the antecubital vein of both arms. After equilibration, 1 ml of 111-I-labeled human serum albumin (12 μCi), followed immediately by a 10 ml bolus of normal saline, was injected into each subject’s right arm. The resulting dilution curve was detected and recorded by a Nuclear Chicago Model 8731 precordial scintillation detector, count rate meter, and a Model 8416 recorder. The probe was positioned perpendicular to the chest wall, over the fourth intercostal space at the left sternal border. This position was marked on each subject to ensure that a constant volume of blood would be viewed by the detector. The concentration of isotope was demonstrated to be at equilibrium 10 min after injection, and at this time a blood sample was withdrawn for use in the blood volume calculation. A Picker Nuclear Model 625105 well counter was used to analyze radioactivity of the injectate and to compute blood volume. The cardiac output was calculated as:

\[
\text{Cardiac output} = \frac{C_e \times BV}{A} \times 60
\]

where \(C_e\) = radioactivity in counts per minute at equilibrium; \(BV\) = blood volume in liters; \(A\) = the area under the primary curve, the ordinate of which represents counts per minute and abscissa of which represents time in seconds. In our laboratory, the correlation coefficient between the radioisotope-dilution curve method and the thermodilution technique for measuring cardiac output is 0.86 (\(r^2 = .74, p < .05\) when \(n = 10\)).

Cardiac index (l/min/m²) was calculated as cardiac output/body surface area and total systemic resistance (dynes·sec·cm⁻⁵) as mean systemic arterial pressure × 80/cardiac output. Systemic blood pressure was measured by cuff and mercury column sphygmomanometer. The disappearance of the Korotkoff sounds was taken as the diastolic blood pressure value. An indwelling upper limb arterial cannula, interphased with Electronics for Medicine M2101 amplification systems was used in six patients in whom Korotkoff sounds were not clearly audible. Mean systemic blood pressure was determined electronically in these six patients; in the remaining patients it was calculated as: (systolic blood pressure – diastolic blood pressure)/3 plus diastolic blood pressure. Systemic blood pressure measurements were made twice (and averaged) for each set of central hemodynamic values.

Hepatic plasma flow was determined by indocyanine green (ICG) clearance. After blood for a plasma blank and the ICG standard was obtained, ICG was injected intravenously at 0.5 mg/kg body weight. Venous blood samples were drawn from the pulmonary artery at 5, 10, 15, and 20 min after injection in the congestive heart failure patients and, because of a higher clearance rate, at 3, 6, 9, and 12 min in the control subjects. The plasma samples were read spectrophotometrically (Beckman DB Model 1401) against the plasma blank at a wave length of 805 μm to determine percent absorbance, which was then converted to plasma concentration by the use of the ICG standard. p-Aminophippurate (PAH) was used to measure effective renal plasma flow. After control blood samples were obtained 40 mg/kg PAH was injected intravenously over 5 min and venous blood was sampled at 15, 30, 45, and 60 min after injection in the patients with heart failure. In the normal subjects 25 mg/kg PAH was injected and venous blood was sampled at 7, 14, 21, and 28 min after injection. The dose and sampling were modified in the normal group because of a more rapid excretory rate, a lesser volume of distribution, and a more marked vasodilatory effect of PAH in normal subjects. The plasma concentrations were determined spectrophotometrically by the paradimethyl aminobenzaldehyde method at a wave length of 465 μm. Calculation of effective renal and hepatic plasma flow was essentially the same. For each determination, the four concentrations were plotted on semilog paper and a line was drawn through the points by the best-fit method. Plasma flow (plasma clearance of dye) was then obtained by multiplying volume of distribution by the elimination constant; the volume of distribution equals the amount of dye injected divided by the concentration at time zero and the elimination constant equals the natural log of 2 divided by the plasma half-life. Blood flow was then calculated by dividing plasma flow by one minus the hematocrit. Hepatic and renal flows were corrected for body surface area. Limb blood flow (right upper extremity) was determined by venous occlusive plethysmography and expressed in milliliters of blood/deciliter limb tissue/minute. Room temperature was held constant at between 21° and 23.5° C. Plethysmography was performed with a Meda Sonics SPG-16 Amplification System interfaced between a SG-21 gallium-indium strain gauge and a R12A strip-chart recorder. A minimum of five determinations were averaged for each limb blood flow value. Regional vascular resistance was calculated by dividing the mean arterial pressure (mm Hg) by the regional blood flow value (in l/min for renal and hepatic, ml/100 ml/min for limb).

The sequence of testing was as follows: central hemodynamic measurements (10 to 15 min), hepatic and limb blood flow (15 to 25 min), renal blood flow (30 to 60 min), and repeat central hemodynamic measurements (10 to 15 min). The two sets of central hemodynamic data were averaged.

Statistical analysis. A Hewlett-Packard 85 computer and curve-fitting program were used to determine the relationship of cardiac index, systemic vascular resistance, and blood pressure to regional blood flow and regional vascular resistance. Inter-group and subgroup comparisons were made with one- and two-way analysis of variance.

Results

The results of this study are presented in figures 1 through 4. Figure 1 depicts mean (± SD) central and regional hemodynamic values for the normal subjects and for the patients with congestive heart failure. The congestive heart failure group was divided into subgroups of those with mild, moderate, and severe disease on the basis of respective cardiac indexes of > 2.5, 2.5 to 2.0, and < 2.0 l/min/m².

The mean cardiac index in the normal population was 3.50 ± 0.48 l/min/m², while that of the entire population with congestive heart failure was significantly re-
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FIGURE 1. Mean cardiac index (A), systemic vascular resistance (B), regional blood flow (C, E, and G), and regional vascular resistance (D, F, and H) measurements in normal subjects (NL) and subgroups of patients with congestive heart failure (CHF).

Reduced to 2.19 ± 0.47 l/min/m². The systemic vascular resistance for each congestive heart failure subgroup was significantly elevated above control and above that of each preceding subgroup (figure 1, B).

Figures 2 through 4 illustrate the regional blood flow and vascular resistance data points plotted against central hemodynamic parameters for each individual in this study. Best-fit regression formulas are included in each figure. Table 1 lists the best- and second best-fit formulas for each plot.

**Hepatic hemodynamics.** The mean hepatic blood flow in the normal subjects was 595 ± 116 ml/min/m². The mean hepatic blood flow for the entire population with congestive heart failure was reduced to 340 ± 153 ml/min/m² (p < .05). Hepatic blood flow was significantly diminished from control for each of the three subgroups (figure 1, C). Mean hepatic vascular resistance for each congestive heart failure subgroup was significantly elevated above control (figure 1, D). Although mean hepatic vascular resistance tended to increase with increasing severity of congestive heart disease, no significant differences were noted between subgroups. A good linear correlation was found between individual cardiac index and hepatic blood flow measurements (figure 2, top left). The relationship of hepatic blood flow to systemic vascular resistance was best described by a logarithmic curvilinear function, with a fairly good negative correlation (figure 2, bottom left). Hepatic blood flow correlated poorly with systemic blood pressure (figure 2, top right), but a good positive correlation was noted between hepatic vascular resistance and systemic vascular resistance (figure 2, bottom right).

**Renal hemodynamics.** Mean renal blood flow in the normal subjects was 607 ± 172 ml/min/m², while in the population with congestive heart failure it was reduced to 395 ± 131 ml/min/m² (p < .05). Renal blood flow was significantly reduced from control for patients in each congestive heart failure subgroup (figure 1, E). Renal flow was significantly less in the moderate compared with the mild heart failure group, but little difference was noted between the moderate and severe disease subgroups. Renal vascular resistance was increased significantly from control in the moderate and severe heart failure subgroups (figure 1, F). The resistance was increased significantly in the moderate compared with the mild failure subgroup and decreased modestly in the severe compared with the moderate congestive heart failure subgroup. For the combined normal and congestive heart failure populations, a positive linear relationship with fair correlation existed between cardiac index and renal blood flow (figure 3, top left). A fair correlation was noted for renal blood flow values and systemic vascular resistance values for the combined normal and congestive heart failure groups; the relationship between these parameters was best described by a logarithmic function (figure 3, bottom left). Little to no correlation existed between renal blood flow and mean systemic blood pressure (figure 3, top right), but a positive correlation was found between renal and systemic vascular resistance (figure 3, bottom right).

**Limb hemodynamics.** The mean limb blood flow in congestive heart failure of 4.52 ± 1.77 ml/100 ml/min was reduced below the normal mean value of 8.22 ± 3.16 ml/100 ml/min (p < .05). For each congestive heart failure subgroup, limb blood flow was significantly reduced below control and below that in each preceding subgroup of patients with less severe disease (figure 1, G). Limb vascular resistance increased significantly from control for each subgroup, but there was no significant difference in resistance between the
heart failure subgroups (figure 1, H). A linear function with a fair-to-good direct correlation described the relationship between cardiac index and limb blood flow for all subjects (figure 4, top left). An exponential function curve, with a fair inverse correlation for all subjects studied, described the relationship between limb blood flow and systemic vascular resistance (figure 4, bottom left). A poor correlation was found between mean systemic blood pressure and limb blood flow (figure 4, top right). Limb vascular resistance showed a fair positive correlation with systemic vascular resistance (figure 4, bottom right).

For most of the regression plots, the second best-fit formula comes very close to the best-fit formula in describing the relationship between two parameters (table 1).

**Discussion**

This study has demonstrated that in a large population of patients with congestive heart failure, blood flow to hepatic, renal, and limb regions is significantly decreased and that this decrease in flow is proportional and, in general, linearly related to the reduction in cardiac output. Little to no correlation was noted between systemic blood pressure and hepatic, renal, or limb blood flow. It is noteworthy that considerable individual variation in regional blood flow and in regional vascular resistance was observed in normal subjects and in all of the congestive heart failure subgroups studied.

The mean hepatic blood flow in normal subjects (595 ml/min/m²) comprised 17% of their mean cardiac index of 3.5 l/min/m². Mean hepatic blood flow in the congestive heart failure patients was found to average 340 ml/min/m², which is 16% of their mean cardiac index of 2.19 l/min/m². A previous report supports the finding that hepatic blood flow drops in proportion to the drop in cardiac output. However, in the earlier report the larger mean hepatic blood flow in normal subjects (841 ml/min/m²) and in congestive heart failure patients (535 ml/min/m²) accounted for approximately 20% of the cardiac index in each group. The most likely explanation for the increased hepatic flow noted in the prior study is that sulfobromophthalein clearance was used to estimate hepatic flow. Extraperitoneal extraction of sulfobromophthalein ranges from 10% to 30% of the total extraction, while ICG is not cleared from the extraperitoneal circulation in any appreciable amount. Microsphere distribution studies in rats have also shown that hepatic blood flow generally
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FIGURE 3. Correlations between renal blood flow and cardiac index, systemic vascular resistance, and mean systemic blood pressure and between renal and systemic vascular resistances. Best curve equation, correlation coefficient, coefficient determination, and statistical significance are given for the normal (NL), congestive heart failure (CHF), and combined populations. The regression lines superimposed on the data points represent the regression formulas for the combined normal and congestive heart failure (NL + CHF) populations.

decreases in proportion to the drop in cardiac output. Renal blood flow in our normal population averaged 607 ± 172 ml/min/m², comprising 17% of mean cardiac index. These values compare favorably with those averaged from several other studies (660 ml/min/m² and 18%). The mean renal blood flow in our congestive heart failure population dropped to 395 ± 131 ml/min/m²; this value represents 18% of the cardiac index, indicating that in the congestive heart failure population as a whole, the drop in renal blood flow was proportional to the reduction in cardiac output. These results are supported by data from studies by Blegen and Aas and Werko et al., who reported mean renal blood flow values of 370 and 404 ml/min/m², respectively, in patients with cardiac and valvular disease and congestive heart failure. In contrast, the mean renal blood flow obtained in several smaller studies compiled by Wade and Bishop was 231 ml/min/m², accounting for 11% of the mean cardiac index; this suggests that in congestive heart failure renal flow is selectively decreased out of proportion to the drop in cardiac output. The explanation for these discrepancies are not clear, but differences in patient population (e.g., severity of disease, prestudy equilibration) and investigative techniques (e.g., continuous infusion vs single bolus PAH) are probably contributory.

Limb blood flow in this study dropped from 8.22 ± 4.16 ml/100 ml/min in normal subjects to 4.52 ± 1.77 ml/100 ml/min in congestive heart failure patients, a 45% reduction. Zelis et al. found limb blood flow in normal and in congestive heart failure populations to be 6.30 ± 0.58(SEM) and 2.94 ± 0.53 ml/100 ml/min, respectively; this represents a comparable drop (53%) in congestive heart failure. The lower absolute blood flow values obtained by Zelis et al. can be explained by differences in methods. In our laboratory, the double-occlusion method (proximal and distal-wrist occlusion) generates limb flow values that range between 9% and 30% lower than the single-occlusion method (proximal) used in this study.

It is important to appreciate the limitations of the techniques used in the investigation of regional blood flow in humans. Although the techniques used produce results that correlate well with more direct measurements, they provide only indirect determinations of blood flow. Hepatic and renal blood flow were estimated by clearance of dye (ICG and PAH, respectively) and limb blood flow by changes in limb vol-
volume/time after proximal venous occlusion. Clearance of dye is not only dependent on blood flow to the organ metabolizing or removing the dye, but also on that organ’s cellular function, extraction of dye by other organs, dosage and rate of dye delivery, and other less prominent variables. Patients with detectable hepatic or renal disease or peripheral vascular disease were excluded from this study. In our laboratory, nonhepatic extraction of ICG was found to range from 2% to 8% and that of PAH from 5% to 18%. The determination of percent dye extraction by a given organ requires the placement of an indwelling catheter in the venous system of the organ and a systemic arterial cannula. These catheters were not placed in the patients in this study. We elected to use 100% for liver and kidney extraction of ICG and PAH, respectively (i.e., 0% other-organ extraction), recognizing that our flow values may be underestimating the actual flow values by 2% to 20%. However, the same techniques and considerations were applied to each participant in both groups in the study, suggesting that intergroup and intragroup comparisons of central and regional hemodynamic values and their various ratios (e.g., regional flow/cardiac output) are quite valid. Various noninvasive methods (e.g., limb conductance, strain gauge, volume displacement) are available to measure limb blood flow and their differences account for some variation in the absolute values that have been reported. In our laboratory, the results with the gallium-indium strain-gauge technique of determining limb volume changes per time correlate well (r = .88) with those with the standard method of volume-displacement water-chamber plethysmography.18

While changes in regional blood flow are proportional to changes in cardiac output for a heart failure population as a whole, differences within the population are apparent. A curvilinear relationship exists between systemic vascular resistance and regional blood flow (bottom left panels of figures 2 through 4); however, it is important to remember that mathematically an inverse curvilinear relationship exists between flow and resistance. By examining regional vascular resis-
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#### TABLE 1

<table>
<thead>
<tr>
<th>Relationship</th>
<th>Group</th>
<th>Equation</th>
<th>Best fit r</th>
<th>Best fit $r^2$</th>
<th>Second-best fit r</th>
<th>Second-best fit $r^2$</th>
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</thead>
<tbody>
<tr>
<td>Hepatic blood flow and cardiac index</td>
<td>NL</td>
<td>$Y = 266.72 \exp^{0.22X}$</td>
<td>.56</td>
<td>.31</td>
<td>.55</td>
<td>.30</td>
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<td>and cardiac index</td>
<td>CHF</td>
<td>$Y = -23.04 + 166.10X$</td>
<td>.51</td>
<td>.26</td>
<td>.50</td>
<td>.25</td>
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<tr>
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<td>.35</td>
<td>-.58</td>
<td>.34</td>
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<td>$Y = 1913.57 - 211.17LnX$</td>
<td>-.35</td>
<td>.12</td>
<td>-.32</td>
<td>.13</td>
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<td>$Y = 1293.92X^{0.18}$</td>
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<td>.006</td>
<td>.071</td>
<td>.005</td>
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<td>and mean blood pressure</td>
<td>NL + CHF</td>
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<td>.013</td>
<td>.10</td>
<td>.010</td>
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<td>.19</td>
<td>.038</td>
<td>.18</td>
<td>.032</td>
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<tr>
<td>and cardiac index</td>
<td>CHF</td>
<td>$Y = 241.89 + 68.77X$</td>
<td>.24</td>
<td>.058</td>
<td>.22</td>
<td>.050</td>
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<td>Renal blood flow and systemic vascular resistance</td>
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<td>.50</td>
<td>.25</td>
<td>.48</td>
<td>.23</td>
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<td>and systemic vascular resistance</td>
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<td>$Y = 2597.82 - 293.37LnX$</td>
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<td>.28</td>
<td>-.49</td>
<td>.24</td>
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<td>.19</td>
<td>.038</td>
<td>.18</td>
<td>.032</td>
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<td>.24</td>
<td>.058</td>
<td>.22</td>
<td>.050</td>
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<td>Limb blood flow and cardiac index</td>
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<td>$Y = 2.60 + 1.60X$</td>
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<td>.30</td>
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<td>.30</td>
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<td>$Y = 8.36 \exp^{-0.000X}$</td>
<td>.51</td>
<td>.26</td>
<td>.50</td>
<td>.25</td>
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</tbody>
</table>

CHF = congestive heart failure; NL = normal subjects.

...tances for normal subjects and patients in three heart failure subgroups (figure 1, D, F, and H), and by plotting regional resistances against systemic vascular resistance (bottom right panels of figures 2 through 4), it appears that regional hemodynamic changes are not quite homogeneous in a degree relative to the severity of heart failure or to the level of systemic vascular resistance. The increase in renal vascular resistance appears to be less for a given increase in systemic vascular resistance at higher levels of resistance (figure 3, bottom right) and as the disease of patients proceeds from moderate to severe (figure 1, F). The attenuation of change in renal vascular resistance probably accounts for the observed lack of change in renal blood flow as the disease progresses from moderate to severe heart failure (figure 1, E), despite a significant drop in cardiac output. This suggests that the sympathetic nervous system, and perhaps other compensatory mechanisms (e.g., renin-angiotensin, vasopressin), play a less dominant role in the regulation of renal blood flow as heart failure becomes more severe. Vascular reactivity to norepinephrine and to nerve stimulation decreases in the animal preparation of congestive heart failure. It is likely that "autoregulation," the mechanisms of which is not yet precisely defined, also plays an important role in the attenuation of changes in renal vascular resistance and flow as heart failure worsens.

In contrast to the renal circulation, attenuation in...
flow and resistance changes with increasing severity of heart failure was not apparent for the hepatic or limb circulations. The explanation for this disparity is not provided by this study, but is probably related to differing vascular regulation (e.g., responsivity, regulatory mechanisms, autoregulation) for the various organ systems as the cardiac function changes from normal to severely diseased.

In conclusion, this study has provided mean values for hepatic, renal, and limb blood flow in normal subjects and patients with congestive heart failure. For the heart failure population as a whole, the decline in blood flow to the renal, hepatic, and limb vascular beds was proportional to the decrease in cardiac output. No disproportionate shunting of blood away from these 'sympathetically innervated' regions was observed in patients in the resting state. In fact, the magnitude of increase in renal vascular resistance and decrease in renal blood flow appeared to become attenuated as the severity of heart failure evolved from moderate to severe. The findings of this study do not pertain to exercising congestive heart failure patients. Exercise appears to elicit more dramatic alterations in renal, hepatic, and limb blood flow through accentuated changes in systemic and regional vascular resistance and blood pressure. More pronounced alterations in regional blood flow are also likely to occur in the setting of acute and/or extreme decompensation of cardiac failure. Finally, although central hemodynamics generally correlated with blood flow to the regions studied, there was great variation in the individual blood flow values at each level of cardiac output and systemic resistance, reflecting the complex nature of regional blood flow regulation. This variability does not allow for a very precise prediction, via regression formulas, of regional blood flow from central hemodynamic data alone and vice versa.

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