Myocardial Injury and Left Ventricular Performance After Subarachnoid Hemorrhage

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Background and Purpose—Electrocardiographic abnormalities and elevations of the creatine kinase myocardial isoenzyme (CK-MB) occur frequently after subarachnoid hemorrhage. In some patients, a reversible and presumably neurogenic form of left ventricular dysfunction is demonstrated by echocardiography. It is not known whether cardiac injury of this type adversely affects cardiovascular hemodynamic performance.

Methods—We retrospectively studied 72 patients admitted to our neuro-ICU for aneurysmal subarachnoid hemorrhage over a 2.5-year period. We selected patients who met the following criteria: (1) CK-MB levels measured within 3 days of onset, (2) pulmonary artery catheter placed, (3) echocardiogram performed, and (4) no history of preexisting cardiac disease. Hemodynamic profiles were recorded on the day after surgery (n=67) or on the day of echocardiography (n=5) if surgery was not performed (mean, 3.3±1.7 days after onset). The severity of cardiac injury was classified as none (peak CK-MB <1%, n=36), mild (peak CK-MB 1% to 2%, n=21), moderate (peak CK-MB >2%, n=6), or severe (abnormal left ventricular wall motion, n=9).

Results—Abnormal left ventricular wall motion occurred exclusively in patients with peak CK-MB levels >2% (P<0.0001), poor neurological grade (P=0.002), and female sex (P=0.02). Left ventricular stroke volume index and stroke work index were elevated above the normal range in patients with peak CK-MB levels <1% and fell progressively as the severity of cardiac injury increased, with mean values for patients with abnormal wall motion below normal (both P<0.0001 by ANOVA). Cardiac index followed a similar trend, but the effect was less pronounced (P<0.0001). Using forward stepwise multiple logistic regression, we found that thick subarachnoid clot on the admission CT scan (odds ratio, 1.9; 95% confidence interval [95% CI], 1.0 to 3.4; P=0.04) and depressed cardiac index (odds ratio, 2.1; 95% CI, 1.0 to 4.1; P=0.04) were independent predictors of symptomatic vasospasm.

Conclusions—Myocardial enzyme release and echocardiographic wall motion abnormalities are associated with impaired left ventricular performance after subarachnoid hemorrhage. In severely affected patients, reduction of cardiac output from normally elevated levels may increase the risk of cerebral ischemia related to vasospasm. (Stroke. 1999;30:780-786.)

Key Words: cardiac output ▪ cardiovascular diseases ▪ creatine kinase isoenzymes ▪ echocardiography ▪ subarachnoid hemorrhage ▪ vasospasm

The association of aneurysmal subarachnoid hemorrhage (SAH) with electrocardiographic (ECG) abnormalities has long been recognized. ECG changes occur in 50% to 100% of patients during the acute stage of SAH, with the most common abnormalities involving the ST segment, T wave, and QT interval.1–3 In most cases, these abnormalities are clinically inconsequential and are attributed to neurally mediated electrophysiological effects. Some SAH patients, however, show evidence of structural cardiac damage. Plasma levels of the creatine kinase myocardial isoenzyme (CK-MB) are mildly elevated in 20% to 50% of patients,3–5 and a characteristic form of myocardial pathology, contraction band necrosis, is commonly found at autopsy6–8 and has been produced in experimental SAH models.9,10 More recently, echocardiographic studies have demonstrated reversible abnormalities of left ventricular contractility in SAH patients.3,11–15 In these investigations, normal coronary arteries were demonstrated in all patients studied by autopsy or coronary angiography,12–15 and in 3 subjects myocardial biopsy confirmed the presence of contraction band necrosis.15 Thus, a reversible form of neurogenic myocardial “stunning,” presumably related to myocardial catecholamine toxicity and contraction band necrosis, may occur after SAH.

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Neurogenic ECG changes after SAH are usually regarded as asymptomatic, primarily because serious cardiac arrhythmias in the hospital occur in only 1% to 4% of patients.\textsuperscript{16,17} The potential impact of neurogenic cardiac injury on left ventricular hemodynamic performance after SAH has received little attention but may have important implications because approximately 30% of patients develop delayed cerebral ischemia related to vasospasm. Clinical studies in humans indicate that vasospasm is associated with a loss of autoregulation,\textsuperscript{18} and experimental studies have shown that cerebral blood flow (CBF) in ischemic areas can vary passively with changes in blood pressure\textsuperscript{19} and cardiac output.\textsuperscript{19,20} Accordingly, hypovolemia has been implicated as a risk factor for symptomatic vasospasm,\textsuperscript{21,22} and augmentation of blood pressure and cardiac output can reverse ischemic deficits in affected patients.\textsuperscript{23-25}

We performed this study to determine (1) whether myocardial injury after SAH adversely affects left ventricular contractility and (2) whether depressed baseline cardiovascular hemodynamic performance is a risk factor for delayed cerebral ischemia related to vasospasm.

Subjects and Methods

Study Population

We retrospectively identified and reviewed the medical records of all patients admitted to the Columbia-Presbyterian Neurological Intensive Care Unit (NICU) between September 1991 and February 1994 who met the following criteria: (1) diagnosis of aneurysmal SAH documented by CT or lumbar puncture and angiography; (2) serum CK-MB levels measured within 3 days of SAH; (3) pulmonary artery catheter (PAC) placed for SAH management; (4) echocardiogram performed; and (5) no history of preexisting cardiac disease. Echocardiography and CK-MB levels were obtained on admission in all SAH patients during the study period, and PACs were placed either at the time of aneurysm clipping for the purpose of monitoring postoperative volume expansion, or on admission for managing hemodynamic instability or pulmonary edema. During this period, eligible patients were recruited for participation in a randomized clinical trial comparing the effects of postoperative PAC-guided hypervolemic and normovolemic therapies on CBF measured by \textsuperscript{133}Xenon clearance.\textsuperscript{26,27}

One hundred and ninety-two patients were admitted to the NICU with SAH during the 2.5-year study period. We excluded 46 patients who were admitted 4 or more days after hemorrhage, 26 who had a normal angiogram or died before angiography could be performed, and 14 who had a history of preexisting cardiac disease (coronary artery disease, valvular heart disease, or arrhythmia). Of the remaining 106 potentially eligible patients, 34 (32%) were excluded because echocardiography, CK-MB, or PAC data were not obtained, leaving 72 subjects for analysis. Forty-six of these patients were enrolled in the hypervolemia/normovolemia CBF trial, 55 were included in a previous study analyzing the relationship between ECG changes and echocardiographic abnormalities after SAH,\textsuperscript{1} and 3 were included in a series of SAH patients with neurogenic pulmonary edema and coexisting echocardiographic left ventricular dysfunction.\textsuperscript{13} Because this study was conducted as a retrospective analysis and did not compromise patient confidentiality, formal review was waived by the Institutional Review Board.

Management Protocol and Data Collection

Data were obtained from hospital records and a prospectively maintained NICU database. Neurological status on admission was rated according to the modified Hunt-Hess scale,\textsuperscript{26} and the amount of blood on admission CT scans was graded by a blinded radiologist using the Fisher scale.\textsuperscript{29} Aneurysm location was classified as anterior cerebral (including anterior communicating artery), internal carotid (including posterior communicating artery), middle cerebral, or vertebrobasilar. Symptomatic vasospasm was recognized by focal neurological signs or deterioration in level of consciousness, with either confirmation of infarction by CT or exclusion of other possible causes of deterioration (eg, rebleeding, hydrocephalus, edema, electrolyte disorder, infection, seizure).\textsuperscript{30} Symptomatic vasospasm was diagnosed by physicians (R.A.S. and L.L.) who were blinded to the cardiovascular hemodynamic data. Patients were evaluated on admission for the presence of pulmonary edema, defined by the presence of characteristic diffuse infiltrates on chest radiography and reduced oxygenation requiring at least 40% supplemental oxygen, and hypotension, defined as a systolic blood pressure <100 mm Hg requiring treatment with intravenous pressors; noncardiac causes of pulmonary infiltrates, hypoxemia, or hypotension were rigorously excluded.

All patients were managed according to a standard protocol,\textsuperscript{31} whether or not they were enrolled in the hypervolemia/normovolemia CBF study. Surgical clipping of the aneurysm was performed within 48 hours of admission, except in 5 patients who were medically or neurologically too unstable for surgery. All patients received 80 mL/h of 5% dextrose and 0.9% saline pre- and postoperatively, with additional isotonic crystalloid provided as clinically indicated. Total fluid input on the day of surgery ranged from 4 to 6 L, resulting in a mildly volume-expanded state on the first postoperative day.\textsuperscript{27} After a baseline cardiovascular hemodynamic profile was measured on the morning after surgery, 250 mL of 5% albumin solution was given every 2 hours if the pulmonary artery diastolic pressure (PAPD) was less than or equal to the following target values: hypervolemic therapy, 14 mm Hg; normovolemic therapy, PAPD 7 mm Hg. Treatment was determined by random assignment for patients enrolled in the hypervolemia/normovolemia CBF study; otherwise, target cardiac filling pressures were determined by the attending physician. All patients received nifedipine (60 mg orally every 4 hours), and most were treated with phenytoin and dexamethasone during the perioperative period.

Cardiovascular hemodynamic profiles were measured once a day by a single investigator (S.A.M.) and recorded in an NICU database. We analyzed hemodynamic profiles on the first postoperative day in the patients who underwent surgery (before assignment to normovolemic or hypervolemic therapy) to control for variations in volume status or on the day that echocardiography was performed in the 5 nonoperated patients. Mean arterial blood pressure (MAPB), central venous pressure (CVP), PAPD, and pulmonary artery wedge pressure (PAWP) were measured using saline-filled catheters with transducers positioned at the level of the right atrium. Cardiac output was measured with a PAC using the iced-saline thermodilution technique. Three measurements were obtained and the average value recorded, with outlying values (>500 mL/min) discarded if necessary. Injections were not timed with respect to the ventilatory cycle. Cardiac index (CI), systemic vascular resistance index (SVRI), left ventricular stroke volume index (LVSVI), and left ventricular stroke work index (LVSWI) were calculated according to standard formulae.\textsuperscript{32} Three patients received vasopressors (dopamine or phenylephrine) at the time the hemodynamic profile was recorded, in 1 patient for hypotension and in 2 patients for symptomatic vasospasm.

Serum CK levels were obtained daily for 3 days on admission to the NICU and approximately every other day thereafter. CK isoenzyme fractionation was performed using agarose gel electrophoresis (Paragon system; Beckman) on all values above normal range (0 to 50 U/L). MB fractions between 2% and 5% are classified as borderline in our laboratory, with values above 5% considered diagnostic of myocardial infarction.

Two-dimensional color-flow Doppler transthoracic echocardiography was performed in the NICU using Hewlett-Packard Sonos 1000 equipment (Hewlett-Packard Imaging Systems Division). All initial studies were performed within 3 days of admission, and most patients underwent a repeat examination 4 to 6 days after the first study. Standard parasternal long axis, short axis, and apical 2- and 4-chamber views were obtained for analysis of left ventricular function. Echocardiograms were reviewed by a cardiologist blinded
Patients, n 72
Age, y 51±13
Women, n (%) 47 (65)
Admission Hunt/Hess grade, n (%) I, mild to moderate headache 16 (22) II, severe headache 20 (28) III, lethargy, confusion, or focal deficit 22 (31) IV, stupor 10 (14) V, coma 4 (6)
Admission Fisher CT grade, n (%) I, no or minimal SAH 5 (7) II, diffuse thin SAH 31 (43) III, thick (>5 mm) SAH 23 (32) IV, large focal ICH or IVH 13 (18)
Aneurysm location, n (%) Anterior cerebral 30 (42) Internal carotid 29 (40) Middle cerebral 7 (10) Vertebrobasilar 4 (6) Unknown 2 (3)

ICH indicates intracerebral hemorrhage; IVH, intraventricular hemorrhage.

to the clinical status of the patient using a standardized evaluation form (Cardioscan Inc.). Wall motion was classified as normal, hypokinetic, akinetic, or dyskinetic in each of 14 anatomic segments. The left ventricular ejection fraction was visually estimated as 1.7 days (range, 0 to 9 days), from SAH to measurement of the cardiovascular hemodynamic data, or day of surgery and the 5 who did not.

Peak CK-MB levels were <1% in 36 patients (50%), 1% to 2% in 21 patients (29%), and >2% in 15 patients (21%). The mean interval from SAH to peak CK-MB in the 36 patients with detectable levels was 1.4±1.3 days. Admission total serum CK levels (mean 216±272 U/L; range, 23 to 1520 U/L) did not differ based on peak CK-MB levels.

Echocardiography revealed abnormal left ventricular wall motion in 9 patients (13%). Abnormal wall motion occurred exclusively in patients with peak CK-MB levels >2% (9/15 versus 0/57, *P*<0.0001), Hunt/Hess grades of III to V (9/36 versus 0/36, *P*=0.002), and female sex (9/47 versus 0/25, *P*=0.02), and all but 1 affected patient had an admission CT Fisher grade of III or IV (8/36 versus 1/36, *P*=0.03; significance judged at *P*<0.0125 using Bonferroni correction). There was no relationship between aneurysm location or laterality and abnormal left ventricular wall motion.

Within 6 hours of onset of SAH, 1 patient with abnormal wall motion developed severe hypotension, 1 developed pulmonary edema, and 4 developed both; none of the patients with normal echocardiograms experienced these complications. Peak CK levels in the 9 patients with abnormal wall motion ranged from 116 to 1520 U/L (mean, 375 U/L), and CK-MB levels ranged from 2.0% to 10.5% (mean, 3.8%). Left ventricular ejection fractions were graded as mildly reduced (40% to 50%) in 2 patients, moderately reduced (30% to 40%) in 5 patients, and severely reduced (20% to 30%) in 2 patients. All 5 patients who underwent serial echocardiography 6 to 44 days after SAH had normalization of their ejection fractions, and all 9 patients had widespread T-wave inversions and QT, prolongation (>440 ms) on at least 1 ECG. Requests for autopsy examination of 3 patients with abnormal wall motion who died were refused.

Among the study group as a whole, indicators of cardiac injury (peak CK-MB levels <1%) and showed progressive reduction as the severity of cardiac injury increased, with values for patients with abnormal left ventricular wall motion below normal (both *P*<0.0001). A similar but less pronounced trend (see the Figure, C) was also seen for CI (*P*<0.0001). SVRI was significantly elevated in patients with abnormal wall motion (*P*=0.0001 by ANOVA), and a trend toward higher mean PADP in patients with abnormal wall motion was near significance (*P*=0.006). The extent of cardiac injury had no significant effect on heart rate, MABP, CVP, or PAWP, and there were no significant differences in mean age, admission CK levels, day of measurement of cardiovascular hemodynamic data, or day of echocardiography between the 4 groups.

Twenty-six (36%) of the 72 study patients developed symptomatic vasospasm. An admission CT Fisher grade of III or IV (*P*<0.001), depressed CI (*P*<0.001), elevated SVRI
TABLE 2. Cardiovascular Hemodynamic Values

<table>
<thead>
<tr>
<th>Variable</th>
<th>Normal Range</th>
<th>All Patients</th>
<th>Peak CK-MB</th>
<th>Peak CK-MB</th>
<th>Peak CK-MB</th>
<th>Peak CK-MB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;1%</td>
<td>1%–2%</td>
<td>&gt;2%</td>
<td>&gt;2%</td>
</tr>
<tr>
<td>n (%)</td>
<td>72 (100)</td>
<td>36 (50)</td>
<td>21 (29)</td>
<td>6 (8)</td>
<td>9 (13)</td>
<td></td>
</tr>
<tr>
<td>Heart rate, beats/min</td>
<td>60–100</td>
<td>79±15</td>
<td>73±12</td>
<td>85±11†‡</td>
<td>79±11</td>
<td>85±20</td>
</tr>
<tr>
<td>MAP, mm Hg</td>
<td>70–105</td>
<td>98±12</td>
<td>98±12</td>
<td>99±12</td>
<td>93±11</td>
<td>96±16</td>
</tr>
<tr>
<td>CVP, mm Hg</td>
<td>0–6</td>
<td>7.6±2.9</td>
<td>8.0±2.7</td>
<td>6.6±3.4</td>
<td>8.0±2.7</td>
<td>7.7±2.4</td>
</tr>
<tr>
<td>PAPD, mm Hg</td>
<td>6–12</td>
<td>13.0±3.6</td>
<td>12.4±3.2</td>
<td>12.7±2.6</td>
<td>12.2±4.4</td>
<td>16.8±4.5§</td>
</tr>
<tr>
<td>PAWP, mm Hg</td>
<td>6–12</td>
<td>12.4±3.5</td>
<td>11.9±3.3</td>
<td>12.5±3.0</td>
<td>11.8±4.4</td>
<td>14.7±4.4</td>
</tr>
<tr>
<td>CI, L·min⁻¹·m⁻²</td>
<td>2.6–4.0</td>
<td>4.0±1.0</td>
<td>4.2±0.8</td>
<td>4.5±1.1</td>
<td>3.6±0.9</td>
<td>2.7±0.8§</td>
</tr>
<tr>
<td>LVSVI, mL/m²</td>
<td>40–50</td>
<td>52±12</td>
<td>58±9</td>
<td>52±9</td>
<td>46±5‡</td>
<td>33±11‖</td>
</tr>
<tr>
<td>SVRI, dyne·s·m⁻² per cm⁻ five</td>
<td>2000–2400</td>
<td>1940±797</td>
<td>1784±500</td>
<td>1742±517</td>
<td>2004±715</td>
<td>2987±1451§</td>
</tr>
<tr>
<td>LVSWI, g·m·m⁻²</td>
<td>50–62</td>
<td>60±16</td>
<td>67±11</td>
<td>60±13</td>
<td>50±5‡</td>
<td>36±14§</td>
</tr>
</tbody>
</table>

*Normal ranges obtained from Reference 32.
†Refers to comparison of means in the 4 groups by factorial ANOVA, with significance (denoted in bold type) judged at the P<0.0055 level based on Bonferroni correction for multiple comparisons.
‡P<0.0083 by Bonferroni-Dunn test, compared with CK-MB <1% group.
§P<0.0083 by Bonferroni-Dunn test, compared with CK-MB <1% group and CK-MB 1–2% group.
¶P<0.0083 by Bonferroni-Dunn test, compared with CK-MB <1% group, CK-MB 1–2% group, and CK-MB >2% group.

(P=0.002), depressed LVSVI (P=0.022), and peak CK-MB >2% (P=0.039) were associated with symptomatic vasoospasm in a univariate analysis (Table 3). In a forward stepwise logistic regression analysis (likelihood ratio statistic, 77; model χ², 17.0; P=0.0002 for the entire model), Fisher CT grade III or IV (coded +1.0=yes, −1.0=no, logistic coefficient 0.6292, odds ratio 1.88, 95% confidence interval 1.02 to 3.43, P=0.041) and CI (logistic coefficient −0.7189, odds ratio 2.05, 95% confidence interval 1.03 to 4.09 for each 1.0 L·min⁻¹·m⁻² reduction, P=0.041) were identified as independent predictors of symptomatic vasoospasm.

Discussion

Our results demonstrate that myocardial enzyme release and echocardiographic wall motion abnormalities are associated with impaired left ventricular performance after SAH and suggest that cardiac output reduction resulting from neurogenic cardiac injury may increase the risk of cerebral ischemia related to vasoospasm.

We excluded patients with preexisting heart disease from this study to avoid cardiac enzyme or echocardiographic abnormalities related to nonneurogenic mechanisms. Indices of cardiac preload (PAPD and PAWP) and left ventricular...
TABLE 3. Univariate Analysis of Variables Associated With Symptomatic Vasospasm

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symptomatic Vasospasm</th>
<th>No Symptomatic Vasospasm</th>
<th>P*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Demographic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female, n (%)</td>
<td>20 (78)</td>
<td>27 (59)</td>
<td>0.112</td>
</tr>
<tr>
<td>Age, n (%)</td>
<td>53±12</td>
<td>49±13</td>
<td>0.215</td>
</tr>
<tr>
<td>White, n (%)</td>
<td>7 (27)</td>
<td>19 (41)</td>
<td>0.222</td>
</tr>
<tr>
<td><strong>Clinical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fisher CT grade III or IV, n (%)</td>
<td>20 (77)</td>
<td>16 (35)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Hunt/Hess Grades III to V, n (%)</td>
<td>16 (62)</td>
<td>20 (43)</td>
<td>0.141</td>
</tr>
<tr>
<td>Anterior circulation aneurysm, n (%)</td>
<td>25 (96)</td>
<td>43 (93)</td>
<td>0.688</td>
</tr>
<tr>
<td>Hypervolemic treatment, n (%)</td>
<td>7/11 (64)</td>
<td>17/35 (49)</td>
<td>0.761</td>
</tr>
<tr>
<td><strong>Past medical history</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypertension, n (%)</td>
<td>10 (38)</td>
<td>24 (52)</td>
<td>0.263</td>
</tr>
<tr>
<td>Cigarette smoking, n (%)</td>
<td>17 (65)</td>
<td>26 (59)</td>
<td>0.576</td>
</tr>
<tr>
<td>Alcohol use, n (%)</td>
<td>8 (31)</td>
<td>12 (26)</td>
<td>0.597</td>
</tr>
<tr>
<td><strong>Cardiovascular</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak CK-MB &gt;2%, n (%)</td>
<td>9 (35)</td>
<td>6 (13)</td>
<td>0.039</td>
</tr>
<tr>
<td>Abnormal wall motion, n (%)</td>
<td>6 (23)</td>
<td>3 (7)</td>
<td>0.063</td>
</tr>
<tr>
<td>Heart rate, beats/min</td>
<td>76±13</td>
<td>80±14</td>
<td>0.172</td>
</tr>
<tr>
<td>MABP, mm Hg</td>
<td>100±14</td>
<td>96±11</td>
<td>0.266</td>
</tr>
<tr>
<td>CVP, mm Hg</td>
<td>8.0±3.1</td>
<td>7.3±2.8</td>
<td>0.396</td>
</tr>
<tr>
<td>PADP, mm Hg</td>
<td>13.7±4.5</td>
<td>12.6±2.9</td>
<td>0.245</td>
</tr>
<tr>
<td>PAWP, mm Hg</td>
<td>12.9±4.5</td>
<td>12.1±2.8</td>
<td>0.334</td>
</tr>
<tr>
<td>Cl, L·min⁻¹·m⁻²</td>
<td>3.5±0.9</td>
<td>4.4±1.0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>LVSVI, mL/m²</td>
<td>47±14</td>
<td>54±10</td>
<td>0.022</td>
</tr>
<tr>
<td>LVSWI, gm·m⁻²</td>
<td>55±18</td>
<td>62±14</td>
<td>0.082</td>
</tr>
<tr>
<td>SVRI, dyne·s·m⁻²·cm⁻⁵ per</td>
<td>2324±1055</td>
<td>1723±500</td>
<td>0.002</td>
</tr>
</tbody>
</table>

*Based on χ² tests for proportions or 2-tailed t tests for mean values. Variables with P<0.05 (shown in bold) were entered into a forward stepwise logistic regression model to identify significant independent predictors of symptomatic vasospasm.

performance (CI, LVSVI, and LVSWI) were elevated in our subjects on the first postoperative day (mean, 3.3 days after SAH), indicative of a volume-expanded and hyperdynamic cardiovascular state (Table 2). Others have reported similar findings in SAH patients treated with volume expansion,23,24,33 in contrast to patients with ischemic stroke, who have higher MABPs and lower cardiac outputs with equivalent cardiac filling pressures.34 Mean SVRI was slightly below the normal range in our patients, which may have resulted in part from the administration of nimodipine, a peripheral vasodilator.

CK-MB elevation was detected in half of our patients, and peak CK-MB fractions exceeded 2% in one fifth of patients, a finding consistent with previous studies.3-5 Abnormal left ventricular wall motion was slightly more common in our patients (13%, 9/72 patients) than in 3 other echocardiographic studies of SAH, which found a combined frequency of abnormal wall motion of 9% (17/184).11,14,15 All 9 patients with abnormal wall motion had widespread T-wave inversions and QT, prolongation (>440 ms) on at least 1 ECG, an association that we have previously reported.3 Wall motion was abnormal only in patients with peak CK-MB levels >2%, poor admission clinical grade (Hunt/Hess grade III to V), and female sex (all P<0.02). Others have also found significant associations between abnormal wall motion, poor neurological grade,11,14,15 and CK-MB elevation14,15 after SAH. The association of left ventricular dysfunction with female sex was of borderline significance but is in agreement with reports describing a striking preponderance of females among patients with abnormal wall motion after SAH (28/31 cases), for reasons unknown.11-15,35-38

Our main finding is the association of CK-MB release and abnormal left ventricular wall motion with impaired left ventricular hemodynamic performance. Indicators of left ventricular performance (LVSVI, LVSWI, and CI) were abnormally high in patients with no CK-MB release, and these measures fell progressively as the severity of cardiac injury increased (see the Figure). In patients with abnormal wall motion, mean LVSVI and LVSWI were well below the normal range, CI was at the lower limit of normal, and SVRI was highly elevated (all P<0.0001). PADP and PAWP were also increased in these patients, consistent with left ventricular failure. These results suggest that activation of the sympathetic nervous system after SAH typically results in a hyperdynamic cardiovascular state and that even small myocardial enzyme elevations reflect relative cardiac decompensation and failure of the left ventricle to meet these inotropic demands. By increasing afterload and further increasing the work of the heart, intense peripheral vasoconstriction may play a role in precipitating severe left ventricular decompensation with impaired contractility. Indeed, before the onset of hypotension and pulmonary edema, some of our patients with abnormal wall motion had severe hypertension and transient lactic acidosis attributed to massive peripheral vasoconstriction.13

Contraction band necrosis is the most likely cause of the wall motion abnormalities seen in our patients. This reversible form of cardiac pathology is found in up to 50% of patients with fatal SAH at autopsy4-8 and results from excessive exposure to catecholamines and cellular calcium entry, leading to a hypercontracted state.5,39 Impaired myocardial contractility related to contraction band necrosis occurs in animals after excessive cardiac sympathetic stimulation,40 and decompensation of the augmented cardiovascular hemodynamic response to SAH has been produced experimentally.41 Among the 9 patients with abnormal wall motion, peak CK-MB values were relatively small compared with the severity of left ventricular dysfunction, which may be characteristic of contraction band necrosis.3 Although previously asymptomatic coronary artery disease may have been present in some of our subjects, it is clear that coronary artery disease is not required to produce the pattern of myocardial injury seen in our patients. Normal coronary arteries have been found in the vast majority of SAH patients with left ventricular hypokinesia after SAH studied by angiography or autopsy.12-15,35-38

We identified severity of SAH on the admission CT scan (Fisher grade III or IV) and depressed CI measured on the first postoperative day as independent predictors of clinical deterior-
ration related to vasospasm. In addition to the extent of blood on CT, which is the most powerful determinant of symptomatic vasospasm,29,42–46 younger age,42 poor clinical grade,42,46 angiographic vasospasm,43 early surgery,43 treatment with antifibrinolytics,44,46 preexisting hypertension,43 and cigarette smoking45 have been previously identified as risk factors for delayed ischemia after SAH. Larger studies that account for all of these variables are required to determine the relative importance of baseline cardiovascular hemodynamic status as a risk factor for symptomatic vasospasm.

The retrospective design, relatively small sample size, and lack of a control group are limitations of this study. Because we required early determination of CK-MB levels, placement of a PAC, echocardiography, and no preexisting cardiac disease, we obtained data in only 68% (72/106) of potentially eligible subjects admitted to our neuro-ICU during the 2.5-year study period. Our inclusion criteria may have led to selection bias and overrepresentation of patients with acute cardiac disturbances. Analysis of a larger sample of consecutively studied subjects would determine more accurately the true frequency of left ventricular dysfunction after SAH, which may have been as low as 4.6% (9/192) during the study period. A control group of patients undergoing elective clipping of unruptured aneurysms would have been desirable, but invasive hemodynamic monitoring is not routinely performed in these patients. Nonetheless, we feel that these limitations do not invalidate our main findings.

In summary, we found that myocardial injury after SAH is associated with impaired left ventricular performance and that reduction of cardiac output in severely affected patients may increase the risk of delayed ischemia from vasospasm. Although we presume the pathogenesis of myocardial injury to be neurogenic in the majority of cases, regardless of cause, our results suggest that SAH patients with significantly reduced cardiac output at baseline may benefit from prophylactic hemodynamic augmentation to minimize the risk of developing delayed cerebral ischemia. Further research is required to confirm the relationship between myocardial injury and impaired hemodynamic performance found in our study and to determine the optimal treatment of cardiac injury in acute SAH.

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References
22. Wijdicks EFM, Vermeulen M, Hijdra A, van Gijn J. Hyponatremia and vasospasm,29,42–46 younger age, 42 poor clinical grade, 42,46 angio-


