Detection and Elimination of Microemboli Related to Cardiopulmonary Bypass

Robert C. Groom, MS, CCP; Reed D. Quinn, MD; Paul Lennon, MD; Desmond J. Donegan, MD; John H. Braxton, MBA, MD; Robert S. Kramer, MD; Paul W. Weldner, MD; Louis Russo, MD; Seth D. Blank, MD; Angus A. Christie, MD; Andreas H. Taenzer, MD; Richard J. Forest, CCP; Cantwell Clark, MS, MD; Janine Welch, MS, CCP; Cathy S. Ross, MS; Gerald T. O’Connor, PhD, ScD; Donald S. Likosky, PhD; for the Northern New England Cardiovascular Disease Study Group

Background—Neurobehavioral impairment is a common complication of coronary bypass surgery. Cerebral microemboli during cardiopulmonary bypass (CPB) are a principal mechanism of cognitive injury. The aim of this work was to study the occurrence of cerebral embolism during CPB and to evaluate the effectiveness of evidence-based CPB circuit component and process changes on the exposure of the patient to emboli.

Methods and Results—M-Mode Doppler was used to detect emboli in the inflow and outflow of cardiopulmonary circuit and in the right and left middle cerebral arteries. Doppler signals were merged into a single display to allow real-time associations between discrete clinical techniques and emboli detection. One hundred sixty-nine isolated coronary artery bypass grafting (CABG) patients were studied between 2002 and 2008. There was no statistical difference in median microemboli detected in the inflow of the CPB circuit, (Phase I, 931; Phase II, 1214; Phase III, 1253; Phase IV, 1125; F [3,158]=0.8, P=0.96). Significant changes occurred in median microemboli detected in the outflow of the CPB circuit across phases, (Phase I, 702; Phase II, 572; Phase III, 596; Phase IV, 85; F [3,157]=13.1, P<0.001). Significant changes also occurred in median microemboli detected in the brain across phases, (Phase I, 604; Phase II, 429; Phase III, 407; Phase IV, 138; F [3,153]=14.4, P<0.001). Changes in the cardiopulmonary bypass circuit were associated with an 87.9% (702 versus 85) reduction in median microemboli in the outflow of the CPB circuit (P<0.001), and a 77.2% (604 versus 146) reduction in microemboli in the brain (P<0.001).

Conclusions—Changes in CPB techniques and circuit components, including filter size and type of pump, resulted in a reduction in more than 75% of cerebral microemboli. (Circ Cardiovasc Qual Outcomes. 2009;2:191-198.)

Key Words: surgery ■ cardiopulmonary bypass ■ cerebrovascular circulation ■ embolism ■ coronary disease

Approximately 427,000 patients undergo open heart surgery every year in the United States.1 Cardiopulmonary bypass (CPB) is commonly used to provide circulatory support during these procedures. Neurological injury subsequent to heart surgery was first reported in 1954 and was attributed to stress and psychoses related to the procedure.2 Gilman in 1965, in a series of patients undergoing open heart procedures using cardiopulmonary bypass, postulated an organic origin stemming from reduced cerebral blood flow owing to microemboli.3 Subsequent research, including that from our group, continues to implicate microemboli as the principal mechanism of neurological injury.4-11 These injuries may include strokes (incidence 1.3% to 4.3%)12 or more prevalent neurobehavioral injuries (incidence 50% at discharge, 24% at 6 months, and 42% at 5 years).13

Whereas some emboli are generated as a result of manipulating the heart and great vessels,14 or the reinfusion of unprocessed shed blood from the surgical field,15-16 the leading source of emboli during surgery is from the cardiopulmonary bypass circuit.17 Gaseous microemboli may enter the cardiopulmonary bypass circuit from cannulation sites at the surgical field and subsequently be infused into the patient’s arterial circulation through the outflow of the cardiopulmonary bypass (CPB) circuit.18,19 Additional sources of gaseous microemboli include the administration of medications into the circuit17,20 or drawing blood samples...
from the circuit.\(^{17,20,21}\) Numerous studies have shown that CPB systems are not capable of completely removing these microemboli.\(^{8,22,23}\) The detection of microemboli requires sophisticated monitoring modalities, such as Doppler ultrasonography, and as such may not be readily available to the surgical team during the major parts of the operation.\(^{24,25}\)

We used a continuous neurological and systemic monitoring system to prospectively study microemboli in the CPB circuit and in the brain during coronary artery bypass grafting (CABG) surgery. We evaluated the effectiveness of the CPB circuit, subsequent to evidence-based changes to the circuit or changes in techniques, in mitigating microemboli delivery to the patient.

**Methods**

**Study Model**

A monitoring system was designed capable of providing real time associations between discrete clinical events/techniques and the detection of microemboli in the CPB circuit and the middle cerebral arteries.\(^{19}\) Blood flow velocity and microemboli were recorded every 8 milliseconds in the cerebral arteries and the inflow and outflow of the CPB circuit, using Doppler ultrasound (TCD 100 mol/L). Digital Transcranial Power M-Mode Doppler [Spencer Technologies, Figure 2].\(^{24}\) A tripod mounted digital video camera was aimed at the surgical field to record audio and video signals of surgical events and technique.

A video was created that synchronized outputs from the Doppler signal of the cerebral arteries and cardiopulmonary bypass circuit (CPB), as well as the surgical video (Figure 2). Images were combined onto one screen in real time using a video splitting device (Keywest Technology).

**Data Collection**

Our protocol received approval from the Institutional Review Board, and written informed consent was received before enrolling patients into the study.

We enrolled 169 patients between the age of 40 and 89 years undergoing isolated CABG procedures between October 2002 and January 2008. A data form was used to collect intraoperative variables. This data were supplemented with the Northern New England Cardiovascular Disease Study Group’s (NNECDGS) cardiac surgery registry. The NNECDGS (http://www.nnecdsg.org/) is a regional collaborative composed of 8 medical centers in northern New England. These centers collaborate with the goal of improving care of patients with cardiovascular disease. Our definitions for variables have previously been reported.\(^{25}\) All authors had full access to the data and take responsibility for its integrity. All authors have read and agree to the manuscript as written.

**Method of Conducting Cardiopulmonary Bypass**

**Management**

Venous drainage consisted of either gravity or augmented siphon from a 35-cm height differential from the right atrium to the inlet of a rigid polycarbonate venous reservoir. A multiple stage single venous cannula was used. Arterial blood return was returned to the ascending aorta with either a 7- or 8-millimeter diameter soft-flow arterial perfusion cannula (Terumo Cardiovascular). Myocardial protection was accomplished with either intermittent cold or continuous warm blood cardioplegia delivered antegrade (via the aortic root) or retrograde (via the coronary sinus) or both. Anticoagulation was accomplished by administering 4 milligrams of heparin per kilogram of body weight as a loading dose. Activated clotting times (ACT) were measured, and additional heparin was delivered as needed to maintain the ACT above 480 seconds. Mean arterial blood pressure during CPB was maintained between 55 mm Hg and 75 mm Hg. The perfusion flow rate was maintained between 2.2 to 2.6 L/min/M\(^2\) to maintain a mixed venous oxygen saturation of greater than 60%. Phenylephrine was used to increase and nitroglycerin or isoflurane to decrease the arterial blood pressure during CPB. A continuous online blood gas monitor (CDI 500, Terumo Cardiovascular Inc) was used to maintain Alpha-Stat blood gas strategy and for surveillance of oxygenation. The CPB system consisted of a hollow fiber membrane oxygenator, an open venous reservoir, and SMARXt coated tubing (The Sorin Group). A Cell Saver device was used to collect and process blood shed from the surgical field. (Hemoretics Corporation).

**Improvement Plan**

Our underlying philosophy for improvement was based on the model previously described by Batalden and colleagues (Figure 1).\(^{26}\) This model involves providing both generalizable evidence from the published literature and also context knowledge to the multidisciplinary team as a catalyst for improvement. We disseminated generalizable knowledge gleaned from the peer-reviewed literature concerning the association between CPB circuit design and microemboli. Context knowledge related to emboli was obtained from our intensive monitoring model and was also made available to the team for analysis and discussion. To that end we studied the generalizable evidence related to neurological injury associated with cardiac surgery and context knowledge about the performance of our system relative to microembolic activity (supplemental Table I). The published evidence and data concerning effectiveness of changes made to the circuit in reducing microemboli (context knowledge) were disseminated to members of the multidisciplinary team at monthly staff meetings, at our regional NNECDGS meetings held 3 times per year, and at regional and national conferences. We used statistical process control charts to display the effectiveness and to monitor the sustainability of the change in our system. Our expectation was that using such a strategy would provide us with ample opportunities for gaining grassroots interest and momentum for reducing microembolic activity during CPB.

A timeline of changes made to the CPB circuit components is described in Table 1.

During Phase I (10/2002 to 4/2004), we conducted the observational portion of the study. Phase II (4/2004 to 12/2005) consisted of the development of our quality improvement group. Additionally, our team stopped initiating CPB with an empty venous line. Our team began discussing findings from each monitored case before leaving the operating room during Phase III (12/2005 to 12/2006). Our team developed and implemented a series of changes during Phase IV (12/2006 to 1/2008), including a smaller pore arterial line filter, a venous reservoir with a smaller pore size integrated screen filter, and a centrifugal pump (incorporated at the end of 2007; previous phases used a nonocclusive roller pump).

During Phases I-III, the CPB circuit consisted of a nonocclusive roller pump, 40-micron arterial line filter and an Optima XP oxygenator (The Sorin Group). This oxygenator used a 105-micron venous reservoir sock. During Phase IV, the CPB circuit consisted of a 27-micron arterial line filter and a PrimO2x oxygenator (The Sorin Group). The PrimO2x oxygenator used a 30-micron venous reservoir.
screen filter. The pump used during the latter half of Phase IV was a Revolution centrifugal blood pump (The Sorin Group).

Statistical Analysis

All analyses were performed using the STATA 10.0 program (Stata Corporation).27 Comparisons between time points and conduct of CPB were assessed using $\chi^2$ tests, and continuous variables with Student t test and Wilcoxon Rank Sum. Microemboli were log-transformed to achieve a near normal distribution. We tested the association between microemboli detected in the circuit and Phase through a linear regression analysis, adjusting for both patient age and sex. We repeated this analysis with the dependent variable being microemboli detected in the brain.

Results

Table 2 displays pre-, intra-, and postoperative characteristics for the 169 individuals enrolled in the study. We stratified these characteristics by Phase of the study, and found no statistically significant differences. Half of the patients had mild aortic disease. The rate of neurological injury (stroke or transient ischemic attack) or mortality was low, as would be expected given enrollment of 169 patients.

There was no statistical difference in microemboli detected in the inflow of the CPB circuit, (Phase I, 931; Phase II, 1214; Phase III, 1253; Phase IV, 1125; F [3, 158] = 0.8, $P$ = 0.96). Significant changes occurred in median microemboli detected in the outflow of the CPB circuit across phases, (Phase I, 702; Phase II, 572; Phase III, 596; Phase IV, 85; F [3, 157] = 13.1, $P$ < 0.001). Significant changes also occurred in median microemboli detected in the brain across phases, (Phase I, 604; Phase II, 429; Phase III, 407; Phase IV, 138; F[3, 153] = 14.4, $P$ < 0.001). Significant reductions in microemboli in the outflow of the CPB circuit and brain were attributed primarily to Phase IV (Figures 3 and 4).

At the beginning of Phase II, modifications were made to the conduct of CPB among cases using controlled vacuum assisted venous drainage. During our observational phase, we noted that there was a trend toward higher levels of microemboli in the inflow of CPB among cases using an empty (mean, 1702; median, 1329) versus primed (mean, 666; median, 598) venous line, $P$ = 0.08. Subsequently, the venous line was primed before the onset of CPB among cases using VAVD. The target median VAVD pressure during CPB was modified during this first phase of the study. During Phase I, 68% of cases using VAVD had higher levels of vacuum (more than $-20$ mm Hg), 53% during Phase II, 25% during Phase III, and 55% during Phase IV ($P$ = 0.05). Our observation of the effect of high vacuum exacerbating inflow emboli

<table>
<thead>
<tr>
<th>Phase</th>
<th>Quality Improvement Workgroup</th>
<th>Discuss Findings of Case Prior to Leaving Operating Room</th>
<th>Method of Venous Drainage</th>
<th>Degree of Vacuum</th>
<th>Arterial Line Filtration</th>
<th>Oxygenator</th>
<th>Pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>No</td>
<td>No</td>
<td>Primed or dry</td>
<td>Target $-40$ mm Hg</td>
<td>40-$\mu$m</td>
<td>105-$\mu$m venous reservoir screen sock</td>
<td>Roller</td>
</tr>
<tr>
<td>II</td>
<td>Yes</td>
<td>No</td>
<td>Primed</td>
<td>Target $-20$ mm Hg</td>
<td>40-$\mu$m</td>
<td>105-$\mu$m venous reservoir screen sock</td>
<td>Roller</td>
</tr>
<tr>
<td>III</td>
<td>Yes</td>
<td>Yes</td>
<td>Primed</td>
<td>Target $-20$ mm Hg</td>
<td>40-$\mu$m</td>
<td>105-$\mu$m venous reservoir screen sock</td>
<td>Roller</td>
</tr>
<tr>
<td>IV</td>
<td>Yes</td>
<td>Yes</td>
<td>Primed</td>
<td>Target $-20$ mm Hg</td>
<td>27-$\mu$m</td>
<td>30-$\mu$m venous reservoir screen filter</td>
<td>Roller and centrifugal</td>
</tr>
</tbody>
</table>

Table depicts time intervals where process were changed or components to the CPB circuit were changed.
prompted our minimizing the amount of vacuum used to a level no higher than necessary to achieve adequate decompression of the right atrium. Overall, the use of either a 27-micron arterial line filter or 30-micron venous reservoir sock (versus their larger pore counterparts) was associated with an 84% reduction in median outflow microemboli over the course of all phases (579 versus 95, \( P < 0.001 \)). Within Phase IV, the use of a centrifugal pump (n = 7) was associated with an 86% (95 versus 13, \( P < 0.02 \)) reduction in outflow microemboli, relative to changes in arterial line filter and oxygenator.

Over the course of the entire study, changes in the cardiopulmonary bypass circuit were associated with an 87.9% (702 versus 85) reduction in median microemboli in the outflow of the CPB circuit (\( P < 0.001 \)), and a 77.2% (604 versus 146) reduction in microemboli in the brain (\( P < 0.001 \)).

### Discussion

There is a growing body of evidence implicating the pernicious nature of microemboli occurring during heart surgery. We sought to reduce the occurrence of microemboli using a 2-fold strategy that involved clinical application of knowledge gained from the published work of others with a robust model for monitoring and contextualizing microembolic activity in the CPB circuit and brain. Although numerous clinical studies have documented microemboli during surgery, our study further contextualized microembolic activity enhancing our understanding of cerebral emboli emanating from the CPB circuit and those related to surgical technique. Through this approach, we were able to assess the effectiveness of changes in technique and technology aimed at reducing microembolic activity. Our initiatives to redesign the cardiopulmonary bypass circuit through both clinical

### Table 2. Pre-, Intra-, and Postoperative Characteristics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Phase I (n=35)</th>
<th>Phase II (n=60)</th>
<th>Phase III (n=37)</th>
<th>Phase IV (n=37)</th>
<th>( P ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preoperative</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age in years, mean (SD)</td>
<td>64 (11)</td>
<td>66 (9)</td>
<td>67 (12)</td>
<td>64 (9)</td>
<td>0.25</td>
</tr>
<tr>
<td>Female, %</td>
<td>20</td>
<td>20</td>
<td>14</td>
<td>14</td>
<td>0.75</td>
</tr>
<tr>
<td>Diabetes, %</td>
<td>29</td>
<td>37</td>
<td>41</td>
<td>32</td>
<td>0.73</td>
</tr>
<tr>
<td>Vascular disease, %</td>
<td>14</td>
<td>22</td>
<td>27</td>
<td>24</td>
<td>0.60</td>
</tr>
<tr>
<td>BMI,* mean (SD)</td>
<td>29 (6)</td>
<td>31 (5)</td>
<td>29 (5)</td>
<td>29 (4)</td>
<td>0.50</td>
</tr>
<tr>
<td>( \geq 3 ) Distal anastomoses</td>
<td>89</td>
<td>90</td>
<td>84</td>
<td>84</td>
<td>0.75</td>
</tr>
<tr>
<td>Aortic disease†‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None, %</td>
<td>44</td>
<td>75</td>
<td>53</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Mild, %</td>
<td>50</td>
<td>75</td>
<td>53</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>Moderate, %</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Severe, %</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Not studied, %</td>
<td>6</td>
<td>11</td>
<td>3</td>
<td>5</td>
<td>0.89</td>
</tr>
<tr>
<td>Renal failure or creatinine</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>( \geq 2 ) mg/dl, %</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Priority, %</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elective</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Urgent</td>
<td>96</td>
<td>94</td>
<td>92</td>
<td>94</td>
<td>0.18</td>
</tr>
<tr>
<td><strong>Intraoperative</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump time in minutes, mean (SD)</td>
<td>108 (26)</td>
<td>108 (27)</td>
<td>104 (26)</td>
<td>108 (37)</td>
<td>0.01</td>
</tr>
<tr>
<td>Clamp time in minutes, mean (SD)</td>
<td>65 (25)</td>
<td>65 (22)</td>
<td>64 (18)</td>
<td>67 (24)</td>
<td>0.09</td>
</tr>
<tr>
<td><strong>Postoperative</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of stay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation date to discharge, mean (SD)</td>
<td>6 (2)</td>
<td>7 (6)</td>
<td>8 (7)</td>
<td>6 (2)</td>
<td>0.24</td>
</tr>
<tr>
<td>Admission date to discharge, mean (SD)</td>
<td>9 (5)</td>
<td>10 (8)</td>
<td>11 (8)</td>
<td>11 (6)</td>
<td>0.59</td>
</tr>
<tr>
<td>Intensive care unit, mean (SD)</td>
<td>31 (30)</td>
<td>34 (30)</td>
<td>50 (53)</td>
<td>33 (31)</td>
<td>0.26</td>
</tr>
<tr>
<td>Extubation time in hours, mean (SD)</td>
<td>6 (5)</td>
<td>7 (9)</td>
<td>10 (14)</td>
<td>8 (10)</td>
<td>0.60</td>
</tr>
<tr>
<td>( \geq 2 ) inotropes at 48 hours (%)</td>
<td>3</td>
<td>2</td>
<td>8</td>
<td>3</td>
<td>0.31</td>
</tr>
<tr>
<td><strong>Neurologic injury</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TIA or stroke, %</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Atrial fibrillation, %</td>
<td>14</td>
<td>22</td>
<td>24</td>
<td>22</td>
<td>0.75</td>
</tr>
<tr>
<td>In-hospital mortality, %</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0.33</td>
</tr>
</tbody>
</table>

* kg/m². † By epiaortic echocardiography updated October 6, 2008.

Table depicts intraoperative and postoperative patient characteristics.
Process and circuit redesign resulted in an 87.9% reduction in microemboli detected in the outflow of the CPB circuit, and a 77.2% reduction in microemboli detected in the cerebral arteries. Ultimately changes in the CPB circuit lowered the CPB outflow count presently to below the cerebral microemboli count. This latter observation suggests the greatest remaining opportunity for reducing cerebral microemboli is through the redesign of processes of surgical care.

Although both gravity venous drainage and VAVD may result in gaseous entrainment through cannulation sites and other incisions in the heart, the risk may be somewhat greater with VAVD, because it uses a higher negative pressure and exacerbates air entrainment. The difference in degree of air entrainment was the focus of previous in vitro investigations. In response to this data, our clinical team made the evidence-based changes shown in supplemental Table I over the course of the study. We consistently observed microemboli entrained into the venous line that was subsequently introduced into the patient’s arterial circulation. This observation was particularly evident during the onset of CPB and during the introduction of the coronary sinus catheter for retrograde cardioplegia solution, even when attempts were made to fill the heart to prevent microemboli entrainment during this maneuver. To prevent microemboli during the onset of CPB, the venous line of the circuit was fluid filled during cases using VAVD sporadically during Phase I, and consistently from Phase II through Phase IV. Without priming the venous line, air within the venous cannula will be delivered to the arterial circulation in a bolus manner. Additional changes included reducing the lower limit of VAVD pressure required to drain the right atrium and maintain suitable conditions for revascularization.

To prevent any remaining microemboli from being delivered to the patient, we coupled our efforts at redesigning the conduct of CPB with the redesign of our circuit components. The newer circuit (Phase IV) incorporates a 30-micron venous reservoir screen filter and 27-micron arterial line filter. This reduced pore size where the blood enters the oxygenator resulted in substantial reduction in the outflow emboli. Standards for blood oxygenators promulgated by the Association for the Advancement of Medical Instrumentation do not set forth performance characteristics for blood oxygenators or reservoirs with regard to microemboli. Consequently manufacturers are not required to comply with a...
benchmark nor do they provide performance characteristics of their products to their customers with regard to microemboli handling. Dickinson compared the effectiveness of manufacturers circuits in an in vitro study model and reported variation in circuit performance related to microemboli handling. The authors did not disclose the model or manufacturer of the circuits tested. A reduction in the pore size of the arterial line filter, the last opportunity for microemboli removal before blood returning to the patient, appeared in Phase IV to prevent most of the microemboli from the venous circulation from traveling to the patient (as evidenced by a statistically significant drop in outflow microemboli without a concurrent change in inflow microemboli during Phase IV). More recently, Riley assessed the pressure drop and filtration efficiency of arterial line filters. This work showed that, generally, smaller pore size resulted in improved filtration of microemboli. Exceptions included the Pall LeukoGuard-6 Leukocyte Reduction Arterial Blood Filter, a 40-micron arterial line filter, which performed similarly to a 20-micron filter with regard to microemboli elimination.

Although we are pleased with our present findings, we cannot rule out whether other circuit component changes would be as effective as those used in the current report. Additionally, our data does not allow us to identify which changes in circuit design and components were most effective at reducing microemboli load to the patient. Nonetheless, our findings suggest that the greatest reduction in microemboli leaving the outflow of the CPB circuit was attributed to Phase IV of our study.

In the current study, additional reductions in microemboli from the CPB circuit were realized through the use of a centrifugal pump. A number of studies have compared centrifugal and roller pumps in relation to microemboli generation, inflammatory markers, and clinical outcomes. Reductions in microemboli likely occur through minimization of gaseous microemboli through its cyclic flow of blood relative to the potential generation and entrapment of gaseous microemboli through negative pressure and cavitation in a roller pump. In a small trial by Wheeldon and colleagues, significantly less microemboli generation, less complement activation, and better preservation of platelet count was observed in patients randomized to a centrifugal pump. Scott identified more neurobehavioral test deficits among the roller pump group, however this difference did not reach statistical significance. A study of 3438 consecutive patients revealed that the use of the centrifugal pump showed a trend toward risk reduction for adverse neurological events. Randomized trials with neurological measures as a primary outcome variable, however, have not demonstrated significant differences in neurobehavioral outcomes or tissue-level markers of brain injury (S100 beta) between types of CPB pumps. In the largest randomized trial, Klein and colleagues assigned 1000 adult cardiac patients to management with a roller pump or a centrifugal pump, with reductions in blood loss, renal function, and neurological outcome demonstrated in the centrifugal group.

Neurological injuries, predominantly embolic in origin, are unwanted sequellae of CABG surgery. The source of microemboli may be eliminated in most cases by the redesign of the cardiopulmonary bypass circuit. The changes appear to substantially reduce microemboli delivered to the patient while at the same not appreciably increasing the cost of delivering care. Changes in the CPB circuit have lowered the CPB outflow count presently to below the cerebral microemboli count. Subsequent work will focus on identifying the sources of these microemboli, which likely may be associated with aortic management techniques.

Reductions in microemboli have likely resulted in part through the feedback of data from our monitoring modalities. Modifications in circuit design and techniques for conducting cardiopulmonary bypass are made every day in operating rooms across this country. The assessment of their effectiveness in reducing adverse sequellae, such as emboli-handling ability, is at times inadequate. The collection of data concerning the principal mechanisms of brain injury, and subsequent feedback of information to the clinical team, has enabled our team to assess the effectiveness of our redesign initiatives.
Figure 4 demonstrates that while improving our ability to minimize gaseous microemboli returning to the patient from the cardiopulmonary bypass circuit, there remains another source of microemboli: the aorta. These microemboli may be gaseous or particulate. The sources of the gaseous microemboli include entrained air and cavitation related to the arterial cannula. The release of particulate microemboli is likely related to aortic manipulation, especially secondary to aortic crossclamps, both partial and complete. Having minimized gaseous emboli from the CPB circuit, we can now focus on changes in processes of care to decrease the aortic microemboli sources. Aortic manipulation using a partial occlusion clamp has been associated with cerebral microemboli.\(^8\) Aortic cannulae insertion technique and carefully deairing the aorta when necessary will likely further reduce the cerebral microembolic count. An aortic arterial cannula with side holes and lower exit velocity, such as the one used in this study, may reduce embolization from the sand-blasting effect characterized by open end hole arterial microemboli.\(^37\)

This study model has provided us with the requisite knowledge necessary to realize significant reduction in microembolic activity. Our strategic use of generalizable evidence from the literature, and modifications of the CPB circuit based on information about the timing and source of microemboli, resulted in a significant and sustainable reduction in the exposure of CABG patients to cerebral microemboli.

Acknowledgments
The authors acknowledge Norma Albrecht for her assistance with manuscript preparation and Catherine LaVopa, RN for assistance coordinating this study. Equipment used for this study was loaned by Spencer Technologies (Seattle, Wash), and Terumo Cardiovascular Systems Inc (Tustin, Calif). The authors thank Dr Gerald T. O’Connor for his steadfast support and guidance on this project.

Sources of Funding
Dr Likosky was supported by a grant from the Agency for Healthcare Research and Quality (1K02HS015663-01A1). Equipment used for this study was loaned by Spencer Technologies (Seattle, Wash), and Terumo Cardiovascular Systems Inc (Tustin, Calif). Sorin Group (Arvada, Colo) provided an unrestricted grant to support study-related expenses. Somanetics Corporation (Troy, Mich) provided funds to support a research coordinator. This work was partially funded by Cardiovascular Systems, Inc (Tustin, Calif). Sorin Group (Arvada, Colo) provided an unrestricted grant to support study-related expenses. None.

Disclosures
None.

References