Contemporary Analysis of Descending Thoracic and Thoracoabdominal Aneurysm Repair
A Comparison of Endovascular and Open Techniques

Roy K. Greenberg, MD; Qingsheng Lu, MD; Eric E. Roselli, MD; Lars G. Svensson, MD, PhD; Michael C. Moon, MD; Adrian V. Hernandez, MD, MSc, PhD; Joseph Dowdall, MD; Marcelo Cury, MD; Catherine Francis, BS; Kathryn Pfaff, BS; Daniel G. Clair, MD; Kenneth Ouriel, MD; Bruce W. Lytle, MD

**Background**—Endovascular repair of thoracic aneurysm has demonstrated low risks of mortality and spinal cord ischemia (SCI), but few large series have been published on endovascular thoracoabdominal aneurysm repair, and reports suffer from a lack of accurate comparison with similar open surgical procedures.

**Methods and Results**—A consecutive cohort of patients with thoracic and thoracoabdominal aneurysms treated electively with endovascular repair (ER) or surgical repair (SR) techniques between 2001 and 2006 were analyzed. The association between repair technique and SCI was evaluated with univariable analysis. Adjustments for potential confounders and for the propensity to receive ER or SR were also performed in multivariable analysis. A total of 724 patients (352 ER, 372 SR) underwent repair. The mean age was 67 years, and 65% were male. ER patients were on average 9 years older ($P<0.001$), had more comorbid conditions, and more frequently had prior distal repair ($P<0.001$) or underwent a type I or IV repair. SR patients more commonly had chronic dissection or required type II or type III repairs ($P<0.001$). Mortality at 30 days (5.7% ER versus 8.3% SR, $P=0.2$) and 12 months (15.6% ER versus 15.9% SR, $P=0.9$) was similar. A borderline difference in SCI was found between repair techniques: 4.3% of ER and 7.5% of SR patients ($P=0.08$) had SCI. In patients with ER, prior distal aortic operation was associated with the development of SCI in univariable analysis (odds ratio 4.1, 95% confidence interval 1.4 to 11.7). Multivariable analysis showed that the type of required repair (type I, II, III, or IV) was the primary factor associated with the development of SCI in ER and SR patients.

**Conclusion**—No significant difference in the incidence of mortality or SCI was found between ER and SR techniques. The strongest factor associated with SCI remains the extent of the disease. Further studies are indicated to compare ER with patients considered eligible for SR.

(Circulation. 2008;118:808-817.)

**Key Words:** spinal cord ischemia ■ stents ■ aorta ■ aneurysm ■ aneurysm, dissecting

Surgical intervention, endovascular treatment, and continued medical management constitute the 3 treatment options for patients with thoracic or thoracoabdominal aneurysms. Treatment is advocated primarily to prevent rupture, yet the potential for spinal cord ischemia (SCI) and respiratory, renal, and cardiovascular complications, including death, as a result of treatment exists and may discourage patients and physicians from pursuing anatomic correction by any intervention. Refinements in surgical techniques and the use of a variety of adjunctive measures for spinal cord protection have decreased but not eliminated the risk of SCI.2,4,6–13 Endovascular repair (ER) has been applied to the treatment of thoracic aneurysms to decrease the risk and magnitude of periprocedural complications, thus expanding the patient population considered eligible for anatomic treatment.14 The possible benefits of ER strategies include avoidance of major thoracic or thoracoabdominal incisions and aortic cross-clamping, limitation of blood loss, decreased perioperative pain, diminished respirator dependency, and diminished incidence of visceral, renal, and spinal cord ischemia.15

**Clinical Perspective p 817**

A relatively low risk of death and paraplegia after ER (1.6% to ≈3%) has been reported; however, these studies were performed on selected patient populations with disease limited to the thoracic aorta. Only recently have alternatives to conventional open surgery been described for extensive

---

Continuing medical education (CME) credit is available for this article. Go to http://cme.ahajournals.org to take the quiz.

Received February 1, 2008; accepted June 10, 2008.

From The Cleveland Clinic Foundation, Cleveland, Ohio.

Drs Greenberg and Lu contributed equally to this work.

Correspondence to Roy K. Greenberg, MD, Cleveland Clinic, 9500 Euclid Ave, Desk S40, Cleveland, OH 44195. E-mail greenbr@ccf.org

© 2008 American Heart Association, Inc.

Circulation is available at http://circ.ahajournals.org

DOI: 10.1161/CIRCULATIONAHA.108.769695

808
aneurysms involving the thoracoabdominal segments. These strategies include the use of extra-anatomic bypass followed by total aortic relining with stent grafts, as well as endovascular repair with branched grafts.20–24

The criteria used to recommend ER, surgical repair (SR), and medical management vary among institutions and physicians depending on patient characteristics and physician familiarity with or availability of repair techniques. The effectiveness of each strategy has been the subject of comparison studies for isolated thoracic aneurysms but have been confounded by differing patient-related variables. The purpose of the present study was to detail the characteristics and outcomes of patients treated for thoracic and thoracoabdominal aneurysms at a single institution where both ER and SR techniques were used.

Methods

A retrospective review of all patients treated between January 1, 2001, and July 31, 2006, who underwent elective open SR or ER of descending thoracic or thoracoabdominal aneurysms was conducted. Patients with aortic rupture or acute dissection and others who underwent emergent operation were excluded. Medical records and radiographic information were reviewed to determine the operative indications, demographic and comorbid information, procedural techniques, complications, and outcomes. Preoperative and postoperative imaging studies were retrieved digitally and analyzed with multiplanar reconstructions and centerline of flow measurement techniques on a workstation (TeraRecon Inc, San Francisco, Calif) using 3-dimensional (3D) image analysis techniques to assess the aortic morphology. Informed consent was established for all patients, and those enrolled into an investigational treatment signed a consent form approved by our institutional review board.

Patient Groups

ER patients underwent implantation of stent grafts with branches to the visceral arteries when necessary (Figure 1), as an isolated procedure, in concert with more distal open surgical procedures (access-related procedures and, uncommonly, infrarenal aneurysm repair), or in a staged fashion to complete a prior proximal repair (such as an elephant trunk graft procedure). Patients treated with mesenteric extra-anatomic bypass followed by aortic relining were not included in the present analysis but were subjected to a separate review.20 Chronic dissection patients were included only if the indication for aortic repair was aneurysmal dilation. A significant number of patients treated with endovascular grafts were participants in clinical research trials; in such cases, they signed an informed consent form approved by our institutional review board. Three types of commercially manufactured endografts, including Zenith (Cook Inc, Bloomington, Ind), TAG (W.L. Gore, Flagstaff, Ariz), and Talent (Medtronic, Santa Rosa, Calif), were used to repair aneurysms. Circulatory adjuncts used during SR varied in accordance with the extent of the repair and physician preferences. Very few patients in the present series underwent circulatory arrest procedures (single-stage arch procedures were excluded), and the majority of extensive aneurysms (types I, II, and III) were treated with the use of some circulatory adjunct (partial left-heart bypass, octopus perfusion technique, or axillary-femoral bypass along with segmental aortic clamping). Whenever possible, intercostal arteries were reimplanted with a patch or bypass technique. Spinal drainage was used with both open surgical and endovascular patients at the discretion of the treating physician. In general, all patients who underwent extensive aortic replacement (type I, II, and III repairs), in addition to those with prior distal aortic repairs, particularly in the setting of compromised pelvic circulation, had spinal drainage catheters inserted preoperatively. The protocol for drainage involved an initial pressure measurement followed by continuous drainage to pressure equivalent to 10 cm H2O, which was begun during or at the conclusion of the procedure. The maximum hourly drainage allowed before capping varied between physicians (range 30 mL/h to no limit).

Classification of Extent of Aneurysmal Disease

All ER and most SR patients underwent postprocedure cross-sectional imaging studies, which were then evaluated on a 3D workstation with multiplanar and centerline of flow reconstructions to calculate the extent of the required repair. In the absence of postprocedure imaging for SR patients, the operative notations were substituted. The Crawford classification system25,26 was used to
**Table 1. Definitions of Types of Repair**

<table>
<thead>
<tr>
<th>Type</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Aortic repair distal to the left common carotid artery terminating above the diaphragm</td>
</tr>
<tr>
<td>I</td>
<td>A repair distal to the left common carotid artery to beyond the diaphragmatic border to above the renal arteries (with or without reimplantation of the mesenteric vessels)</td>
</tr>
<tr>
<td>II</td>
<td>Aortic repair distal to the left common carotid artery, proximal to the 6th intercostal space, to a region below the renal arteries (requiring reimplantation of the visceral segment)</td>
</tr>
<tr>
<td>III</td>
<td>An aortic repair originating distal to the 6th intercostal space but above the diaphragm terminating below the renal arteries</td>
</tr>
<tr>
<td>IV</td>
<td>A repair originating below the diaphragm and above the renal arteries terminating below the renal arteries</td>
</tr>
</tbody>
</table>

The definitions in this table were applied universally to ER and SR patients to determine the extent of aneurysm repair.

categorize the aortic disease (0 to IV; Table 1) on the basis of the extent of the aortic repair. Prior aortic procedures were recorded as proximal if they occurred proximal to the left common carotid artery or distal when they were caudal to the planned repair (carotid-subclavian bypasses were not considered prior proximal procedures).

**Neurological Assessment**

Each patient’s neurological status was evaluated and classified as “deficit” or “no deficit” and then further categorized according to a previously described neurological deficit scoring system (Table 2). Deficits present on awakening from anesthesia and within 24 hours of the procedure were considered “immediate,” whereas those that occurred after a normal postoperative examination were termed “delayed.” For each patient with a deficit, the lowest score was used to categorize the deficit, regardless of the degree or rate of any subsequent improvement.

**Mortality**

In addition to medical records, the Social Security death index was used to supplement mortality results. Deaths were categorized as those that occurred within 30 days of the surgery, within 12 months, or later during follow-up. Data on circumstances of each death were collected when available.

**Statistical Analysis**

Demographic and periprocedural characteristics are shown as mean±SD or number and percentage. Comparisons between repair techniques were made with t tests for continuous variables and with χ2 test for categorical variables. Univariable logistic regression models assessed the effect of demographic and periprocedural characteristics on mortality and the presentation of SCI. Multivariable logistic regression models examined the association between repair technique and SCI, with adjustment for other patient characteristics. These analyses were performed overall and stratified by repair technique.

In addition, propensity score analyses were performed. This technique employed a logistic regression model that was built with type of repair technique as the dependent variable and several patient characteristics as independent variables (extent of aneurysm repair, age, gender, race, smoking, diabetes mellitus, coronary artery dis-
ease, chronic obstructive pulmonary disease, cancer, glomerular filtration rate, aortic diameter, dissection, history of proximal aortic surgery, and history of distal aortic surgery). The score derived from this model ranges from 0 to 1 (the closer to 1, the higher the odds of the patient receiving ER), a number that was then used in 2 separate multivariable models that have been demonstrated as the best ways to adjust for propensity score29: (1) A logistic model that included both the repair technique and the propensity scores and (2) a logistical model that included repair technique, a selected group of variables (extent of aneurysm repair, age, gender, diabetes mellitus, coronary artery disease, aortic diameter, dissection, history of proximal aortic surgery, and history of distal aortic surgery), and the propensity scores.

Strength of associations are shown as odds ratio (OR) and 95% confidence interval (CI). Kaplan-Meier analyses were conducted to estimate survival rates between the repair techniques groups, and differences were tested with the log-rank test. Mortality rates are expressed as estimates determined from life-table analyses and cases per person-year. In all cases, a probability value \( p < 0.05 \) was considered significant. All analyses were performed with SAS version 9.1 (SAS Inc, Cary, NC) and S-Plus 6.1 (Insightful Corp, Seattle, Wash).

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

### Results

A total of 724 patients underwent repair over the 5-year study period. The mean age was 67±12 years; 65% of the patients were male. Patients treated with ER were on average 8.6 years older (71.3±12 versus 62.7±13 years, \( p < 0.001 \)) than those treated with an SR, but no gender differences between repair types were found. Our bias has been to treat patients who are younger or have fewer comorbid factors with conventional surgery, a tendency that is readily reflected in the preoperative patient characteristics (Table 3). The average aneurysm diameter was 6.2 cm for SR and 6.3 cm for ER groups (\( p = 0.9 \)). ER was more commonly used to treat aneurysms limited to the supradiaphragmatic and infradiaphragmatic aorta (types 0 and IV), whereas open repair was more frequently used to treat type II and III thoracoabdominal

### Table 4. Mortality and SCI Classified by Extent of Aneurysmal Disease

<table>
<thead>
<tr>
<th>Extent</th>
<th>Repair Technique</th>
<th>n</th>
<th>n</th>
<th>%*</th>
<th>Rate†</th>
<th>n</th>
<th>%*</th>
<th>Rate†</th>
<th>SCI</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>ER</td>
<td>163</td>
<td>8</td>
<td>5</td>
<td>0.62</td>
<td>20</td>
<td>12</td>
<td>0.14</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SR</td>
<td>136</td>
<td>8</td>
<td>4</td>
<td>0.73</td>
<td>15</td>
<td>11</td>
<td>0.13</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>ER</td>
<td>82</td>
<td>6</td>
<td>7</td>
<td>0.94</td>
<td>15</td>
<td>19‡</td>
<td>0.25</td>
<td>8</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SR</td>
<td>51</td>
<td>1</td>
<td>2</td>
<td>0.24</td>
<td>2</td>
<td>4</td>
<td>0.04</td>
<td>7</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>ER</td>
<td>16</td>
<td>1</td>
<td>6</td>
<td>0.80</td>
<td>5</td>
<td>36</td>
<td>0.45</td>
<td>3</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SR</td>
<td>59</td>
<td>10</td>
<td>17</td>
<td>2.36</td>
<td>13</td>
<td>22</td>
<td>0.30</td>
<td>13</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>ER</td>
<td>22</td>
<td>2</td>
<td>9</td>
<td>1.16</td>
<td>7</td>
<td>34</td>
<td>0.52</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SR</td>
<td>62</td>
<td>8</td>
<td>12</td>
<td>1.68</td>
<td>13</td>
<td>21</td>
<td>0.27</td>
<td>6</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>ER</td>
<td>69</td>
<td>3</td>
<td>4</td>
<td>0.55</td>
<td>8</td>
<td>12</td>
<td>0.18</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SR</td>
<td>64</td>
<td>4</td>
<td>6</td>
<td>0.80</td>
<td>16</td>
<td>22</td>
<td>0.30</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>ER</td>
<td>352</td>
<td>20</td>
<td>6</td>
<td>0.72</td>
<td>55</td>
<td>16</td>
<td>0.21</td>
<td>15</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SR</td>
<td>372</td>
<td>31</td>
<td>7</td>
<td>1.07</td>
<td>59</td>
<td>15</td>
<td>0.19</td>
<td>28</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

*Kaplan-Meier estimate.
†Incidence rates are defined as deaths per person-year.
‡Statistically significant difference between ER and SR with log-rank test.
aneurysms. Chronic dissections were more frequently treated with open surgery (113 SR versus 44 ER, \( P < 0.001 \)).

**Mortality**

Survival by repair technique is shown in Figure 2. The 30-day mortality rate was 8.3% in SR and 5.7% in ER patients (\( P = 0.2 \)). No intraoperative deaths occurred in the present series. One-year mortality rates were 15.9% and 15.6%, respectively, for SR and ER (\( P = 0.9 \); Table 4).

**Spinal Cord Injury**

The proportion of patients who developed SCI is shown in Figure 3. Spinal cord injury was detected in 15 ER patients (4.3%) and 28 SR patients (7.5%; log-rank \( P = 0.08 \)). The repair technique used was not associated with the presentation of SCI in the univariable analysis (OR 0.55, 95% CI 0.3 to 1.0), multivariable analysis (OR 0.56, 95% CI 0.3 to 1.3), after adjustment for a selected group of variables and the propensity score (OR 0.56, 95% CI 0.2 to 1.3), or after adjustment for the propensity scores alone (OR 0.66, 95% CI 0.3 to 1.4). In contrast, the extent of the required aneurysm repair was strongly associated with the development of SCI regardless of statistical adjustments (Table 5). In both groups, the occurrence of spinal cord injury was highest for type II aneurysms, followed by types I, III, and then IV, with the lowest incidence noted for patients with isolated thoracic aneurysms (type 0, <1%; Table 4). The severity of the SCI (paraplegia versus paraparesis) and the potential for recovery did not differ between treatment modalities (Table 6). SCI was more commonly noted immediately after SR (29% versus 13%) and in a delayed presentation (up to 6 days) after ER; however, the differences were not statistically significant (\( P = 0.2 \); Fisher exact test). No cases of SCI with ER for chronic dissections occurred; however, SCI occurred in 11 (10%) of 113 chronic dissection patients treated with SR. Univariable analysis suggested that this observation was significant, yet differences in the extent of aneurysm treated were marked, which precluded any definitive conclusions (Table 7). The only other finding of significance that arose from the univariable analysis was the association of prior distal aortic operations with the development of SCI (\( P = 0.004 \)) in ER patients (Table 8).

**Ruptures and Conversions**

No ruptures in SR or ER patients occurred during follow-up. Furthermore, no conversions from ER to SR occurred, with the exception of a single patient who had a persistent proximal endoleak after ER. This patient was treated with an open surgical anastomosis of the proximal endograft to the arch under hypothermic circulatory arrest. Three patients required endovascular graft placement during SR to control anastomotic bleeding, but they were analyzed with the SR group.

**Discussion**

Complications after surgical and endovascular repair of thoracic and thoracoabdominal aneurysms are potentially devastating and multifactorial in origin.\(^2\) The link between SCI and death is clear,\(^1\) and several factors contribute to the development of SCI.\(^26,32\) In spite of the numerous strategies designed to ameliorate the risk,\(^1,2,4,7–12,26\) even at centers of excellence, SCI still occurs in up to 11.4% of patients.\(^6–9,12\) Statewide Medicare data analysis noted an alarmingly high mortality risk after SR that approached 20% at 30 days and 31% at 12 months.\(^33\) The most important factor that contributes to surgical risk is the extent of the aneurysmal disease, which implies a relationship between risk and the magnitude of the required repair procedure.\(^1,2,6\) The less-invasive nature of an endovascular approach is intended to diminish the magnitude of the repair by limiting incisions to the groin, avoiding aortic cross-clamping, and minimizing perioperative end-organ ischemia, blood loss, fluid shifts, and insult to the cardiac and respiratory system.

Prior studies have contrasted ER patients with SR patients treated either on a concurrent or historical basis.\(^16,34,35\) The Gore TAG study noted a lower perioperative mortality (2.1% versus 11.7%) and incidence of SCI (3% versus 14%) for patients treated with ER. Complications such as renal insufficiency and respiratory failure were also less frequent in ER patients, whereas peripheral vascular complications and reinterventions were more commonly noted for ER patients.\(^16,34\)
### Table 5. Association Between Patient Characteristics and SCI in the Overall Population

<table>
<thead>
<tr>
<th>Patient Characteristics</th>
<th>SCI Univariable</th>
<th></th>
<th></th>
<th>Multivariable</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes (n=43)</td>
<td>No (n=681)</td>
<td>OR 95% CI</td>
<td>P</td>
<td>OR 95% CI</td>
<td>P</td>
</tr>
<tr>
<td>Repair technique, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Endovascular</td>
<td>35</td>
<td>49</td>
<td>0.6 0.3–1.0</td>
<td>0.06</td>
<td>0.6 0.3–1.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Open surgery</td>
<td>65</td>
<td>51</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Age, y, mean±SD</td>
<td>66.6±13</td>
<td>66.9±13.2</td>
<td>0.97 0.7–1.4</td>
<td>0.9</td>
<td>1.1 0.6–1.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Gender, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>74</td>
<td>64</td>
<td>1.7 0.8–3.3</td>
<td>0.2</td>
<td>1.7 0.8–3.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Female</td>
<td>26</td>
<td>36</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Race, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black</td>
<td>7</td>
<td>9</td>
<td>0.8 0.2–2.6</td>
<td>0.7</td>
<td>0.7 0.2–2.7</td>
<td>0.6</td>
</tr>
<tr>
<td>White</td>
<td>93</td>
<td>91</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Smoking, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>67</td>
<td>57</td>
<td>1.6 0.8–3.0</td>
<td>0.2</td>
<td>1.6 0.8–3.6</td>
<td>0.2</td>
</tr>
<tr>
<td>No</td>
<td>33</td>
<td>43</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Diabetes mellitus, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>5</td>
<td>9</td>
<td>0.5 0.1–2.2</td>
<td>0.4</td>
<td>0.6 0.1–2.5</td>
<td>0.4</td>
</tr>
<tr>
<td>No</td>
<td>95</td>
<td>91</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>CAD, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>51</td>
<td>41</td>
<td>1.5 0.8–2.8</td>
<td>0.2</td>
<td>1.0 0.5–2.0</td>
<td>0.9</td>
</tr>
<tr>
<td>No</td>
<td>49</td>
<td>59</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>History of COPD, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>14</td>
<td>23</td>
<td>0.5 0.2–1.3</td>
<td>0.2</td>
<td>0.5 0.2–1.3</td>
<td>0.1</td>
</tr>
<tr>
<td>No</td>
<td>86</td>
<td>77</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>History of cancer, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>12</td>
<td>11</td>
<td>1.1 0.4–2.9</td>
<td>0.9</td>
<td>0.7 0.3–2.2</td>
<td>0.6</td>
</tr>
<tr>
<td>No</td>
<td>88</td>
<td>89</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>BMI (mean±SD)*</td>
<td>27.3±5.7</td>
<td>27.2±8.4</td>
<td>1 0.8–1.3</td>
<td>0.9</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>GFR (mean±SD)</td>
<td>68.5±42.1</td>
<td>72.3±28.9</td>
<td>0.9 0.6–1.2</td>
<td>0.4</td>
<td>0.9 0.6–1.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Aortic diameter, cm (mean±SD)</td>
<td>6.6±1.2</td>
<td>6.2±1.3</td>
<td>1.3 1.0–1.8</td>
<td>0.07</td>
<td>1.1 0.7–1.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Extent of aneurysm repair, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>5</td>
<td>44</td>
<td>1 ...</td>
<td>&lt;0.0001</td>
<td>1 ...</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>I</td>
<td>35</td>
<td>17</td>
<td>18.9 4.3–83.8</td>
<td>...</td>
<td>19.2 4.2–87.8</td>
<td>...</td>
</tr>
<tr>
<td>II</td>
<td>37</td>
<td>9</td>
<td>40.3 9.0–179.9</td>
<td>...</td>
<td>31.8 6.9–147.5</td>
<td>...</td>
</tr>
<tr>
<td>III</td>
<td>16</td>
<td>11</td>
<td>13.5 2.8–66.3</td>
<td>...</td>
<td>9.2 1.8–48.1</td>
<td>...</td>
</tr>
<tr>
<td>IV</td>
<td>7</td>
<td>29</td>
<td>3.4 0.6–20.8</td>
<td>...</td>
<td>2.3 0.3–14.9</td>
<td>...</td>
</tr>
<tr>
<td>Chronic dissections, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>26</td>
<td>21</td>
<td>1.3 0.6–2.6</td>
<td>0.5</td>
<td>1.1 0.5–2.8</td>
<td>0.8</td>
</tr>
<tr>
<td>No</td>
<td>74</td>
<td>79</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>History of surgery for proximal aorta, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>28</td>
<td>24</td>
<td>1.2 0.6–2.4</td>
<td>0.6</td>
<td>0.9 0.4–1.9</td>
<td>0.71</td>
</tr>
<tr>
<td>No</td>
<td>72</td>
<td>76</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>History of surgery for distal aorta, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>37</td>
<td>21</td>
<td>2.2 1.2–4.3</td>
<td>0.01</td>
<td>2.0 1.0–4.2</td>
<td>0.07</td>
</tr>
<tr>
<td>No</td>
<td>63</td>
<td>79</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

CAD indicates coronary artery disease; COPD, chronic obstructive pulmonary disease; BMI, body mass index; and GFR, glomerular filtration rate.

*BMI was not included in the multivariable model owing to a high proportion of missing data (27%).
Stone and colleagues \(^3\) published a retrospective comparison of 74 ER and 83 SR patients with degenerative nonruptured aneurysms. Similar patterns of complications, including perioperative mortality (8.1% ER versus 9.6% SR), SCI (10.4% ER versus 7.2% SR), and stroke (11.9% ER versus 6% SR), were observed between ER and SR patients. However, both the series by Stone et al\(^3\) and the TAG study\(^4\) involved patients with repairs limited to the descending thoracic aorta; patients with aneurysms involving the aortic arch (proximal to the left subclavian artery) and aneurysms abutting or involving the visceral segment were excluded. In addition, the relatively strict anatomic characteristics for proximal and distal landing zones required for ER patients caused inherent disparity between patient groups. Others have reported that unfavorable morphology of proximal and distal landing zones is the most common reason to preclude an ER\(^3\). However, in such cases, SR may be entertained.

In the present series, the uniformity of the retrospective method by which both SR and ER patients were classified provides a means of comparing factors that relate to the anatomic extent of the disease. The availability of branched endografts allowed for either treatment option to be used for most degenerative aneurysms, although our practice evolved during this 5-year period. The portions of aneurysms that involved the aorta proximal to the left common carotid artery and aneurysms abutting or involving the visceral segment were excluded. In addition, the relatively strict anatomic characteristics for proximal and distal landing zones required for ER patients caused inherent disparity between patient groups. Others have reported that unfavorable morphology of proximal and distal landing zones is the most common reason to preclude an ER\(^3\); however, in such cases, SR may be entertained.

### Table 6. Timing of SCI Presentation

<table>
<thead>
<tr>
<th></th>
<th>Open Repair (N=372)</th>
<th>ER (N=352)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immediate SCI (&lt;1 d)</td>
<td>8 (29%)</td>
<td>2 (13%)</td>
</tr>
<tr>
<td>Delayed SCI (≥1 d)</td>
<td>20 (71%)</td>
<td>13 (87%)</td>
</tr>
<tr>
<td>Total</td>
<td>28 (63%)</td>
<td>15 (48%)</td>
</tr>
</tbody>
</table>

\(P=0.2\) for difference of immediate SCI between open and endovascular groups (Fisher exact test).

### Table 7. Univariable Association of Patient Characteristics and SCI, Stratified by Repair Technique

<table>
<thead>
<tr>
<th>Patient Characteristic</th>
<th>ER OR 95% CI</th>
<th>SR OR 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>1.6 (0.6–4.0)</td>
<td>1.6 (0.6–4.0)</td>
</tr>
<tr>
<td>Gender (male/female)</td>
<td>1.5 (0.5–4.8)</td>
<td>1.5 (0.5–4.8)</td>
</tr>
<tr>
<td>Black race</td>
<td>0.9 (0.1–7.4)</td>
<td>0.9 (0.1–7.4)</td>
</tr>
<tr>
<td>Smoking</td>
<td>2.6 (0.7–9.3)</td>
<td>2.6 (0.7–9.3)</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>1.2 (0.3–5.7)</td>
<td>1.2 (0.3–5.7)</td>
</tr>
<tr>
<td>CAD</td>
<td>1.1 (0.4–3.2)</td>
<td>1.1 (0.4–3.2)</td>
</tr>
<tr>
<td>History of COPD</td>
<td>0.4 (0.1–1.6)</td>
<td>0.4 (0.1–1.6)</td>
</tr>
<tr>
<td>History of cancer</td>
<td>0.5 (0.1–3.7)</td>
<td>0.5 (0.1–3.7)</td>
</tr>
<tr>
<td>GFR</td>
<td>0.5 (0.2–1.0)</td>
<td>0.5 (0.2–1.0)</td>
</tr>
<tr>
<td>Aortic diameter</td>
<td>1.4 (0.9–2.3)</td>
<td>1.4 (0.9–2.3)</td>
</tr>
<tr>
<td>Extent of aneurysm repair</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I vs 0</td>
<td>21.5 (2.6–142.6)</td>
<td>17.5 (2.2–142.6)</td>
</tr>
<tr>
<td>II vs 0</td>
<td>37.4 (3.6–385.1)</td>
<td>37.4 (3.6–385.1)</td>
</tr>
<tr>
<td>III vs 0</td>
<td>7.7 (0.5–128.0)</td>
<td>7.7 (0.5–128.0)</td>
</tr>
<tr>
<td>IV vs 0</td>
<td>4.8 (0.4–54.2)</td>
<td>4.8 (0.4–54.2)</td>
</tr>
<tr>
<td>Chronic dissections</td>
<td>0.0008 *</td>
<td>0.0008 *</td>
</tr>
<tr>
<td>History of surgery for proximal aorta</td>
<td>1.2 (0.3–4.3)</td>
<td>1.2 (0.3–4.3)</td>
</tr>
<tr>
<td>History of surgery for distal aorta</td>
<td>1.4 (1.4–11.7)</td>
<td>1.4 (1.4–11.7)</td>
</tr>
</tbody>
</table>

CAD indicates coronary artery disease; COPD, chronic obstructive pulmonary disease; and GFR, glomerular filtration rate.

*Broad and nonsignificant CI.

The evolution of ER devices to treat these complicated patients occurred throughout the time period of the present review and continues today. Rapid advances in device development and procedural techniques create difficulties when one attempts to contrast newer approaches with a standard of care. In spite of the availability of the first commercialized device midway through the present series (May 2003) to treat thoracic aneurysms, ER repair for aneurysm that involved the visceral vessels was clearly not an established, broadly disseminated technology. The use of such devices remains investigational in the United States (although it is now commercialized in Europe, Australia, and Canada), and several design iterations occurred throughout the present series. The frequent improvements that were made to the implants and delivery systems relegated event-experienced interventionalists to a continuous, steep learning curve with respect to device design, implantation techniques, and follow-up paradigms. Yet, there exist some fundamental skills for all forms of branched endografting, which can be underscored. Proper design techniques mandate the ability for clinicians to use 3D workstations to generate centerline of flow analyses and interpret multiplanar reconstructions. The mechanical construct of the aortic prostheses in the present series had side branches or reinforced fenestrations to preserve critical side branches (mesenteric and renal vessels), which have both been described previously in detail. An understanding of the fundamental engineering issues with the variety of modular joints, constructs of the mating stent grafts, and methods by which they can be deployed is imperative. Finally, the ability to
TABLE 8. Multivariable Association of Patient Characteristics and SCI, Stratified by Repair Technique

<table>
<thead>
<tr>
<th>Patient Characteristic</th>
<th>SR OR 95% CI</th>
<th>ER OR 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>1.0 0.5–2.1</td>
<td>1.2 0.3–4.7</td>
</tr>
<tr>
<td>Gender (male/female)</td>
<td>1.5 0.6–4.3</td>
<td>1.3 0.3–6.2</td>
</tr>
<tr>
<td>Black race</td>
<td>0.7 0.1–3.7</td>
<td>0.6 0.03–1.3</td>
</tr>
<tr>
<td>Smoking</td>
<td>1.3 0.5–3.3</td>
<td>3.3 0.7–1.7</td>
</tr>
<tr>
<td>Diabetes</td>
<td>0.002 *</td>
<td>1 0.17–6.1</td>
</tr>
<tr>
<td>CAD</td>
<td>1.4 0.6–3.6</td>
<td>0.5 0.1–1.7</td>
</tr>
<tr>
<td>History of COPD</td>
<td>0.6 0.2–2.1</td>
<td>0.2 0.04–1.2</td>
</tr>
<tr>
<td>History of cancer</td>
<td>1.1 0.3–4.1</td>
<td>0.3 0.03–2.6</td>
</tr>
<tr>
<td>GFR</td>
<td>1.2 0.7–2.2</td>
<td>0.4 0.2–9.0</td>
</tr>
<tr>
<td>Aortic diameter</td>
<td>0.9 0.6–1.5</td>
<td>1.6 0.7–3.2</td>
</tr>
<tr>
<td>Extent of aneurysm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>repair</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I vs 0</td>
<td>26.5 2.9–242.1</td>
<td>20 2.2–181.3</td>
</tr>
<tr>
<td>II vs 0</td>
<td>38.8 4.8–317.4</td>
<td>14.1 1.1–188.6</td>
</tr>
<tr>
<td>III vs 0</td>
<td>14.3 1.5–133.6</td>
<td>2.6 0.1–54.8</td>
</tr>
<tr>
<td>IV vs 0</td>
<td>1.8 0.1–32.5</td>
<td>2.6 0.2–35.8</td>
</tr>
<tr>
<td>Chronic dissections</td>
<td>1.3 0.5–3.7</td>
<td>0.0009 *</td>
</tr>
<tr>
<td>History of surgery</td>
<td>0.8 0.3–2.1</td>
<td>1 0.2–5.3</td>
</tr>
<tr>
<td>for proximal aorta</td>
<td></td>
<td></td>
</tr>
<tr>
<td>History of surgery</td>
<td>1.8 0.6–5.6</td>
<td>3 0.8–1.2</td>
</tr>
<tr>
<td>for distal aorta</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CAD indicates coronary artery disease; COPD, chronic obstructive pulmonary disease; and GFR, glomerular filtration rate.

*Broad and nonsignificant CI.

work in 3 dimensions during implantation procedures that use standard angiographic (2-dimensional) imaging is important to ensure proper longitudinal and rotational device orientation.

Shortcomings of branched endovascular repair include the lack of dissemination of the technology, limited long-term follow-up, and the considerable delay related to the manufacturing of customized devices. Many of these factors have precluded the application of ER in urgent situations. In an effort to overcome some of these limitations, a number of clinicians have described hybrid procedures, such as extra-anatomic (mesenteric) bypasses followed by aortic relining with thoracic stent graft devices. However, reported series quote mortality rates of up to 20% with this technique, along with several other types of complications that are analogous to those with conventional SR. We excluded all patients treated with mesenteric bypasses at our institution from the present analysis and have reported them elsewhere. Currently, such procedures are very uncommon and are reserved primarily for the unusual patient with contraindications to both SR and branched ER.

Despite the similarities in overall outcome, observations on subgroup analyses should be noted. Prior distal aortic repair that preceded ER increased the risk of SCI development, as has been suggested by other authors. The explanation likely relates to the loss of lumbar arteries that provide collateral spinal cord perfusion in concert with the lateral sacral artery and internal iliac artery. The subsequent disruption of segmental thoracic intercostals that occurs during ER may place these patients at higher risk for SCI. In contrast, the presence of a prior distal aortic procedure was not associated with SCI after SR, likely because of the benefit of reimplantation of intercostals. These observations have caused us to carefully consider the use of ER in patients with prior distal repairs, particularly in the presence of compromised internal iliac circulation. In a number of cases in the SR group (after 2004), internal iliac branched grafts were used in concert with visceral branch devices to maintain antegrade pelvic blood flow. The absence of SCI after the ER of aneurysms with aortic dissections was also noted; however, most patients with aneurysmal dilation and chronic aortic dissections had limited distal aortic involvement. This may be related to a selection bias rather than constituting a true relationship. The timing of SCI onset differed between groups. All but 2 SCI cases occurring after ER were delayed (13/15, 93%), in contrast to the development of immediate deficits in 29% of patients with SCI after SR, yet the differences were not statistically significant (P=0.2). These data are concordant with previously published ER series that noted the vast majority of SCI occurs in a delayed manner after ER. Most cases of delayed SCI were also associated with hypotension or other complications manifested by failure of at least 1 other organ system. Evidence of recovery after SCI deficits between the 2 groups in the present study was equivalent. In spite of the similar outcomes, the general treatment paradigm used at our institution is to treat healthier, younger patients with SR and older less fit patients with ER. The use of ER in healthier, younger patients may be appealing in that the minimally invasive approach would presumably be associated with fewer complications, yet we remain hesitant to wholeheartedly endorse this concept in the absence of longer-term follow-up data.

Several questions are raised by the observations in the present report. The risk of death and paraplegia for the repair of extensive and complex aneurysms in the present series is clearly lower than that cited in Crawford’s original series, but the absolute risk to patients with type II aneurysms remains high. When an individual patient is treated, these risks must always be balanced against the risk of rupture of untreated aneurysms. These considerations are also reflected in our practice. Prior reports of subsets of these data noted a maximal aneurysmal diameter of 77 mm for type I, II, and III aneurysms, whereas type IV aneurysms were on average 66 mm, and aneurysms isolated to the descending thoracic aorta were slightly smaller than that. As the risks of the procedure have diminished, the size threshold at which the clinician and patient agree on a repair strategy diminishes.

The vast majority of the endovascular devices used in the present study were not commercially available in the United States but were used in the context of a physician-sponsored investigational device exemption study. The available data on costs are not reflective of what a device might cost after approval. Throughout the study, several technique refinements occurred. We observed a marked decrease in the amount of intra-arterial contrast and radiation exposure over the 5 years of implantation. The availability of a longer mating stent graft has eliminated many modular joints and limited the number of required implants per case. All of these factors further support the concept that the technology has not
reached a plateau and make it considerably difficult to attempt to determine projected costs for broadly used, minimally invasive treatment of extensive aortic aneurysms.

Although the optimal method to compare SR and ER treatments of complex aortic aneurysms would be the construction of a prospective randomized trial, several limitations to such a design exist. Many patients are not considered to be surgical candidates and thus are not eligible for randomization. To include such patients would require the creation of registry arms that would allow for the treatment of high-risk patients. Alternatively, a medical treatment arm could be created and patients randomized to medical therapy versus ER when deemed unfit for surgical resection. Such a trial design closely resembles the EndoVascular Aneurysm Repair (EVAR) trials,50 which have become the subject of significant criticism. Additional challenges include the need for a large number of patients and broadly disseminated endovascular skills and the rapid technological improvements that occur for branched endovascular devices. Consequently, we are currently relegated to series such as the present one in which both techniques were used, irrespective of the extent of the anatomic disease, in concert to treat a complex group of patients who remain at high risk of complications.

Conclusions

Similar outcomes with respect to mortality and SCI exist between open and endovascular repair of thoracic and thoracoabdominal aneurysms when evaluated in the context of the extent of the repair despite the greater prevalence of sicker and older patients treated with ER. The extent of the aneurysmal disease overshadowed other potential risk factors for SCI, with type II aneurysm patients most at risk, followed by types I, III, IV, and 0. SCI was more likely to manifest early after SR than ER, but the potential for recovery from the injury was similar between groups.

Disclosures

Dr Greenberg receives research support and an intellectual property license from Cook Inc; he also receives research support from W.L. Gore, Boston Scientific, and TeraRecon Inc. Dr Roselli is a consultant and speaker for Cook Inc and Medtronic. K. Pfaff is a paid consultant for Cook Inc. Dr Clair is a consultant for Medtronic, Cordis, and Boston Scientific and receives research support from W.L. Gore. The remaining authors report no conflicts.

References

Numerous comparisons have been conducted between open and endovascular repair of aortic lesions; however, in nearly all reports, with the exception of the prospective randomized trials involving infrarenal abdominal aortic aneurysm, significant anatomic differences exist between groups. The present contemporary comparison of 724 consecutive patients treated with open surgical repair. On the basis of the observations of this study, it is clear that endovascular repair of extensive aneurysms is feasible and capable of producing results similar to open surgical techniques, even in more physiologically challenged patients.
Contemporary Analysis of Descending Thoracic and Thoracoabdominal Aneurysm Repair: A Comparison of Endovascular and Open Techniques

Roy K. Greenberg, Qingsheng Lu, Eric E. Roselli, Lars G. Svensson, Michael C. Moon, Adrian V. Hernandez, Joseph Dowdall, Marcelo Cury, Catherine Francis, Kathryn Pfaff, Daniel G. Clair, Kenneth Ouriel and Bruce W. Lytle

_Circulation_. 2008;118:808-817; originally published online August 4, 2008; doi: 10.1161/CIRCULATIONAHA.108.769695

_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231

Copyright © 2008 American Heart Association, Inc. All rights reserved.

Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:

http://circ.ahajournals.org/content/118/8/808

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in _Circulation_ can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:

http://www.lww.com/reprints

Subscriptions: Information about subscribing to _Circulation_ is online at:

http://circ.ahajournals.org//subscriptions/