Reoperative coronary artery bypass grafting (CABG) carries a greater morbidity and mortality than primary CABG due to the higher risk profile of reoperative CABG patients and the technical difficulty of reoperative CABG. Thoracic multidetector computed tomographic angiography (CTA) can identify high-risk features such as adherence or proximity of the right ventricle or aorta to the chest wall or bypass grafts crossing midline near (or adhered to) the sternum. The identification of these features allows modification of the surgical approach to include implementation of preventive surgical strategies (PSS: peripheral cardiopulmonary bypass, circulatory arrest, and nonmedian sternotomy). We sought to define the cost-effectiveness of CTA using a Markov model.

Methods and Results—We studied outcomes and costs of CTA and non-CTA strategies in a modeled cohort of 10,000 patients undergoing redo coronary artery bypass grafting. Rates of PSS implementation were anticipated to follow identification of risk by CTA. Transitions, costs, and utilities were informed by our experience and the literature. Sensitivity analyses included testing a range of costs of CTA and PSS on model outcome. In the reference case, cost and quality-adjusted life years accrued with the use of CTA ($74,869; 4.63 quality-adjusted life-years) were slightly higher than nonuse ($73,471; 4.59 quality-adjusted life-years), yielding an incremental cost-effectiveness ratio of $34,950/quality-adjusted life-years. Cost of PSS (equipment and operating time) was the most significant determinant of incremental cost-effectiveness ratio. In the reference case (cost of CTA =$300), identification and avoidance of potential procedural difficulties with CTA rendered it cost-effective if the cost of PSS was <$12,000. Across a range of CTA costs, incremental cost-effectiveness ratio was not materially influenced by outcomes across a broad range of imputed values.

Conclusions—The cost of CTA appears justified in the setting of isolated reoperative coronary artery bypass grafting, because it aids in appropriate selection of PSS. The cost-effectiveness of this imaging seems more influenced by the costs of subsequent PSS than by the cost of CTA. (Circ Cardiovasc Qual Outcomes. 2012;5:705-710.)

Key Words: cost-effectiveness • computed tomography (multidetector) • coronary artery bypass grafting
WHAT IS KNOWN

• Thoracic multidetector computed tomographic angiography (CTA) aids in the assessment of high-risk features to better guide the implementation of preventive surgical strategies in the setting of isolated reoperative coronary artery bypass grafting.

• The cost-effectiveness of using CTA in the setting of reoperative coronary artery bypass grafting is undefined.

WHAT THE STUDY ADDS

• A Markov model, using parameters of health states, utilities, and costs derived from the literature, indicated that CTA has an incremental cost-effectiveness ratio of $34,950 in the setting of isolated reoperative coronary artery bypass grafting, thus meeting accepted criteria for incremental cost-effectiveness.

• The incremental cost-effectiveness ratio of CTA in this setting is dependent on the cost of the preventive surgical strategies used, rather than the cost of CTA, with CTA incrementally cost-effective if preventive surgical strategies cost is <$12,000.

Health States and Transitions

Data on transitions between health states and outcomes were obtained from the literature, and assessed using weighted averages and SDs (Table 1). Differences in perioperative clinical outcomes, including mortality, myocardial infarction, stroke, and urgent reoperation have been defined in 2 studies that evaluated CTA in the setting of isolated reoperative CABG.4,5 The frequency of identification of high-risk features from CTA was assumed to parallel that reported in an existing registry of reoperative CABG patients.2 The presence of high-risk features was anticipated to prompt the use of PSS in a certain proportion of patients as delineated by the same registry.2 The employment of PSS in patients with low-risk CTA findings was assumed to translate into similar clinical outcomes as patients with low-risk CTA findings who did not merit PSS. Mortality related to perioperative complications was defined by literature pertaining specifically to mortality rates of urgent reoperation, myocardial infarction, and stroke after reoperative CABG.4,5 The mortality of patients without perioperative complications was as defined in a study of early and late outcomes after reoperative CABG.7 Mortality rates not defined annually were assumed to be linear and not to vary between cycle lengths for the duration of the model.

Health Outcomes Information

Information regarding health outcomes was obtained from the literature. Utility was age-adjusted, declining by 0.3% per year of age,11 and utility weights (Table 2) were multiplied by the duration in each health state to calculate QALYs.12–14 The utility weight of myocardial infarction was obtained from a large study that examined health burden associated with individual medical conditions.12 Utilities of stroke survivors vary widely; based on a comprehensive systematic review, we used a utility for disabling stroke derived from time trade-off and standard gamble methods.13 To our knowledge, the utility of patients after reoperative CABG, and those who have undergone urgent reoperation after reoperative CABG, have not been studied. We assumed the utility postreoperative CABG to be similar to that of postinital CABG.14 Patients suffering complications from urgent reoperation caused by complications of redo surgery (which are associated with failure to use PSS) have a high level of morbidity, especially due to heart failure, a condition which is associated with poor quality of life.12,15 Urgent reoperation would also translate into

Table 1. Transition Probabilities and Mortality Rates (±SD)

<table>
<thead>
<tr>
<th>Health State</th>
<th>CTA, %</th>
<th>No CTA, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perioperative mortality4,5</td>
<td>9.4±2.2</td>
<td>9.1±2.6</td>
</tr>
<tr>
<td>Myocardial infarction4,5</td>
<td>0.3±0.5</td>
<td>3.2±3.4</td>
</tr>
<tr>
<td>Stroke4,5</td>
<td>1.8±2.6</td>
<td>5.0±0.8</td>
</tr>
<tr>
<td>Urgent reoperation4,5</td>
<td>7.2±3.2</td>
<td>5.4±1.0</td>
</tr>
<tr>
<td>High-risk CTA</td>
<td>46</td>
<td>N/A</td>
</tr>
<tr>
<td>Preventive surgical strategies4</td>
<td>86</td>
<td>28</td>
</tr>
<tr>
<td>Annual mortality</td>
<td>86</td>
<td>28</td>
</tr>
<tr>
<td>Myocardial infarction8</td>
<td>2 y: 6.8</td>
<td></td>
</tr>
<tr>
<td>Stroke9</td>
<td>First y: 11±2</td>
<td>Subsequent y: 11±11</td>
</tr>
<tr>
<td>Urgent reoperation10</td>
<td>First y: 11</td>
<td>Subsequent y: 3.9±1.1</td>
</tr>
<tr>
<td>Postreoperative CABG2</td>
<td>5 y: 17.6±2.7</td>
<td></td>
</tr>
</tbody>
</table>

CTA indicates computed tomographic angiography; CABG, coronary artery bypass grafting; and N/A, not applicable.

Table 2. Utility Values for Each Health State

<table>
<thead>
<tr>
<th>Health State</th>
<th>Utility Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myocardial infarction12</td>
<td>0.70±0.03</td>
</tr>
<tr>
<td>Stroke13</td>
<td>0.46±0.01</td>
</tr>
<tr>
<td>Urgent reoperation12</td>
<td>0.66±0.04</td>
</tr>
<tr>
<td>Postreoperative CABG14</td>
<td>0.78±0.26</td>
</tr>
</tbody>
</table>

CABG indicates coronary artery bypass grafting.
a longer postoperative hospitalization, diminishing utility further in the short term. Given these assumptions, both figures were subject to sensitivity analysis.

### Cost Information

The analysis took the perspective of the healthcare provider and consequently used the amount reimbursed to the provider as the cost of care. Information regarding costs was obtained primarily from the literature, including diagnostic related groups, and Medicare payments for current procedural terminology codes (Table 3).17–21 The cost of CTA was obtained from a study evaluating the cost-effectiveness of CTA in assessing patients with chest pain in the emergency department.21 Given that CTA cost may differ given different protocols and indications for the imaging, it was subject to sensitivity analysis. Annual follow-up costs for patients with periprocedural myocardial infarction, stroke, and urgent reoperation were additive on the cost of follow-up after reoperative CABG. The cost of PSS has not been stated in the literature, but was estimated from experience at our institution, and included estimation of direct technical costs of anesthesia, surgical equipment, added operative time, and nursing. Costs could not be itemized beyond this estimated figure. Given this uncertainty regarding PSS cost, the value was subject to sensitivity analysis.

### Analyses

One-way sensitivity analyses were performed to identify the critical sources of variation in the input data. Probabilistic sensitivity analyses were performed from the Markov model using a Monte Carlo analysis. Beta distributions were assigned to probabilities and utility weights, and gamma distributions were assigned to costs on the basis of standard errors derived from the associated literature. Means and 95% credible intervals (95% confidence interval) for each of the posterior distributions were computed on the basis of 10,000 iterations. Meaningful increments in quality of life were based on previous studies. An incremental cost-effectiveness ratio of <$100,000/QALY gained was used as the willingness-to-pay threshold of acceptable cost-effectiveness. The net monetary benefit for a willingness-to-pay of $100,000 was evaluated in sensitivity analyses.

### Results

#### Health Outcomes and Costs of CTA

The use of CTA was associated with a lifetime QALY gain of 0.04 after adjustment and discounting (expected QALYs with and without CTA being 4.63 and 4.59, respectively). However, the lifetime cost with CTA use was higher than without CTA ($74,869 versus $73,471), yielding an incremental cost-effectiveness ratio of $34,950/QALY.

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### Table 3. Costs Associated with Each Health State

<table>
<thead>
<tr>
<th>Health State</th>
<th>Mean Cost (±SD Where Available)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CABG</td>
<td>$306.08</td>
</tr>
<tr>
<td>Redo CABG</td>
<td>$32,201±23,059</td>
</tr>
<tr>
<td>Myocardial infarction</td>
<td>$11,091±18,09</td>
</tr>
<tr>
<td>Stroke</td>
<td>$18,552</td>
</tr>
<tr>
<td>Urgent reoperation</td>
<td>$18,809</td>
</tr>
<tr>
<td>Preventive surgical strategies</td>
<td>$100,000±2,000</td>
</tr>
<tr>
<td>Perioperative mortality</td>
<td>$42,887±18,519</td>
</tr>
</tbody>
</table>

CTA indicates computed tomographic angiography; CABG, coronary artery bypass grafting.

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### Figure 2. Incremental cost-effectiveness plane for the computed tomographic angiography strategy from 10,000 simulations of the decision-analytic model. Ellipse represents 95% confidence interval. Line represents the willingness-to-pay with slope of $100,000/QALY (quality-adjusted life-years). Fifty-two percent of simulations lie below the willingness-to-pay.

### Monte Carlo Simulation

The distribution of simulated cost-effectiveness of the CTA strategy (Figure 2) show the majority of simulations (52%) within the 95% confidence ellipse as being under the willingness-to-pay slope. The spectrum of costs with CTA exceed that without CTA, as does the spectrum of benefit.

### Sensitivity Analyses

Threshold analyses were used to investigate the limits of transition probabilities, mortality rates, costs, and utilities that could influence the outcome of the model. Each factor was analyzed across a clinically plausible range. Cost of PSS was the only factor that drove net monetary benefit in favor of a particular strategy. As shown in the 1-way sensitivity analysis in Figure 3, if the cost of PSS remained below $12,000, the CTA strategy derived superior net monetary benefit. The cost of CTA had no influence on the superiority of a given strategy when varied across a broad range ($0–$20,000), as shown in the 1-way sensitivity analysis in Figure 4. The lack of influence CTA cost had over the model is further demonstrated in the 2-way sensitivity analysis depicted in Figure 5. Because CTA cost is

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### Figure 3. One-way sensitivity analysis evaluating net monetary benefits across a broad range of preventive surgical strategy (PSS) cost (cPreventive), given willingness-to-pay (WTP) of $100K. Net monetary benefit is higher with the use of computed tomographic angiography (CTA) if the cost of PSS is <$12K.
varied across a broad range, the particular threshold at which CTA derives superior net monetary benefit is largely driven by the cost of PSS.

Scenario Analysis
Given the results of the sensitivity analyses above, an additional scenario was examined that explored alternative rates of PSS in the setting of high- and low-risk CTA findings. Because PSS cost drives the cost-effectiveness of this imaging modality in the setting of reoperative CABG, the rate at which it is implemented might influence the cost-effectiveness as well. Figure 6 details the effects of modifying the rate at which PSS is used and the result on CTA cost-effectiveness. As shown in Figure 6A, the rate of PSS use with high-risk CTA findings does not impact the cost-effectiveness of CTA. Alternatively, as presented in Figure 6B, the rate of PSS used with low-risk CTA findings appears to modify cost-effectiveness of CTA (and render it not cost-effective) if PSS is used in >47% of cases with low-risk CTA findings.

Discussion
Reoperative CABG can be high risk due to potential procedural complications, which can be averted via identification of high-risk features on CTA and implementation of PSS, when warranted. In our decision-analytic model, the use of CTA in the setting of isolated reoperative CABG provided a small benefit in QALYs over noneuse, and although the lifetime cost with CTA use is slightly higher, the incremental cost-effectiveness ratio with CTA of $34,950/QALY appears to satisfy usual criteria of incremental cost-effectiveness. In our model, PSS cost was the sole driver of net monetary benefit. Thus, implementing PSS adds to the overall cost of reoperative CABG, and PSS should only be used when deemed necessary, a decision that is guided heavily, if not solely, by findings on CTA. In the reference case, when PSS cost was <$12,000, CTA use derived superior net monetary benefit. This finding is especially important given the small difference in QALYs (0.04) derived from CTA use versus no CTA use.

Use of Decision Analysis in Justifying the Plan of Care
Advances in cardiovascular imaging (in this case, CTA) are commonly adopted into care pathways on the basis of perceived need, without formal evaluation of cost-effectiveness. In this situation, the necessity for PSS is now largely defined by the identification of high-risk features on CTA. The benefits of CTA would now be difficult to study in a randomized trial, so a decision-analysis approach, with its ability to study variations in assumptions in sensitivity analyses, represents a reasonable option to define the benefit of the addition of CTA.

The calculation of incremental cost-effectiveness is only valid when benefit is identified. An increment of 0.04 QALY (2 additional weeks of life at full quality) is within the realm of what has been defined previously as a meaningful increment in survival, based on a difference in QALYs of >0.03 falling outside the 95% confidence intervals of reported utilities. In addition, net monetary benefit, which assigns monetary value to a unit of effectiveness that is then multiplied by the net number of units of effectiveness achieved, showed that the cost of CTA use was less than the value of the additional benefit achieved.

Model Assumptions
Assumptions regarding transition probabilities, outcomes, and costs are inherent in the modeling process, although they are largely informed by the literature. However, in our model, assumptions pertaining to transition probabilities (eg, the linear event rate assumed from nonlinear data), utilities (eg, the assumption of utility posturgent CABG being equivalent to that of heart failure), and costs (eg, the estimate of PSS cost from our institutional experience) were subject to sensitivity analyses. These values were studied across a broad range to determine the impact of these assumptions on model outcome. The only variable that had impact on net monetary benefit was PSS cost. The cost of PSS in our institution, which was estimated at $10,000, may be different at other institutions. However, our analysis provides a threshold at which to interpret...
this cost with regards to its impact on the incremental cost-effectiveness of CTA use.

Aside from limitations related to assumptions above, which have been largely addressed by sensitivity analyses, the transition probabilities used in our model were based on 2 studies in the literature that described outcomes of CTA use in cohorts undergoing reoperative CABG. These were retrospective studies, and although they compared well-matched study groups, the possibility of confounding, selection bias, and unmeasured variables should be considered. In addition, the implications of more frequent PSS use need to be studied further and are not clarified by the present analysis. Given that the cost-effectiveness of CTA in the setting of reoperative CABG is driven by the cost of PSS, it would be useful to study whether more frequent PSS use, at the surgeon's discretion, would be justified by the added costs associated with PSS. Our scenario analysis, which showed the influence of the rate of subsequent PSS on the cost-effectiveness of CTA, speaks to the clinical utility of CTA in reoperative CABG and the practicality of its use.

Conclusions

The use of CTA in the setting of isolated reoperative CABG appears to satisfy the standard criteria for cost-effectiveness. Most importantly, this Markov model demonstrates that cost of PSS is a more important driver of cost-effectiveness than the cost of CTA itself. In an era where the cost of imaging is coming under increasing scrutiny, decision analysis is a valuable means of understanding the cost and outcome implications of adding imaging tests to clinical protocols.

Disclosures

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Cost-Effectiveness of Computed Tomographic Angiography Before Reoperative Coronary Artery Bypass Grafting: A Decision-Analytic Model
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