Original Investigation

Value of Robotically Assisted Surgery for Mitral Valve Disease

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IMPORTANT

The value of robotically assisted surgery for mitral valve disease is questioned because the high cost of care associated with robotic technology may outweigh its clinical benefits.

OBJECTIVE

To investigate conditions under which benefits of robotically assisted surgery mitigate high technology costs.

DESIGN, SETTING, AND PARTICIPANTS

Clinical cohort study at a large multispecialty academic medical center comparing costs of robotically assisted surgery with 3 contemporaneous conventional surgical approaches for degenerative mitral valve disease. From January 1, 2006, through December 31, 2010, a total of 1290 patients with a mean (SD) age of 57 (11) years underwent mitral valve repair for regurgitation from posterior leaflet prolapse. Robotically assisted surgery was performed in 473 patients, complete sternotomy in 227, partial sternotomy in 349, and anterolateral thoracotomy in 241. Comparisons were based on intent to treat, with 3 propensity-matched groups formed based on demographics, symptoms, cardiac and noncardiac comorbidities, valve pathophysiologic disorders, and echocardiographic measurements: robotic vs sternotomy (198 pairs) vs partial sternotomy (293 pairs) vs thoracotomy (224 pairs).

INTERVENTIONS

Mitral valve repair.

MAIN OUTCOMES AND MEASURES

Cost of care (expressed as robotic capital investment, maintenance of equipment, and direct technical hospital costs) and benefit of care (based on differences in recovery time).

RESULTS

Cost of care (median [15th and 85th percentiles]) for robotically assisted surgery exceeded that of alternative approaches by 26.8% (–5.3% and 67.9%), 32.1% (–6.1% and 69.6%), and 20.7% (–2.4% and 48.4%) for complete sternotomy, partial sternotomy, and anterolateral thoracotomy, respectively. Higher operative costs were partially offset by lower postoperative costs and earlier return to work: a median (15th and 85th percentiles) of 35 (19 and 63) days for robotically assisted surgery, 49 (21 and 109) days for complete sternotomy, 56 (30 and 199) days for partial sternotomy, and 42 (18 and 90) days for anterolateral thoracotomy. Resulting net differences (median [15th and 85th percentiles]) in the cost of robotic surgery vs the 3 alternatives were 15.6% (–14.7% and 55.1%), 15.7% (–19.4% and 51.2%), and 14.8% (–7.4% and 43.6%), respectively. Beyond a volume threshold of 55 to 100 robotically assisted operations per year, distribution of the cost of this technology broadly overlapped those of conventional approaches.

CONCLUSIONS AND RELEVANCE

In exchange for higher procedural costs, robotically assisted surgery for mitral valve repair offers the clinical benefit of least-invasive surgery, lowest postoperative cost, and fastest return to work. The value of robotically assisted surgery that is similar to that of conventional approaches can be realized only in high-volume centers.

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obotically assisted surgery is the least invasive approach for treating myxomatous mitral valve disease. Benefits include less trauma, faster recovery leading to a quicker return to work or normal activities, and superior cosmesis, with comparable success, safety, and effectiveness. However, the value of this emerging technology for mitral valve repair is questioned because associated incremental costs beyond those of conventional surgery—capital investment, maintenance, and robotic-specific disposable instruments—may outweigh these clinical benefits. The purpose of this study was to investigate the value of robotically assisted surgery for mitral valve repair by assessing whether benefits mitigate the additional cost. We compared its cost with those of conventional approaches, including offsets from shorter recovery and earlier return to work or normal activities.

Methods

Patients

From January 1, 2006, through December 31, 2010, a total of 1290 patients with degenerative mitral valve disease underwent first-time isolated posterior leaflet repair via complete sternotomy (n = 227), partial sternotomy (n = 349), anterolateral thoracotomy (n = 241), or robotically assisted surgery (n = 473) (Figure 1). The total number of intended robotically assisted mitral valve operations during that time was 622, which includes our entire initial experience; however, the study was limited to the 473 patients with myxomatous disease of the posterior leaflet to facilitate comparisons in a homogeneous patient population. Robotic mitral valve repair was performed exclusively by 2 surgeons (T.M. and A.M.G.) with similar extensive previous experience with conventional and newer approaches for mitral valve repair. We excluded patients who underwent concomitant procedures, with the exception of suture closure of a patent foramen ovale or pulmonary vein isolation for atrial fibrillation. After propensity matching, 1173 patients remained in the study. Mean (SD) patient age was 57 (11) years, 344 (26.7%) were women, and 605 (49.2%) were asymptomatic or minimally symptomatic with severe (1027 [79.6%]) mitral valve regurgitation (Table). Preoperative and operative variables were retrieved from the Cleveland Clinic Cardiovascular Information Registry, an ongoing, prospective, concurrent registry of all cardiac operations, and by review of patients’ medical records and a back-to-work questionnaire. All data used in this study have been approved for use in research by the institutional review board of the Cleveland Clinic, with patient consent waived.

End Points

End points were (1) cost of care, expressed as robotic capital investment, maintenance of equipment, and direct technical hospital costs, and (2) benefit of care, expressed as recovery time translated into income difference.

Cost of Care

Robotic costs included capital investment and fixed yearly maintenance costs for a da Vinci Surgical System (Intuitive Surgical). Direct technical hospital costs, obtained from Cleveland Clinic’s financial database, were categorized as operative or postoperative costs (see eBox in the Supplement for cost categories). Costs of robotic-specific instruments and procedure-specific disposables, such as double-lumen endotracheal tubes, external defibrillator patches, and special cannulae for cardiopulmonary bypass, were included in the operative costs. Cost of any reoperation within the initial hospitalization was incorporated as a postoperative cost. Indirect costs, including institutional indirect costs and costs of capital equipment used for all operations, could not be estimated on a per-patient basis and are not included, but they are assumed to be distributed uniformly across groups.

Benefit of Care

Recovery time was assessed using a return-to-work survey (see Appendix 1 in the Supplement), which incorporated questions from earlier studies that were predictive of return to work. For this study, we focused on self-reported work status, time to return to work after surgery, hours worked per week, and work-related income category before and after surgery. We mailed the survey to all 1173 patients, from whom we received 918 responses (78.3%): complete sternotomy, 139 (70.2%); partial sternotomy, 219 (74.7%); anterolateral thoracotomy, 164 (73.2%); and robotically assisted surgery, 396

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Figure 1. CONSORT Diagram Showing Patient Groups by Approach

![Figure 1](https://example.com/figure1.png)

Ninety-one percent of patients matched (87.2% of complete sternotomy, 83.9% of partial sternotomy, 92.9% of anterolateral thoracotomy, and 96.8% of robotic groups). MV indicates mitral valve.
(86.4%). Recovery time was translated into difference in income earned based on time to return to work. Specifically, patients were stratified by the questionnaire’s income levels: $0, $1 to $24 999, $25 000 to $49 999, $50 000 to $74 999, $75 000 to $99 999, and $100 000 or greater. We queried the US Internal Revenue Service database of 140 million tax returns from 2009 (most recent data available: http://www.irs.gov/pub/irs-soi/09in11si.xls and http://www.irs.gov/uac/SOI-Tax-Stats---Individual-Statistical-Tables-by-Size-of-Adjusted-Gross-Income) to estimate mean income within each income level (using the $100 000 to $2 million category for the greater than $100 000 group, excluding only 0.04% of the US population), applied these to our patients, and took the median to estimate the weekly income: $1660. We multiplied this estimated income by the difference taken to return to work between the robotically assisted surgery group and the comparison groups.

**Data Analysis**

**Analysis Strategy**

Patients were analyzed on an intent-to-treat basis. In the partial sternotomy group, 8 were converted to a complete sternotomy; in the anterolateral thoracotomy group, 3 were converted to a partial sternotomy and 3 to a complete sternotomy; and in the robotically assisted surgery group, 19 were converted to an anterolateral thoracotomy, 21 to a partial sternotomy, and 13 to a complete sternotomy. In the robotically assisted surgery group, 24 of 53 patients were

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<table>
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<th>Variable</th>
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<th>Complete Sternotomy (n = 227)</th>
<th>Partial Sternotomy (n = 349)</th>
<th>Anterolateral Thoracotomy (n = 241)</th>
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<td></td>
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<td>Total No.</td>
<td>No. (%) or Mean [SD]</td>
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<td>Preoperative calculated LV end-diastolic volume, cm³</td>
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<td>47 [23]</td>
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<td>70 [21]</td>
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<td>LV ejection fraction, %</td>
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<td>60 [4.5]</td>
<td>216</td>
<td>59 [5.4]</td>
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</table>

Abbreviations: BSA, body surface area; COPD, chronic obstructive pulmonary disease; LA, left atrial; LV, left ventricular; NYHA, New York Heart Association. SI conversion factors: To convert creatinine to micromoles per liter, multiply by 88.4.

*All patients were considered on an intent-to-treat basis to have mitral valve repair, but several were converted intraoperatively to mitral valve replacement.*

*Patients with data available.*
converted because of inappropriate small vessel size for peripheral cannulation or difficulties in peripheral catheter placement, and 29 were converted after chest incision. A low threshold for conversion was maintained for all approaches so patient safety and repair effectiveness would not be compromised. Patients remained in their intended procedure group for all analyses.

Propensity Matching and Comparisons
Characteristics of patients undergoing robotically assisted surgery differed from those of patients who had a more conventional approach for mitral valve repair (eTable in the Supplement). To reduce selection bias, we used propensity matching.24-26 Because our focus was on patients who underwent robotically assisted surgery, we created 3 propensity models: robotically assisted surgery vs (1) full sternotomy, (2) partial sternotomy, and (3) anterolateral thoracotomy.

We used preoperative variables (eAppendix 2 in the Supplement) and multivariable logistic regression analysis to identify statistically significant factors associated with robotically assisted surgery in each of the 3 comparisons (parsimonious models). We then added other variables representing groups of patient factors that might be related to unrecorded selection factors to create semi-saturated propensity models (see the footnotes in eAppendix 2 in the Supplement). We calculated 3 propensity scores for each patient by solving the propensity models for the probability of receiving robotically assisted surgery vs a conventional approach. Using the propensity score only, robotically assisted cases were matched to nonrobotic cases using a greedy matching strategy (eFigures 1 and 2 in the Supplement). We calculated 3 propensity scores for each patient by solving the propensity models for the probability of receiving robotically assisted surgery vs a conventional approach. Using the propensity score only, robotically assisted cases were matched to nonrobotic cases using a greedy matching strategy (eFigures 1 and 2 in the Supplement).27 Robotically assisted cases with propensity scores deviating more than 0.1 from those of nonrobotic cases were considered unmatched.

Cost Analysis

Robotic Costs | Amortization for the robot was made on a yearly case-volume basis, in which fixed costs included the initial capital cost of the robot divided by an expected life span of 7 years, plus the yearly fixed maintenance costs. To obtain a mean per-patient robotic cost, we divided the amortized robotic cost by 167, the mean yearly volume of all types of robotically assisted cardiac surgical procedures performed at Cleveland Clinic during the study time frame.

Hospital Direct Technical Costs | We examined 3 categories of cost: operative direct technical costs, postoperative direct technical costs, and the sum of these: total hospital direct technical costs. The cost ratio for each robotic to nonrobotic propensity-matched pair was computed.

Income Related to Return to Work | Although differences in income ideally would be calculated between propensity-matched pairs, response to the survey was incomplete (as previously described). In addition, some patients were retired and out of the workforce: 54 (38.8%) in the complete sternotomy group, 73 (33.3%) in the partial sternotomy group, 38 (23.2%) in the anterolateral thoracotomy group, and 99 (25.0%) in the robotically assisted surgery group. Therefore, in subsequent calculations, we used the median ratio based on income of the workforce in each group rather than the median of paired ratios. Within each matched group, we also assessed the distribution of ratios for all possible pairs to provide a measure of variability.

Net Cost | Net cost was the sum of hospital direct technical costs, amortized per-patient robotic costs, and the difference in median income due to return-to-work status.

Case Volume-Cost Simulation | To illustrate the relationship of per-patient net cost of robotic vs conventional approaches to yearly case volume, we mathematically constructed curves showing how patient volume affects the net cost of robotically assisted surgery. For this process, only amortized cost of the robot was varied as a function of yearly case volume, with all other components of net cost set at their median value.

Amortization of robotic costs was divided by yearly patient volume ranging from 1 to 300 rather than the 167 specific to this study. We added the resulting mathematically derived yearly amortization cost per patient to the median cost ratio of direct hospital cost and income related to return to work. To obtain its distribution, we reported the calculations using corresponding 15th and 85th percentiles in place of the median.

Statistical Analysis
Continuous variables are summarized as mean (SD) or as 15th, 50th, and 85th percentiles when data are skewed. Pairwise comparisons were made using the Wilcoxon rank sum test and, for comparisons of more than 2 groups, the Kruskal-Wallis test. Categorical data are summarized by frequencies and percentages. Comparisons were made using the x² or Fisher exact test when frequency was less than 5. All analyses were performed using SAS statistical software, version 9.1 (SAS, Inc). Median cost ratios are accompanied by 15th and 85th percentiles within parentheses.

Results

Costs
Direct technical operative costs, including specialized disposable robotic instruments, were 36.9%, 37.1%, and 19.6% higher for robotically assisted surgery for mitral valve repair than for operations performed through a complete sternotomy, partial sternotomy, or anterolateral thoracotomy, respectively (Figure 2).

Direct technical postoperative costs were 19.1%, 17.4%, and 10.4% lower for robotically assisted surgery than for these 3 alternatives, resulting in total direct hospital technical costs that were 18.1%, 23.6%, and 11.8% higher, respectively.
Total cost of care, including total hospital direct technical costs plus amortized capital investment and maintenance costs of the robot, were 26.8% (−5.3% and 67.9%), 32.1% (−6.1% and 69.6%), and 20.7% (−2.4% and 48.4%) higher than for complete sternotomy, partial sternotomy, and anterolateral thoracotomy, respectively (Figure 2).

Cost of recovery from surgery, expressed as median time from discharge to return to work (with 15th and 85th percentiles), was 35 (19 and 63) days for patients undergoing robotically assisted surgery, 49 (21 and 109) days after a complete sternotomy, 56 (30 and 119) days after a partial sternotomy, and 42 (18 and 90) days after an anterolateral thoracotomy. Thus, return to work was 28.6%, 37.5%, and 16.7% earlier after robotically assisted surgery than after the alternative approaches, respectively (Figure 2).

Overall net cost of care, including operative and postoperative direct technical costs and amortized robotic costs, partially offset by the difference in estimated income due to earlier return to work, was 15.6% (−14.7% and 55.1%), 15.7% (−19.4% and 51.2%), and 14.8% (−7.4% and 43.6%) higher for robotically assisted surgery than for the 3 alternatives, respectively (Figure 2).

**Case Volume–Cost Simulation**

Mathematically, higher yearly case volume leads to a linear decrease in amortized costs of robotic technology. However, because other costs remain, an increase in case volume causes an exponentially decreasing cost per case, almost reaching an asymptotic yearly case volume between 55 and 100, at which point the lower 15th percentile of costs for robotically assisted surgery for mitral valve disease overlaps the estimate for conventional approaches (Figure 3).
Discussion

The principal finding of this study is that the cost of care associated with robotically assisted mitral valve repair is substantially higher than that of conventional approaches, but this cost is mitigated in large part by benefits of lesser invasiveness, resulting in lower postoperative costs, a shorter hospital stay, and an earlier return to work. However, the value of robotically assisted mitral valve repair that is comparable to conventional approaches can be realized only in high-volume centers.

Three unique aspects of our study paint a more comprehensive picture of the introduction of new technology than generally has been the case. First, this was an intent-to-treat study design. Although such a design may seem to dilute the benefits of robotically assisted surgery, it faithfully portrays a real-world robotic program as well as mimics a randomized clinical trial design. Second, it includes capital investment and maintenance costs of the robot. Few previous studies of robotically assisted surgery for mitral valve repair have emphasized initial capital investment, which substantially increases the total cost of care for robotically assisted procedures.28,29 Instead, studies dealing with new technologies focus on clinical results and hospital outcomes, neglecting potential downstream cost savings. Third, it considers what might be termed the social aspect of health care: rapidity of recovery from surgery. With increasing health care costs, it is important to review the introduction of new technologies from such a broad public health perspective to assess their value (benefit/cost).30 Our study takes a holistic view of patient health care cost by addressing the entire value proposition of a robotically assisted surgery program.

Apart from technology investment, other potential reasons behind the high operative costs we experienced include costs of additional personnel necessary for the safe conduct of the procedure during its initial implementation, longer operative times, and more conversions from robotically assisted to conventional surgery to maintain patient safety, all associated with the inclusion of cases from the inception of our robotic experience. We must emphasize that this study is limited by technology that is still evolving away from large and expensive instruments. As with most advances in technology, in the future, these instruments will become smaller, more flexible, and more affordable. As surgical team efficiency and safety of the procedure improve, personnel costs, operative times, and conversions should decrease.

Strengths and Limitations

This single-institution study includes only patients undergoing mitral valve repair for posterior leaflet prolapse. Despite the problem of generalizing results from a single institution, this enabled a high level of detail in our analysis. In addition, in our environment, we use a surgical robot dedicated to cardiac surgery. Cost calculations could be different in a setting where the surgical robot is a shared resource for cardiac, thoracic, general, urologic, and gynecologic surgery. To compensate for selection bias in this nonrandomized observational study, we used the intent-to-treat principle and propensity scores to match patients with similar demographic and comorbidity profiles and similar extent of mitral valve disease to procedures performed contemporaneously by experienced surgeons at our institution.

A strength of our study is the use of actual direct technical cost data rather than charges; however, we were unable to estimate indirect costs per patient for bricks and mortar, custodial services, security, and the like. Had these been added uniformly, the incremental relative cost of robotic surgery would have been less (more favorable).

Incorporating information about recovery from surgery and its monetary transformation as we have done has several limitations. First, we used return to work as a surrogate for length of recovery in the same spirit as used in studies of the introduction of new therapies for ischemic heart disease in the 1970s. Second, patients having a sternotomy are instructed to resume normal activities and return to work after about 6 weeks to ensure union of the sternum, whereas those undergoing operations that do not involve cutting through bone (anterolateral thoracotomy and robotically assisted surgery) are told to resume these activities when they feel well enough to do so. Although this may introduce psychologic incentives, it also reflects real differences in healing time. Third, the study translates differences in return to work into financial terms. We agree with Murphy and Topel,30 who show that advances in health care contribute positively in often unacknowledged ways to the gross domestic product, and faster recovery and return to productive work have this social benefit apart from a clinical benefit. Fourth, we were able to obtain only ranges of individual-patient income data from our back-to-work questionnaire. Thus, we used reported income ranges and census data to approximate median income.

Clinical Implications

The major determinant of invasiveness in cardiac surgery is often not the size of the incision needed to perform the intracardiac procedure but the size needed to expose the heart. Another determinant of incision size, and thus invasiveness, is the space needed to use the instruments for the procedure. Robotic instrumentation is a positive disruptive technology that minimizes invasiveness by affecting both these determinants. The often superior quality of visualization with robotic assistance is delivered through sophisticated 3-dimensional technology. Small-caliber articulated instruments allow conduction of highly complex operations while being inserted through small port-like incisions. The overall result is uncompromised quality, accuracy, and precision of surgical manipulation. We envision that further refinement of robotic technology will lead to its wider adoption in cardiac surgery.

Evaluation of the value of new technology during its early phase of introduction into medical practice must consider not only its current value but also future applications that inevitably follow technical accomplishments that increase its value. In numerous cases, new technology implementation in surgery has encountered early economic obstacles but then fol-
allowed a path to wider adoption and application. Laparoscopic procedures in general surgery and gynecology, as well as thorascopic procedures in thoracic surgery, are now used more commonly than open approaches, but each had to prove its value before wider implementation. Consider laparoscopic cholecystectomy, now performed in more than 90% of patients. Early literature suggested higher costs due to longer operative times, the learning curve, and the cost of disposable instruments, yet later literature established its higher value. Introduction of video-assisted thoracic surgery followed a similar path. We anticipate that implementation of robotic technology in cardiac surgery will progress in the same fashion, with a transition to newer and technologically more advanced procedures.

Conclusions
Robotic assisted surgery for mitral valve repair offers the clinical benefit of the least invasive surgery, lowest postoperative cost, and fastest return to work in exchange for higher procedural costs. However, the maximum value of robotically assisted mitral valve surgery can be realized only in high-volume centers.

ARTICLE INFORMATION
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Author Contributions: Dr Blackstone and Ms Williams had full access to all the data in the study and take responsibility for the integrity of the data and accuracy of the data analysis. Study concept and design: Mihaljevic, Koprivanac, Kelava, Jarrett, Gillinov, Blackstone. Acquisition, analysis, or interpretation of data: Mihaljevic, Koprivanac, Kelava, Goodman, Jarrett, Williams, Gillinov, Bajwa, Mick, Bonatti.

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Critical revision of the manuscript for important intellectual content: Mihaljevic, Koprivanac, Kelava, Goodman, Jarrett, Williams, Gillinov, Bajwa, Mick, Bonatti, Blackstone.

Statistical analysis: Mihaljevic, Koprivanac, Kelava, Jarrett, Williams, Blackstone.

Obtained funding: Mihaljevic.

Administrative, technical, or material support: Goodman, Bajwa, Blackstone.

Study supervision: Mihaljevic, Gillinov, Blackstone.

Conflict of Interest Disclosures: Dr Gillinov reported serving as a consultant to Intuitive Surgical, Edwards Lifesciences, St Jude Medical, Medtronic, Abbott, and On-X. No other disclosures were reported.

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Role of the Sponsor: The funding sources had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Additional Contributions: Albert Oberman, MD, PhD, at the University of Alabama at Birmingham helped develop the return-to-work survey. Penny Houghtaling, MS, performed parts of the statistical analysis and verified all numeric data in the manuscript.

REFERENCES
Assessing the Value of Surgical Robotics Not Your Grandfather’s Widget

David D. Yuh, MD

Mihaljevic and colleagues1 have courageously entered the fray in assigning and assessing relative “value” in health care. Unlike applying conventional profit-loss analyses in producing and marketing widgets in business school, health care administrators and physicians must grapple with the conundrum of justifying the quantifiable costs of new technologies with vaguely defined measures of patient benefit, even more ambiguous assessments of benefit to society, and the perpetually moving target of marketing advantage. The need for a cogent method to optimize value in health care is accentuated by the nation’s focus on rising health care costs and unfavorable value comparisons to other nations’ health care systems.

The authors rightly acknowledge the imperfections of their method. Translating faster recovery into monetary equivalents and comparing these with direct hospital costs begs scrutiny and criticism but represents a reasonable attempt to draw on precedent to conceptualize patient and societal benefits. Furthermore, the psychological overlay that might encourage patients undergoing robotically assisted surgery to return to work earlier should not be underestimated, although it could be argued that this is just as valid a benefit of less invasive approaches as smaller incisions.

Ultimately, the import of this study does not lie in validating robotic surgery. As with catheter-based interventions and other less invasive technologies, robotic surgical platforms will continue to evolve and perhaps even become cost-neutral.2 Certainly, the notion that less invasive surgical approaches lead to many clinical benefits has been validated excessively3,4 and will continue to drive further development. The significance of this and similar studies lies in developing frameworks for determining relative short- and long-term values of high-priced technologies in this era of “value-based purchasing.” The oft-used justification that the high costs of a given new innovative device will ultimately decline and pay for itself (eg, laparoscopy) should not be assumed in this era of entrepreneurial technological innovation. Ironically, surgical robotics may demonstrate that expensive new technologies may be replaced with expensive newer technologies.

ARTICLE INFORMATION

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REFERENCES


