RESEARCH ARTICLE

Cost Effectiveness of Laminar Flow Systems for Total Shoulder Arthroplasty: Filtering Money from the OR?

Daniel E. Davis, MD, MS; Benjamin Zmistowski, MD; Joseph A. Abboud, MD; Surena Namdari, MD, MSc

Research performed at the Rothman Orthopaedic Institute, Philadelphia, Pennsylvania, USA

Received: 08 October 2018   Accepted: 23 December 2018

Abstract

Background: Laminar flow ventilation systems were developed to reduce surgical contamination in joint arthroplasty to avoid periprosthetic joint infection (PJI). The goals of this study are to evaluate the cost-effectiveness and economic viability of installing and maintaining a laminar flow system in an operating room.

Methods: A Monte Carlo simulation was used to evaluate the cost effectiveness of laminar flow. The variables included were cost to treat PJI, incidence of PJI, cost of laminar flow, years of operating room use, and arthroplasty volume as the dependent variable.

Results: Laminar flow would be financially-justified when 1,217 (SD: 319) TSA cases are performed annually with assumed 10% reduction in PJI from laminar flow and 487 (SD: 127) with assumed 25% reduction. In a high volume OR, laminar flow costs $25.24 per case (assuming 10% reduction) and $8.24 per case (assuming 25% reduction). Laminar flow would need to reduce the incidence of PJI by 35.1% (SD: 9.1) to be a cost-effective strategy.

Conclusion: This analysis demonstrates the substantial arthroplasty volume and large reduction in PJI rates required to justify the installation and maintenance costs of this technology. This high cost of implementation should be considered prior to installing laminar flow systems.

Level of evidence: II

Keywords: Cost effectiveness, Laminar flow, Laminar flow cost effectiveness, Laminar flow efficacy, Sensitivity analysis, Total shoulder arthroplasty

Introduction

As the number of total shoulder arthroplasty (TSA) cases performed increases each year, there is an increased focus on cost reduction and value based care (1, 2). Periprosthetic joint infection (PJI) of the shoulder has a reported incidence of approximately 1% and is a large driver of unexpected cost and patient morbidity (3–5). While a gold standard for shoulder PJI treatment has yet to be identified, treatment typically requires hospitalization, surgical intervention, and long-term intravenous and oral antibiotics. In addition to the associated health-care costs, shoulder PJI results in societal costs from lost work, decreased functional status, and associated mortality cannot be ignored (6).

In the development of major joint arthroplasty, Sir John Charnley appreciated the significant burden of PJI (7). At that time, Charnley identified and adopted numerous measures for the prevention of infection (8). Ultimately, he concluded that utilizing air cleanliness and laminar flow technology created a large reduction in the risk of PJI from 8.9% to 1.3% (9). As total joint arthroplasty was

Corresponding Author: Daniel E. Davis, Department of Orthopaedic Surgery, The Rothman Institute at Thomas Jefferson University, Philadelphia, PA, USA

Email: danielle.davis@gmail.com

adopted internationally, the principle of laminar flow in operating rooms was replicated and is still used a half-century later. However, in recent systematic reviews and registry studies, clinical reduction of PJI rates have not been observed with utilization of laminar flow (10, 11). Furthermore, the implementation of laminar flow requires substantial capital costs and complicates efficient scheduling of TSA cases by limiting the available operating rooms. Therefore, this break-even cost analysis was undertaken to identify the necessary TSA volume and efficacy in PJI reduction to justify the installation and use of laminar flow.

Materials and Methods
A Monte Carlo break-even cost-analysis was used to determine the required efficacy of laminar flow in reducing the incidence of PJI and the annual arthroplasty volume necessary for laminar flow utilization to be a cost-effective strategy in PJI reduction. The model was a basic life-cycle cost analysis utilizing net present value adjustments of future savings. The variables included in this formula were cost to treat PJI, baseline risk of PJI, cost of installation and maintenance of laminar flow, years of operating room use, efficacy of laminar flow in decreasing PJI, and arthroplasty volume [Figure 1]. By solving the equation for the desired variable (TSA volume, PJI efficacy, etc.), simulated results providing break-even cost could be determined [Figure 2].

To solve for the dependent variables (laminar flow efficacy and arthroplasty volume), we established the known values for the remaining variables listed above [Table 1]. Installation and annual maintenance cost estimates were provided from this institution’s experience. The cost to treat PJI was gathered from three separate articles detailing the cost of treatment (3–5). As the three studies identified from literature search had variable cost data and sample sizes, the cost data used for the equation was weighted by sample size. Similarly, the risk of PJI was defined by findings from a large national dataset over multiple years (5). The risk of PJI for each year was weighted by the number of TSA’s performed within that year. The longevity of use of a filtration system is highly dependent on the continued maintenance of the equipment, but for the purposes

![Mathematical formula for break-even analysis](image)

Figure 1. Formula for break-even analysis adjusting future cost and savings to net-present-value (NPV). PJI cost = cost of treating PJI; PJI incidence = baseline risk of PJI; Effect = rate of reduction of PJI by laminar flow; Installation = cost of installation; Maintenance = annual cost of maintenance; Longevity = expected years of ventilation (laminar flow) system use; TSA = annual volume of total shoulder arthroplasty.

![Mathematical formula for solving break-even analysis](image)

Figure 2. An example of solving the break-even formula (Figure 1) for a desired variable; in this instance, annual volume of total shoulder arthroplasty.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Mean</th>
<th>SD</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation Cost</td>
<td>I</td>
<td>$140,000</td>
<td>5,000</td>
<td>Quote from Hospital</td>
</tr>
<tr>
<td>Longevity</td>
<td>L</td>
<td>15 years</td>
<td>2</td>
<td>Estimate</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>M</td>
<td>$5,500</td>
<td>1,000</td>
<td>Quote from Hospital</td>
</tr>
<tr>
<td>Risk of PJI</td>
<td>PJI</td>
<td>1%</td>
<td>0.2%</td>
<td>Literature</td>
</tr>
<tr>
<td>Discount Rate</td>
<td>D</td>
<td>8%</td>
<td>0.05%</td>
<td></td>
</tr>
<tr>
<td>Effect of Laminar Flow</td>
<td>E</td>
<td>Incremental</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of PJI</td>
<td>C</td>
<td>$18,908</td>
<td>56.6</td>
<td>Literature</td>
</tr>
<tr>
<td>Arthroplasty Volume</td>
<td>TSA</td>
<td>Incremental</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SD = standard deviation; PJI = periprosthetic joint infection
of this study we estimated that time period to be 20
years. There is potential for significant variation in the
discount rate between institutions depending upon their
weighted average cost of capital for funding projects. For
this analysis, we used the local currency cost of capital as
provided by New York University Stern School of Business
from a review of United States hospitals and healthcare
facilities. For smaller firms, or those in financial distress,
cost of capital may be higher.

Due to the uncertainty in many of these variables, a
Monte Carlo simulation was used when solving for the
primary outcomes. From this the mean and standard
deviation of the findings are reported. First, we
determined the average cost of operating laminar flow
per case for increasing TSA volume. Second, we solved
the break-even cost formula for arthroplasty volume
and performed a Monte Carlo simulation at the defined
increments of laminar flow efficacy. This provided a
minimum number of annual TSA cases necessary to
justify laminar flow installation at various rates of PJI
reduction of PJI. Third, we performed a Monte Carlo
simulation to determine the efficacy of laminar flow in
reducing PJI needed to justify the installation cost of this
system at our institution. We used the average annual
case volume in our busiest operating room (350 cases)
to calculate this efficacy. We then solved the break-even
cost equation for installation costs. We used a Monte
Carlo simulation to calculate the maximum laminar flow
installation cost for theoretical for efficacy in the ability
of laminar flow to reduce the rate of PJI in TSA. We made
the estimates with two assumed rates of PJI reduction,
10% and 25% efficacy (reduction in rate of PJI). Due to the
low rate of PJI in TSA and the multifactorial nature of its
causes, finding the true efficacy of laminar flow requires
a very large volume of cases, therefore these numbers
were used as estimates to calculate is cost value. For
each calculation, sensitivity analysis was performed to
determine the contribution of each variable to outcome
variance. Simulations were performed in YASAI (2.6,
Rutgers University, Piscataway, NJ).

Results
The cost of laminar flow per case decreased exponentially
with increasing number of annual arthroplasties: $139.2
(standard deviation [SD]: 24.4) per case for 100 TSA
cases annually, decreasing to $27.8 (SD: 4.9) per case for
500 TSA cases annually [Figure 3]. Assuming laminar
flow provided a ten-percent reduction in the rate of
PJI, installation and maintenance of a system would be
economically viable when 1,216.9 (SD: 318.5) TSA cases
are performed in a single operating room (OR) annually
[Figure 4]. The volume threshold decreased to 486.8 (SD:
127.4) TSA cases with an assumed PJI reduction of 25%.

Using this institution’s average of 350 cases in the highest
volume OR, installation and continued maintenance of
laminar flow cost $129,534 (SD: 33,038; $25.24 per case)
assuming a reduced PJI incidence of 10% and $41,084
(SD: 64,036; $8.24 per case) for an assumed reduction of
25%, even after adjusting for savings from reduced PJI.

For laminar flow technology to be considered cost-
effective based on our institution’s current surgical
volume, installation costs would need to be reduced
by 92.6% to $10,345.79 (SD: 23,827) assuming a ten-
percent reduction in the incidence of PJI from laminar

![Figure 3. Per case cost of laminar flow utilization for each annual volume of total shoulder arthroplasty studied.](image-url)
Alternatively, assuming a 25% reduction in PJI the installation cost would need to be reduced by 28.7% to $99,794 (SD: 56,776). Lastly, at the current pricing, laminar flow technology would need to demonstrate a reduction of PJI by 35.1% (SD: 9.1) to be a cost-effective strategy [Table 2].

**Discussion**

PJI following TSA is a significant complication that is costly to treat and can result in substantial patient morbidity (12). Recent analyses have shown implant-related infection to be the most common complication following both anatomic and reverse TSA, and the most common surgical cause for readmission within 90-days (13, 14). As such, many attempts have been made to minimize the risk of PJI following TSA, including the use of laminar flow to improve operating room air cleanliness. While Charnley et al. demonstrated significantly decreased rates of PJI following total hip arthroplasty after the implementation of laminar flow, more recent analyses have not found a difference (9-11). As more efficient surgical settings are erected, the necessity of this expensive technology is called into question. Therefore, the purpose of this study was to perform a cost-analysis of laminar flow installation and maintenance with regards to reduction of periprosthetic joint infection.

**Table 2. This table demonstrates the change tested variables based on tested arthroplasty volumes as well as changing optimal installation and maintenance costs**

<table>
<thead>
<tr>
<th>Cost of Laminar Flow Per Case</th>
<th>Volume of TJA (10% Efficacy)</th>
<th>Volume of TJA (25% Efficacy)</th>
<th>Installation and Maintenance Cost (10% Reduction)</th>
<th>Installation and Maintenance Cost (25% Reduction)</th>
<th>Optimal Installation Cost (10% efficacy)</th>
<th>Optimal Installation Cost (25% efficacy)</th>
<th>Optimal Efficacy (350 cases)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk of PJI</td>
<td>N/A</td>
<td>68.6%</td>
<td>32.5%</td>
<td>24.0%</td>
<td>16.7%</td>
<td>1.45%</td>
<td>60.0%</td>
</tr>
<tr>
<td>Installation</td>
<td>55.8%</td>
<td>1.83%</td>
<td>2.2%</td>
<td>40.5%</td>
<td>60.5%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cost of PJI</td>
<td>N/A</td>
<td>19.6%</td>
<td>31.0%</td>
<td>0.73%</td>
<td>0.8%</td>
<td>0.3%</td>
<td>29.6%</td>
</tr>
<tr>
<td>Longevity</td>
<td>8.8%</td>
<td>1.6%</td>
<td>0.05%</td>
<td>14.2%</td>
<td>6.5%</td>
<td>97%</td>
<td>9.6%</td>
</tr>
<tr>
<td>Deduction</td>
<td>N/A</td>
<td>6.2%</td>
<td>33.4%</td>
<td>16.7%</td>
<td>12.9%</td>
<td>1.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Effects of Laminar Flow</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Annual Cost</td>
<td>35.4%</td>
<td>2.2%</td>
<td>0.8%</td>
<td>3.9%</td>
<td>2.6%</td>
<td>0.1%</td>
<td>0.7%</td>
</tr>
</tbody>
</table>

Figure 4. The number of annual volume of total shoulder arthroplasties required in a single operating room to break-even on the investment of laminar flow for varying rates of reduction of periprosthetic joint infection.
the variables in formulating this cost-analysis, most specifically operating room longevity. We attempted to overcome this limitation by using the annual maintenance cost of laminar flow systems and using the Monte Carlo simulation to provide margins-of-error accounting for this uncertainty. Second, the scope of this study does not address the social or societal impacts of PJI. For this analysis, as the institutions bear the cost of installation and maintenance of air filtration systems, the scope for the cost of PJI is narrowed to the institutional costs of subsequent treatment. However if considering patient quality-of-life and cost to society from lost work-time, the necessary efficacy and TSA volume needed to justify laminar flow may be substantially decreased. Lastly, this study does not further the evidence regarding the effect of laminar flow on the rate of PJI.

Despite these limitations, this study did demonstrate the substantial cost of laminar flow installation. Unfortunately, the evidence does not suggest that this cost is justified. Although Charnley demonstrated a significant reduction in PJI with the introduction of clean-air systems, more recent analyses-involving over one-hundred thousand patients-have not demonstrated a decreased rate of PJI with laminar flow. In actuality, Hooper et al and Gastmeier et al found that the use of laminar flow increased the rate of PJI (10, 11). While the methodologies of these studies have limitations, the increased rate of PJI is potentially explained by obstruction of laminar flow from overhead theater lights leading to eddies of contaminated air above the surgical field, and possible introduction of hypothermia due to large volumes of air through the wound bed (15, 16).

This study found that a minimum of 1,261.9 and 486.8 TSA annually would be necessary for laminar flow to be cost-effective for 10% and 25% reduction in PJI, respectively. Even at this high-volume shoulder institution, laminar flow would need to provide a 35.1% reduction in PJI to be economically viable. This presents a significant hurdle for this technology. First, it is unlikely that laminar flow application will be optimally utilized in most operating suites. In his initial review Charnley stated "perfect illumination of the surgical area takes precedence over perfection of laminar flow" (8). Today this reality remains unchanged. Second, laminar flow is designed to prevent contamination of the wound from contaminated air. Approximately one-third of shoulder PJI is secondary to Propionibacterium acnes (P. acnes) P. acnes likely contaminates the surgical wound directly from the skin, upon incision (17, 18). Third, some PJI present in a delayed fashion (14, 19). While it is possible that bacteria introduced into the surgical wound at the time of surgery may remain dormant until much later, it is more probable that the majority of these late presenting infections are via hematogenous introduction (20).

In summary, laminar flow remains a widely-used technology in TSA despite conflicting evidence. This analysis illuminated the substantial cost necessary to implement laminar flow in preparation for TSA. Furthermore, the unrealistic reduction in PJI (35% at this high-volume institution) required to justify laminar flow installation and maintenance was demonstrated. Therefore, despite the theoretical efficacy, the installation of overhead laminar flow systems is likely an unwise use of resources in this cost-conscious era of healthcare.

References


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1 Department of Orthopaedic Surgery, The Rothman Institute at Thomas Jefferson University, Philadelphia, PA, USA


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