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MAJOR ARTICLE

Cost-effectiveness of an Environmental Cleaning Bundle for Reducing Healthcare-associated Infections

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Background. Healthcare-associated infections (HAIs) remain a significant patient safety issue, with point prevalence estimates being ~5% in high-income countries. In 2016–2017, the Researching Effective Approaches to Cleaning in Hospitals (REACH) study implemented an environmental cleaning bundle targeting communication, staff training, improved cleaning technique, product use, and audit of frequent touch-point cleaning. This study evaluates the cost-effectiveness of the environmental cleaning bundle for reducing the incidence of HAIs.

Methods. A stepped-wedge, cluster-randomized trial was conducted in 11 hospitals recruited from 6 Australian states and territories. Bundle effectiveness was measured by the numbers of *Staphylococcus aureus* bacteremia, *Clostridium difficile* infection, and vancomycin-resistant enterococci infections prevented in the intervention phase based on estimated reductions in the relative risk of infection. Changes to costs were defined as the cost of implementing the bundle minus cost savings from fewer infections. Health benefits gained from fewer infections were measured in quality-adjusted life-years (QALYs). Cost-effectiveness was evaluated using the incremental cost-effectiveness ratio and net monetary benefit of adopting the cleaning bundle over existing hospital cleaning practices.

Results. Implementing the cleaning bundle cost $349 000 Australian dollars (AUD) and generated AUD$147 500 in cost savings. Infections prevented under the cleaning bundle returned a net monetary benefit of AUD$1.02 million and an incremental cost-effectiveness ratio of $4684 per QALY gained. There was an 86% chance that the bundle was cost-effective compared with existing hospital cleaning practices.

Conclusions. A bundled, evidence-based approach to improving hospital cleaning is a cost-effective intervention for reducing the incidence of HAIs.

Keywords. cost-effectiveness; infection control; healthcare-associated infections; environmental cleaning; hospital.

Infection-control programs deliver evidence-based strategies aimed at preventing healthcare-associated infections (HAIs) [1]. Improving hand hygiene compliance [2], healthcare worker education [3], and optimal clinical practice bundles [4] has been effective in reducing HAI burden, resulting in cost savings for health services and health benefits for patients [5]. Nonetheless, HAIs remain a significant patient safety issue, with point prevalence estimates being approximately 5% in high-income countries [6, 7].

Environmental cleaning is an important element of an infection-control program [8]. Pathogens responsible for HAIs survive on surfaces for many months [9], increasing the risk of patient acquisition [10]. To date, evaluations of environmental cleaning have been limited to the management of outbreaks or quasi-experimental studies [11]. However, growing evidence supporting the link between environmental contamination and pathogen transmission [12] has motivated research into the impact of improving routine cleaning practices on HAI rates [13].

In 2016–2017, the Researching Effective Approaches to Cleaning in Hospitals (REACH) study evaluated an environmental cleaning bundle for reducing HAI rates in 11 Australian hospitals [14]. The bundle implemented 5 interventions targeted at improving cleaning practices, which emphasized engagement with environmental services staff. Bundle effectiveness was measured by improvements in frequent touch-point cleaning and rate reductions in *Clostridium difficile* infection (CDI),

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Staphylococcus aureus bacteremia (SAB), and vancomycin-resistant enterococci (VRE) infection.

Investment in new infection-control initiatives redirects scarce resources from competing programs [15]. The economic returns of new programs should ideally exceed those for programs that are displaced, and cost-effectiveness analysis is useful for deciding which programs should be supported. In this paper, we evaluate the cost-effectiveness of the REACH cleaning bundle. Our analysis considered the costs of implementing the bundle, expected cost savings from fewer infections, and changes to health outcomes. The results are intended to inform hospital decision makers about whether to adopt the cleaning bundle as part of a hospitalwide infection-control program. Methods and outcomes are reported in accordance with the Consolidated Health Economic Reporting Standards (CHEERS) statement (Supplementary File 1).

METHODS

Setting and Study Design

Eleven hospitals participated in the REACH study, representing over 1700 environmental services staff and 6100 overnight beds in large public and private hospitals. All hospitals had an established HAI surveillance program in place before enrollment, which included data collection on healthcare-associated CDI, SAB, and VRE infections [14, 16].

The intervention was an environmental cleaning bundle with 5 evidence-based components targeting audit, communication, technique, training, and product [14]. A full description of each bundle component is provided in Supplementary File 2. The bundle was implemented in all hospitals using a stepped-wedge cluster-randomized design, with intervention timings randomized after all hospitals were enrolled. Before switching to the intervention, hospitals completed a 4-week establishment and an 8-week control period. The length of the intervention varied between 20 and 50 weeks, with an average length of 35 weeks. The design allowed all hospitals to receive the intervention, with each acting as its own control. The sequential roll-out of the bundle maximized the feasibility and consistency of implementation across sites, allowing researchers to work with individual hospitals. Given baseline differences between hospitals in cleaning practices [17], a pragmatic approach to implementation was taken, which allowed the bundle to be tailored to individual hospitals based on changes required to meet best-practice cleaning guidelines.

Ethics approval for the REACH study was obtained locally from all participating hospitals, the Uniting Health Human Research Ethics Committee (approval number 1413), and the Queensland University of Technology Human Research Ethics Committee (approval number 1400000828).

Analysis

We evaluated the cost-effectiveness of the intervention over current hospital cleaning practices using data collected alongside the REACH study. Changes to costs reflected the healthcare system perspective and were defined as the cost of bundle implementation minus cost savings from modeled reductions in infection rates. Changes to health benefits were measured in quality-adjusted life-years (QALYs). Cost-effectiveness was evaluated over 62 weeks, from the start of the establishment period in the first hospital until the end of the study.

Implementation costs covered the purchase of consumables and the value of staff time spent on bundle activities. Consumables were valued using unit costs and included promotional and training materials, audit equipment, and disinfectant for frequent touch-point cleaning. Staffing costs were based on time contributions from hospital management and environmental services staff and were valued using wage rates. Costs were valued in 2016 Australian dollars. No discounting was applied for time preferences given the short time horizon. Further details are in Supplementary File 3.

Total implementation costs were organized by bundle component for preintervention (establishment/control) and intervention phases (Supplementary Table 1). This allowed us to estimate the costs of establishing and maintaining the bundle and the relative contribution of different components. Expected per-hospital costs were calculated to inform on the implementation costs at a future site, accounting for differences in intervention length, occupied bed days, and numbers of environmental services staff employed.

Bundle effectiveness was modeled using hospital surveillance data collected between May 2015 and July 2017 [16]. Statistical models estimated the expected within-hospital change in infection rates per 10 000 occupied bed days from the intervention and were fitted separately to each infection. Models accounted for between-hospital differences in preintervention rates and included a linear time trend to capture pre-existing trends. Effectiveness was modeled by a binary step change, which started after the first 4 weeks of the intervention phase to account for an initial leaning period. For infections where the relative risk of the intervention was less than 1, model parameters were used to estimate the number of infections prevented under the intervention.

Cost savings were measured by the value of bed days released and treatment costs avoided (Table 1). Excess length-of-stay estimates were sourced from studies identified by systematic reviews [18, 19]. Where possible, we used separate estimates for the general ward and intensive care unit (ICU) and for different patient outcomes (died in hospital or discharged). The economic value of total bed days released was determined using 2 approaches representing different healthcare payer perspectives. The first approach was based on an Australian hospital chief executive officer's (CEO's) stated willingness to pay (WTP)

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Table 1. Parameter Estimates and Prior Distributions for Evaluating the Cost-effectiveness of the Cleaning Bundle

Parameter	Estimate	Prior Distribution
Staphylococcus aureus bacteremia		
Log infection rate per 10 000 occupied bed days, pre-intervention	−0.03	Normal (−0.03,0.13)
Log relative risk, intervention	−0.20	Normal (−0.20, 0.16)
Excess length of stay from infection, days [25]	12.7 (general ward, discharged)	Normal (12.7, 2.2)
	−1.5 (general ward, died)	Normal (−1.5, 3.3)
	0.9 (ICU, discharged)	Normal (0.9, 0.7)
	1.4 (ICU, died)	Normal (1.4, 0.6)
Treatment costs per infection [23, 24]	$1017	Fixed
Probability of death [25]	0.06 (not infected)	Beta (175, 2775)
	0.17 (infected)	Beta (124, 620)
Average patient age [26], years	62	Fixed
Life expectancy at time of infection, years [27]	25.0 (female); 22.1 (male)	Fixed
VRE infection		
Log infection rate per 10 000 occupied bed days, preintervention	−1.0	Normal (−1.0, 0.46)
Log relative risk, intervention	−0.46	Normal (−0.46, 0.14)
Excess length of stay from infection, days [18]	3.8	Uniform (3.0, 4.6)
Mortality risk [28]	0.07 (not infected)	Beta (35, 497)
	0.10 (infected)	Beta (52, 480)
Treatment costs per infection [23]	$1708 (BSI); $844 (UTI)	Fixed
Log odds of VRE BSI vs VRE UTI[a]	0.38	Normal (−0.49, 0.42)
Average patient age [28], years	66	Fixed
Life expectancy at time of infection, years [27]	21.5 (female); 18.9 (male)	Fixed
Clostridium difficile infection		
Log infection rate per 10 000 occupied bed days, preintervention	0.85	Normal (0.85, 0.21)
Log relative risk, intervention[b]	0.07	Normal (0.07, 0.10)
Health benefits		
Health utilities, Australian norms [29]	0.80 (75+ years)	Beta (546,136)
	0.82 (65–74 years)	Beta (2066, 594)
Dollar value per bed day released		
Willingness to pay [20, 22]	$284 (general ward)	Normal (284, 23)
	$573 (ICU)	Normal (573, 86)
Accounting cost [21, 30]	$1667 (general ward); $6280 (ICU)	Fixed

Abbreviations: BSI, bloodstream infection; ICU, intensive care unit; REACH, Researching Effective Approaches to Cleaning in Hospitals; UTI, urinary tract infection; VRE, vancomycin-resistant enterococci.

[a]Determined from REACH study data.

[b]Insufficient evidence of bundle effectiveness to assign cost savings and health benefits.

for a bed day to reflect the perspective of the hospital decision maker [20]. The second approach considered the accounting value of a hospital bed day based on historical spending. Accounting estimates were calculated using reported recurrent expenditure on admitted care and patient days in Australian public hospitals [21, 29]. Dollar values were adjusted to 2016 Australian dollars to account for inflation in healthcare expenditure [22]. Treatment costs covered diagnostic testing and antibiotics [23, 24] following consultation with infectious disease experts. Vancomycin-resistant enterococci treatment costs were estimated by the weighted average of costs for treating bloodstream and urinary tract infections, as these accounted for 98% of reported preintervention infections.

Out of the number of infections prevented, we assumed that a proportion of patients would have died due to infection. Mortality risks were sourced from the same studies identified for extra length of stay if available (Table 1). Total years of life gained were calculated as the difference between the average age of infected patients and life expectancies at the time of infection [27]. Years of life gained were converted to QALYs using age-group–specific health utilities measured in the Australian general population [29]. Total QALYs were discounted by 3% per annum to reflect the reduced future value of health benefits [31].

The cost-effectiveness of the intervention was evaluated using the incremental cost-effectiveness ratio (ICER) and net monetary benefit (NMB), which offered different summaries of the change in costs versus health benefits. The ICER reports the incremental cost per QALY gained, which is compared with a maximum WTP per QALY:

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$$\text{ICER} = \frac{\text{Change in costs}}{\text{Change in QALYs}}$$

In contrast, NMB is a rearrangement of the ICER that summarizes the difference between the economic value of health benefits and the change in costs:

$$\text{NMB} = (\text{WTP} \times \text{Change in QALYs}) - \text{Change in costs}$$

Interventions with a positive NMB or an ICER less than the chosen WTP threshold are cost-effective. Our analysis used a WTP threshold of $28 000/QALY, which reflected the opportunity cost of additional healthcare expenditures under a constrained budget [32].

Probabilistic sensitivity analysis was undertaken to account for uncertainty in model parameters and its impact on cost-effectiveness outcomes. Selected prior distributions characterized uncertainty in bundle effectiveness, literature-based parameters, and hospital costs (Table 1). Uncertainty in staff time costs was modeled using uniform distributions by staff role, defined by minimum and maximum hourly rates. Uniform distributions were also used to add a 10% margin of error to weekly incremental costs for disinfectant to reflect the likelihood that hospitalwide changes in product use were not exclusively driven by recommended changes in frequent touch-point cleaning. Outcomes from sensitivity analyses were based on 10 000 simulations. Given issues with interpreting uncertainty in the ICER [33], the probability that the intervention was cost-effective was calculated as the proportion of model simulations that returned a positive NMB.

RESULTS

REACH Bundle Effectiveness

The intervention was associated with a decrease in SAB and VRE infection rates, with a combined 40 infections prevented over approximately 1.3 million occupied bed days. Bundle effectiveness estimates were larger for SAB (23.5 infections prevented; 95% confidence interval [CI], −15.3 to 62.0) compared with VRE (16.0 infections prevented; 95% CI, 0.1–32.1); however, the former had greater statistical uncertainty. Insufficient evidence of effectiveness on CDI rates (relative risk, 1.07; 95% CI, 0.88–1.30) led to its exclusion from subsequent analysis, given our focus on cost savings and health benefits from fewer infections. Infections prevented under the intervention resulted in a combined gain of 43 QALYs (95% CI, −17.8 to 160.5).

Cost Outcomes

Implementing the cleaning bundle cost approximately $349 000 (95% CI, $331 000–$367 000), or $2430 per 10 000 occupied bed days during the intervention phase (Figure 1). Changing disinfectant represented 34% of total costs ($118 000; 95% CI, $107 000–$129 000) or $823 per 10 000 occupied bed days.

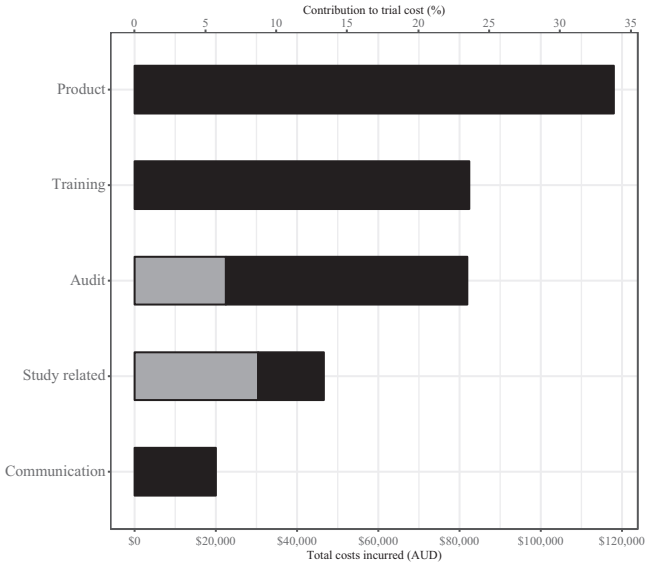


Figure 1. Summary of total trial costs across all hospitals by phase and bundle component. Estimates are expected values from 10 000 model simulations. Gray = preintervention; black = intervention. Abbreviation: AUD, Australian dollars.

Preintervention audit activities and study-related implementation incurred similar costs; however, their overall contribution was relatively small, consuming 15% of total costs. After accounting for differences in occupied bed days, the expected per-hospital costs of establishing and maintaining the cleaning bundle were approximately $4960 (95% CI, $4700–$5200) and $29 400 (95% CI, $27 700–$31 000), respectively. Hospital-level disinfectant costs were a key source of heterogeneity between hospitals, ranging from $838 saved to an additional $3090 spent per 10 000 intervention-occupied bed days. A further breakdown of costs is provided in Supplementary Tables 2 and 3.

Fewer infections during the intervention phase released 346 bed days and generated $147 000 in savings under the CEO WTP approach to valuing bed days (Table 2). Approximately one-third of savings were from treatments avoided, with cost savings marginally higher for SAB ($23 900; 95% CI, −$16 000 to $63 000) compared with VRE ($18 800; 95% CI, $125–$38 000). Total savings based on accounting values were higher, resulting in a net cost saving of $375 000 (95% CI, -$1 486 000 to $605 000). Because extra length-of-stay estimates for VRE were not available separately for the general ward and the ICU, our analysis assumed cost savings for this infection based on general ward values only. A follow-up analysis of this assumption and its impact on expected cost savings is provided in Supplementary Table 4.

There was strong evidence that the intervention was cost-effective; however, outcomes were affected by the approach taken for valuing bed days (Figure 2). Under the conservative CEO WTP approach, the NMB of the cleaning bundle was

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Table 2. Estimated Cost Savings From Fewer *Staphylococcus aureus* bacteremia and vancomycin-resistant enterococci Infections

	Estimate (95% CI)	
Outcome	SAB	VRE
Bed days released		
General Ward	263 (−162 to 751)	61 (−.1 to 127)
ICU	22 (−18 to 89)	…
Dollar value of bed days released		
Accounting	$579 507 (−$346 131 to $1 647 934)	$101 404 ($652 to $210 925)
CEO WTP	$87 547 (−$54 856 to $246 323)	$17 272 ($110 to $36 498)
Treatment costs avoided	$23 884 (−$15 537 to $63 109)	$18 814 ($125 to $38 255)
Accounting	$25 721 ($15 481 to $36 082)	$7508 ($6226 to $8795)
CEO WTP	$4749 ($3342 to $6249)	$2254 ($1927 to $2603)
Change in total costs		
Accounting	−$374 708 (−$1 485 578 to $605 129)	
CEO WTP	$201 398 ($4507 to $385 570)	

Abbreviations: CI, confidence interval; ICU, intensive care unit; CEO, chief executive officer; SAB, *Staphylococcus aureus* bacteremia; VRE, vancomycin-resistant enterococci; WTP, willingness to pay.

approximately $1.02 million, with an expected ICER of $4684 per QALY. In contrast, higher dollar values assigned to general ward and ICU bed days under the accounting approach returned a NMB of $1.6 million and an expected savings of $8685 per QALY. Despite these differences, the probability that the intervention was cost-effective was consistently high, with 86% and 88% of model simulations returning a positive NMB under CEO WTP and accounting approaches, respectively.

DISCUSSION

Our study has shown that the REACH cleaning bundle is likely to be a cost-effective intervention for reducing HAI burden. Using data collected from a representative mix of Australian hospitals, adopting the bundle cost $4684 per QALY and had greater than an 80% chance of being cost-effective. Pragmatic implementation of the bundle in real-world hospital settings combined with prospective data collection under a stepped-wedge design produced high-quality evidence that the bundle would be cost-effective if implemented elsewhere in similar hospitals for reducing healthcare-associated SAB and VRE infections.

Differences between approaches to valuing bed days highlighted the importance of healthcare payer perspective and its impact on decision making. While cost-effectiveness probabilities were robust, the use of accounting values predicted net cost savings from fewer SAB and VRE infections. Unlike resources such as antibiotics that incur direct expenditure, bed days are an opportunity cost of treating an HAI [34], and their release for use by other patients does not result in immediate cash savings [15]. As the outcomes of cost-effectiveness analysis are intended to inform decisions about the reallocation of scarce resources, the WTP approach is recommended to avoid overstating expected savings from proposed interventions.

Insufficient evidence of the bundle in reducing CDI rates led to its exclusion from analysis. We have no plausible reason to believe that the intervention increased CDI rates, as it was implemented alongside ongoing infection-control activities. A possible explanation for this result is the impact of CDI reservoirs in the community and subsequent transmission of genetically diverse strains into the hospital setting [35]. Furthermore, not all hospitals used a sporicidal disinfectant [17] and, because the bundle did not prescribe specific cleaning products, it is likely that some products used were ineffective against CDI.

Costing information sought to inform on real-world implementation costs but was subject to limitations. Low-quality data on detergent use led to their exclusion from analysis; however, the effect of this was likely to be small as practice changes predominantly involved increased disinfectant use for frequent touch-point cleaning. Furthermore, costs were not attributed to improving cleaning technique as this would have required time-in-motion studies. Instead, we assumed that the number of cleaning staff within a hospital did not change, and that staff would be cleaning more effectively due to improved product use and cleaning technique. No major changes to staffing were reported as part of routine monitoring throughout the study.

Cost savings relied on secondary data sources for extra length of stay and infection-related mortality. Outcomes from multistate modeling studies were used for SAB to minimize the risk of time-dependent bias [19, 36, 37]; however, similar studies for VRE infection were unavailable. Vancomycin-resistant enterococci estimates were sourced from studies with comparable patient infection case mix and were comparable with other HAI studies [38, 39]. Future studies of VRE outcomes should

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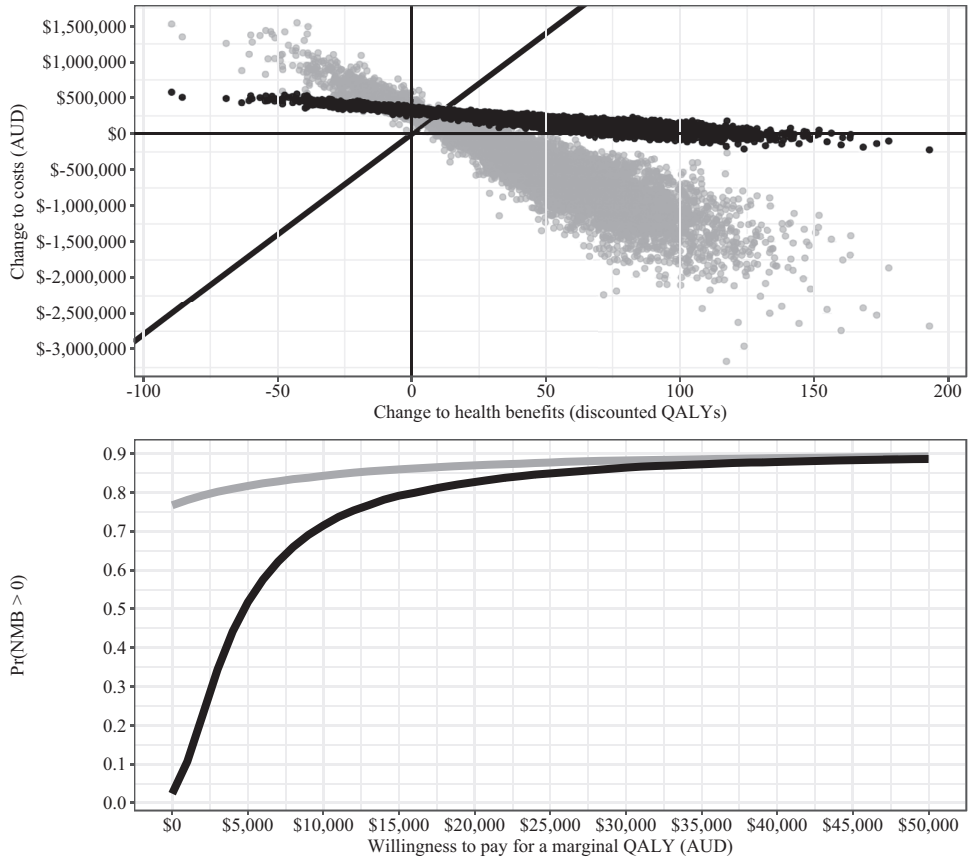


Figure 2. Cost-effectiveness plane (*top panel*). Distribution of NMB (*bottom panel*). Outcomes are colored according to the approach for valuing hospital bed days (gray = accounting; black = CEO willingness to pay). Abbreviations: AUD, Australian dollars; CEO, chief executive officer; NMB, net monetary benefit; Pr, probability; QALY, quality-adjusted life-year.

prioritize the use of multistate modeling to address this limitation and the differential effects of bloodstream versus urinary tract infection.

Treatment costs per infection were based on expert opinion and are a potential limitation of our model. However, resulting cost savings were conservative compared with other studies. For example, a retrospective cohort analysis on the costs of SAB-related hospitalizations between 2010 and 2014 reported estimates of US$15 578–$40 725 for methicillin-susceptible Staphylococcus aureus and US$14 792–$34 526 for methicillin-resistant S. aureus [40]. Attributable costs per VRE infection of US$6565–$14 850 have also been published [41, 42].

It is possible that a Hawthorne effect contributed to bundle effectiveness outcomes, as hospital staff were likely to change behavior because they were being monitored. Given the inclusion of monthly audits as a fixed element of the bundle, such an effect can be considered as part of the bundle as staff were likely to change their behavior precisely because they were being monitored.

Findings from this study compare favorably against other HAI prevention strategies and provide evidence for allocating hospital resources to improving cleaning. In the United States, a 10-year study of investment in infection-prevention measures produced an ICER of US$23 278 (AUD$31 457; 1 AUD = 0.74 USD) per QALY based on reductions in central line–associated bloodstream infections and ventilator-associated pneumonia [5]. A retrospective evaluation of the Australian National Hand Hygiene Initiative reported similar outcomes for SAB, with an incremental program cost of AUD$29 700 per QALY [26]. While this comparison raises questions about disinvestment from more expensive prevention strategies, we stress that our analysis describes the incremental cost-effectiveness of improved cleaning conditional on existing measures. Decision makers should therefore consider these results in the context of current hospital practices and the relative effectiveness of current infection-control measures.

Supplementary Data

Supplementary materials are available at *Clinical Infectious Diseases* online. Consisting of data provided by the authors to benefit the reader, the posted materials are not copyedited and are the sole responsibility of the authors, so questions or comments should be addressed to the corresponding author.

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Notes

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