Quantifying and interpreting inequality of surgical site infections among operating rooms

Quantification et interprétation de l'inégalité des infections opératoires entre les salles d'opération

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Abstract

Purpose The incidence of surgical site infection differs among operating rooms (ORs). However, cost effectiveness of interventions targeting ORs depends on infection counts. The purpose of this study was to quantify the inequality of infection counts among ORs.

Methods We performed a single-centre historical cohort study of elective surgical cases spanning a 160-week period from May 2017 to May 2020, identifying cases of infection within 90 days using International Classification of Diseases, Tenth Revision, Clinical Modification diagnosis codes. We used the Gini index to measure inequality of infections among ORs. As a reference, the Gini index for inequality of household disposable income in the US in 2017 was 0.39, and 0.31 for Canada.

Results There were 3,148 (3.67%) infections among the 85,744 cases studied. The 20% of 57 ORs with the most and least infections accounted for 44% (99% confidence interval [CI], 36 to 52) and 5% (99% CI, 2 to 8), respectively. The Gini index was 0.40 (99% CI, 0.31 to 0.50), which is comparable to income inequality in the US. There were more infections in ORs with more minutes of

cases (Spearman correlation $\rho = 0.68$; $P < 0.001$), but generally not in ORs with more total cases ($\rho = 0.11$; $P = 0.43$). Moderately long (3.3 to 4.8 hr) cases had a large effect, having greater incidences of infection, while not being so long as to have just one case per day per OR. There was substantially greater inequality in infection counts among the 557 observed combinations of OR specialty (Gini index 0.85; 99% CI, 0.81 to 0.88).

Conclusions Inequality of infections among ORs is substantial and caused by both inequality in the incidence of infections and inequality in the total minutes of cases. Inequality in infections among OR and specialty combinations is due principally to inequality in total minutes of cases.

Résumé

Objectif L'incidence d'infections opératoires diffère d'une salle d'opération (SOP) à une autre. Toutefois, le rapport coût-efficacité des interventions ciblant les SOP dépend de l'incidence des infections. Le but de cette étude était de quantifier l'inégalité du nombre d'infections entre les SOP.

Méthode Nous avons effectué une étude de cohorte historique et monocentrique des cas chirurgicaux non urgents couvrant une période de 160 semaines allant de mai 2017 à mai 2020. Nous avons identifié les cas d'infection dans les 90 jours suivant l'opération à l'aide des codes de diagnostic de la Classification internationale des maladies, dixième révision, modification clinique. Nous avons utilisé l'indice de Gini pour mesurer l'inégalité des infections entre les SOP. À titre de référence, en 2017, l'indice de Gini pour l'inégalité du revenu disponible des ménages était de 0,39 aux États-Unis et de 0,31 pour le Canada.

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Résultats Il y a eu 3148 (3,67 %) infections parmi les 85 744 cas étudiés. Les quintiles des 57 SOP ayant le plus et le moins d'infections représentaient 44 % (intervalle de confiance [IC] 99 %, 36 à 52) et 5 % (IC 99 %, 2 à 8) des infections, respectivement. L'indice de Gini était de 0,40 (IC 99 %, 0,31 à 0,50), ce qui est comparable à l'inégalité des revenus aux États-Unis. Il y avait plus d'infections dans les SOP comptant plus de minutes de cas (corrélation de Spearman $\rho = 0,68$; $P < 0,001$), mais généralement pas dans les SOP avec un nombre plus élevé de cas totaux ($\rho = 0,11$; $P = 0,43$). Les cas modérément longs (3,3 à 4,8 heures) ont eu un effet important, ayant des incidences plus importantes d'infection, tout en n'étant pas suffisamment longs pour n'avoir qu'un seul cas par jour et par SOP. Une inégalité sensiblement plus prononcée a été remarquée dans le nombre d'infections parmi les 557 combinaisons observées de spécialité de SOP (indice de Gini 0,85; IC 99 %, 0,81 à 0,88).

Conclusion L'inégalité des infections entre les SOP est importante et causée à la fois par l'inégalité dans l'incidence des infections et par l'inégalité dans la durée totale (en minutes) des cas. L'inégalité dans les infections entre les SOP et les combinaisons de spécialités est principalement due à l'inégalité dans le nombre total de minutes des cas.

Keywords surgical site infection · operating room management · cost effectiveness · operations research · analytics · Gini index

Surgical site infections have an overall population incidence of approximately 3.6%.^{1,2} That incidence can be reduced by interventions applied to each case (including specialized hand hygiene device, double gloving during tracheal intubation, and intravenous catheter hub care) and feedback to anesthesiologists, surgeons, and other personnel by monitoring *Staphylococcus aureus* transmission within and between cases as a marker for noncompliance.^{3–6} Previously, we examined study designs, including sample size, for monitoring *Staphylococcus aureus* transmission intraoperatively to screen for high transmission and to assess the impact of behavioural measures on preventing infections.^{5,7} We included an example of how to define the population for transmission sampling by using infection data from four studies of closed lumen intravenous systems and hand decontamination.⁵ Among 298 combinations of operating room (OR) and specialty, there were only ten that accounted for 1.0% or greater of surgical cases and had at least 0.20 surgical site infections per eight hours of cases.⁵ Limiting sampling of *Staphylococcus aureus*

transmission (e.g., from the hands of the anesthesiologists at the start and end of cases)^{3–5} to only a few ORs and/or OR specialty combinations may be a more cost effective protocol than monitoring randomly selected cases.⁶ However, that conclusion was based on data pooled among hospitals, studies, and time periods.⁵ In addition, raw percentages of infections were considered, compared with formal statistical analyses of inequality.⁵

While the previously mentioned interventions can be applied to individual cases, there are also OR management interventions to reduce surgical site infection that are limited to specific ORs (e.g., special ventilation systems or germicidal lighting).⁸ For example, ORs differ in their numbers of air changes per hour, ceiling air diffuser designs, room geography, and types of airflow (e.g., laminar or turbulent).^{9–13} Some ORs are designed with door locks and electronic signage to prevent main and inner core doors from being open at the same time.¹⁴ Germicidal OR lighting can also be installed.¹⁵ Anesthesia machines with greater ease of decontamination can be purchased.¹⁶ In addition, categories of procedures at greater risk for contamination can be limited to a few ORs.^{17,18} Because such interventions to reduce infections are implemented for select ORs, knowing the extent to which resulting infections differ among ORs is important. That knowledge could then be applied to making decisions to mitigate infection by investing in infection prevention measures for some but not all ORs.

In the current historical cohort study, we addressed the preceding questions by obtaining data from a single large teaching hospital with surgical site infections routinely identified as part of infection control surveillance. We used those data to quantify the magnitude of inequality of surgical site infections among ORs. We evaluated whether the inequality is sufficiently large that targeting individual ORs is warranted compared with preventing surgical site infections in general. We examined the mechanism for that inequality in surgical site infections among ORs. Finally, we repeated the analyses for combinations of OR and procedural specialty.

Methods

The University of Iowa institutional review board determined that the project “does not meet the regulatory definition of human subjects research and does not require [further] review by the institutional review board because the activity is limited to analyses of deidentified data.”

Data and ORs analyzed

We studied surgical cases of all specialties, excluding obstetrics, performed during 160 consecutive weeks between 1 May 2017 and 24 May 2020, at a large teaching hospital in Iowa. There were $N = 57$ ORs, all available for use throughout the study period. The start date was the first regular workday after the institution's new pediatric hospital, with its own surgical suite for children, was fully open. The end date was the last full four-week period 90 days preceding the start of our study; 90 days was chosen as it matched the US Centers for Medicare & Medicaid Services' postoperative period for physician payment.¹⁹

We included only elective (scheduled) surgery defined as cases with a patient able to wait at least three days for surgery. From the OR information system data, each case's date of surgery, specialty, minutes of OR time ("wheels in" to "wheels out"), and a blinded encounter number were obtained. That file was linked with another file, using the same blinded encounter number, containing the dates of all visits (e.g., phone call, video meeting, or subsequent hospitalization) of the same patient, and with one or more relevant International Classification of Diseases, Tenth Revision, Clinical Modification (ICD-10-CM) diagnosis codes. The included codes are listed in Table 1.^{20,21} These data were all collected as part of the hospital's routine practice. We treated a case as having a surgical site infection if the patient had one of the predefined ICD-10-CM codes noted in the electronic health record (Epic; Epic Systems, Verona, WI, USA) from the date of surgery through 90 subsequent days.

Statistical measures of inequality of postoperative surgical site infection among ORs

We used three measures of inequality among the surgical site infection counts among ORs.^{22–28} Infection counts were deliberately used (vs incidences of infection) because counts are not proportional to the incidences of infection. This is a consequence of inequality in the numbers of cases (i.e., the denominators) among ORs.

The first measure of inequality of counts of surgical site infections was the coefficient of quartile variation, measured among the ORs. The coefficient of quartile variation equals the difference of the 3rd and 1st quartiles of the infection counts divided by the sum of the quartiles.²² If each OR had the same number of infections, the coefficient of quartile variation would be zero as the 1st and 3rd quartiles would be identical. The coefficient of quartile variation has an accurate analytical confidence interval.²² Nevertheless, this coefficient has no specific relationship with ORs and cannot be decomposed into sources of variability in the infection counts.

The second measure of inequality involved calculation of percentile shares. Percentile shares of infection counts, counts of surgical cases, and total OR minutes can be compared among the upper quintile of ORs, lower quintile, and so forth.²³ The percentile shares are the percentages of infections, cases, and minutes that fall into each of the quintile intervals.²³ For example, when determining the quintile intervals for total OR minutes, the $n = 57$ totals were sorted in ascending order from 1 to 57. Then, essentially, the number of minutes corresponding to the 11.4th, 22.8th, 34.2nd, and 45.6th ORs were selected to achieve an equal count ($11.4 = 57/5$) of ORs in each of the five intervals; interpolation was applied because

Table 1 International Classification of Diseases (ICD-10-CM) diagnosis codes for identification of surgical site infection among postoperative encounters within 90 days

Code	Count	Description
T81.4	2909	Infection following a procedure
T82.7	245	Infection and inflammatory reaction due to other cardiac and vascular devices, implants, and grafts
T83.5	249	Infection and inflammatory reaction due to prosthetic device, implant, and graft in the urinary system
T84.5	1272	Infection and inflammatory reaction due to internal joint prosthesis
T84.6	151	Infection and inflammatory reaction due to internal fixation device
T84.7	255	Infection and inflammatory reaction due to other internal orthopedic prosthetic devices, implants, and grafts
T85.7	319	Infection and inflammatory reaction due to other internal prosthetic devices, implants, and grafts

All listed codes included all subsequent 6th, 7th, and 8th digits. For comparison, two previous studies used ICD-10-CM diagnosis codes for hip and knee arthroplasty cases. Lethbridge *et al.* used three of the codes we specified (T84.5, T84.6, and T84.7)²⁰ and Rennert-May used the three ICD-10-CM codes mentioned above plus T81.4.²¹ They also used T81.82, persistent postoperative fistula.²¹ We excluded that code because it is not necessarily indicative of new infection among patients undergoing elective surgery. Note that the current study did not include obstetrical patients; hospitals that would include patients undergoing Cesarean delivery would also include T86.0, infection of obstetric surgical wound.

$n = 57$ is not an equal multiple of five. We used quintiles because we expected the confidence intervals to be wide with only 11 to 12 observations per interval. Percentile shares are easy to interpret (e.g., if there were no inequality, each quintile of ORs would have 20% of infections, cases, etc.). Confidence intervals for the proportional shares of surgical site infections were calculated using the bias corrected and accelerated bootstrap method, with 1,000 replications.²³ The software used was the STATA (StataCorp LLC, College Station, TX, USA) function *pshare*.²³

The most complicated measure of inequality among infections that we used, albeit the most informative, was the Gini index.^{24–28} The Gini index is the mean absolute difference in the surgical site infection counts, case counts, or total minutes among all pairwise combinations of ORs. The formula is given in equation (1) of the Appendix. Previously, we used the Gini index to understand changes in the distribution of surgical cases over time among hospitals in Iowa.²⁸ The mathematics of the Gini index are included in the Appendix. Our interest is the relative effect on the Gini index of the marginal percentage change in the count of infections, cases, or minutes among surgical cases of each category. The categories are cases of different durations. Case duration is considered because cases of longer duration have a greater risk for surgical site infection, but ORs with more extended duration cases have fewer cases per day.⁸ Non-homogeneity in the number of cases per day among ORs is important because the inequality of the infection counts among ORs (using any of the three different measures of inequality) would be the same as the inequality of the incidence of infections among ORs if all ORs had the same overall count of cases. Nevertheless, that is obviously untrue (e.g., ORs mostly used for cataract surgery have vastly more cases per day overall than ORs mostly used for cardiac surgery). Confidence intervals for the Gini index and for the relative marginal effects were calculated using the bias corrected bootstrap method, with 1,000 replications.²⁷ The software used was the STATA function *descogini*.²⁷

When quantifying inequality, we deliberately made no adjustment for patient factors. For example, if all orthopedic patients with diabetes and expected to have blood transfusion were assigned to one OR, then adjusting for patient risk factors would shrink each of these cases' surgical site infections' values from 1.0 to a lesser value close to the overall incidence of infection. That would not be desired, because these cases were assigned to the OR (i.e., cases in that OR should have disproportionate target for reductions in infections). The desired inferential adjustments for covariates would be characteristics of the ORs or cases influencing assignment, not the patients, and

the most logical covariate would be the specialty of the operating surgeon. Analyses were repeated for combinations of OR and surgical specialty.

Other statistical methods

Incidences of infection were compared among quarter-year periods of data. Confidence intervals for these ratios of infection counts to case counts were calculated with Huber robust standard errors clustered by OR and by combination of OR and specialty, respectively. We used the STATA *ratio* function. Concordances and discordances were calculated in Excel and reported including consideration of ties using Kendall's τ_b . Comparisons of the Gini indices were made using the Z-test with corresponding *P* values. These analyses were repeated using the combinations of OR and specialty, as sensitivity analyses and because of their relevance to the study of intraoperative *Staphylococcus aureus* transmission (see Discussion). Confidence intervals for Spearman correlation coefficients were calculated using the Fisher transformation; STATA *cir* function. Confidence intervals for odds ratios were calculated using the Cornfield interval; STATA *csi* function.

Results

Among the 85,744 elective cases performed over the 160 weeks, there were 3,148 (3.67%) with one or more postoperative ICD-10-CM codes indicating the presence of a surgical site infection. The data were initially segmented into four consecutive periods of 40 weeks. Table 2 shows that there was no detectable effect of the period either on the inequality of the infection counts among ORs or on the incidences of infection over time. Subsequent analyses were therefore pooled among the 160 weeks.

Figure 1 shows the inequality in counts of surgical site infections among the 57 ORs. The 20% of ORs with the most surgical site infections accounted for 44% of the infections (99% CI, 36 to 52), and the 20% of ORs with the fewest infections had 5% of the infections (99% CI, 2 to 8).²³ There were 65% of the ORs with at least 20% of cases performed by > 1 specialty, 75% with at least 10% performed by > 1 specialty, and 79% with at least 5% performed by > 1 specialty. The corresponding percentages based on minutes were 61%, 74%, and 77%, respectively.

The inequality of the counts of surgical site infections among the 57 ORs did not match the inequality of incidences of infection among ORs. In other words, the ORs with substantial infection counts often lacked

Table 2 Changes over time in the distribution of surgical site infections among operating rooms and among operating room and specialty combinations

Criteria	Period	Result (99% confidence interval)
Gini index among operating rooms	1 st 40-weeks	0.42 (0.35 to 0.51)
	2 nd 40-weeks	0.40 (0.32 to 0.49)
	3 rd 40-weeks	0.42 (0.35 to 0.52)
	4 th 40-weeks	0.43 (0.32 to 0.55)
Infections per case, estimated while clustering by operating room	1 st 40-weeks	3.6% (2.8 to 4.5)
	2 nd 40-weeks	3.7% (2.9 to 4.6)
	3 rd 40-weeks	3.7% (2.8 to 4.6)
	4 th 40-weeks	3.6% (2.7 to 4.6)
Gini index among the combinations of operating room and specialty	1 st 40-weeks	0.87 (0.85 to 0.91)
	2 nd 40-weeks	0.88 (0.85 to 0.90)
	3 rd 40-weeks	0.88 (0.84 to 0.90)
	4 th 40-weeks	0.88 (0.84 to 0.92)
Infections per case, estimated while clustering by the combinations of operating room and specialty	1 st 40-weeks	3.6% (2.9 to 4.4)
	2 nd 40-weeks	3.7% (3.0 to 4.5)
	3 rd 40-weeks	3.7% (2.9 to 4.5)
	4 th 40-weeks	3.6% (2.8 to 4.5)

The first eight rows each have a sample size of $n = 57$ operating rooms. The second set of eight rows each have a sample size of $n = 557$ combinations of operating room and specialty.

Fig. 1 Inequality in the percentage shares of surgical site infections among the 57 operating rooms. The percentile shares along the vertical axis are the percentages of cases that fall into each quintile.²³ The range of each quintile is displayed on the horizontal axis. The 20% of rooms with the most surgical site infections accounted for 44% of the infections (99% confidence interval [CI], 36 to 52), and the 20% of rooms with the fewest infections had 5% of the infections (99% CI, 2 to 8). If there were no inequality, each decile would have had 20% of cases.²³

concordance with ORs with high incidences of infection (Kendall's $\tau_b = 0.68$, discordances 15.7% of the 1596 pairwise comparisons).

The Gini index was used to quantify the inequality of surgical site infections among the 57 ORs. The Gini index

equalled 0.40 (99% CI, 0.31 to 0.50), significantly greater than zero for equality ($P < 0.001$).^A For judging the magnitude of the effect size of the inequality of surgical site infection distribution, 0.39 was the Gini index for household disposable income in the United States of America in 2017.^{29, B} The inequality of surgical site infections among ORs was greater ($P < 0.001$) than the inequality of total OR minutes among ORs (Gini index, 0.21; 99% CI, 0.15 to 0.30). The inequality of surgical site infections among ORs (Gini index, 0.40) was also greater ($P = 0.002$) than the inequality of cases among ORs (Gini index, 0.22; 99% CI, 0.15 to 0.31). Similarly, the coefficients of quartile variation were greater for infections than for cases (Table 3). These results show: 1) count inequality of surgical site infections and incidences were not the same; and 2) whereas longer workdays in some ORs than in others is well recognized, the inequality of postoperative surgical site infections was greater.

Operating rooms with more surgical site infections had more total minutes of cases (Spearman rank correlation

^A We repeated the calculation excluding the 16.6% of infections with diagnosis within one day of surgery (i.e., some of these cases probably had surgery for wound infection). The Gini index equalled 0.39 (99% CI, 0.30 to 0.49), $P = 0.93$ compared with the estimate with all cases.

^B For perspective, the 2017 Gini index for household income in Canada was 0.31, much less than for the USA and for the inequality of surgical site infections among ORs.²⁹

coefficient $\rho = 0.68$; $P < 0.001$), but ORs with more infections generally did not have more cases (Spearman $\rho = -0.11$; $P = 0.43$) (Fig. 2).³⁰ The latter relationship was caused by ORs with greater mean hours per case having greater incidences of infections (Spearman $\rho = 0.77$; $P < 0.001$) (e.g., due to the biology of tissue injury) but fewer cases (Spearman $\rho = -0.64$; $P < 0.001$) (Table 4). The observation that there were fewer cases in ORs with longer mean case durations was a consequence of the OR management decisions that aimed to limit the number of work hours per day.

The advantage of quantifying inequality of postoperative infections using the Gini index is that decomposition can be used to identify the subgroup of cases of different durations causing the greatest inequality among ORs. The decomposition and Table 5 are explained in the Appendix. The OR case durations were divided into four equal quartiles and the counts of surgical site infections determined for each quartile. Cases that were 3.3 to 4.8 hr long had greater incidences of surgical site infection (Table 5). They also were sufficiently long to reduce the counts of cases in an OR per day, but not so long as to have a whole day with only one or two cases per OR.^C Consequently, more of these cases in a given OR substantively increased the inequality of infections among ORs. Figure 3 was subsequently created and found to show that relationship graphically.

There was substantially greater inequality in counts of surgical site infections among the 557 observed combinations of OR and specialty than among the 57 ORs (Tables 2–3). The 10% of ORs and specialty combinations with the largest counts of surgical site infections accounted for 76% (99% CI, 69 to 83) of the infections, while 46.9% of ORs and specialty combinations had no observed infections.^D The Gini index for the count of infections equalled 0.85 (99% CI, 0.81 to 0.88). Nevertheless, the inequality of total OR time among ORs

and specialties was comparable (Gini index, 0.82; 99% CI, 0.81 to 0.84; $P = 0.10$). The Spearman correlation between infections and total minutes was $\rho = 0.80$ (99% CI, 0.76 to 0.84). The inequality of cases among ORs and specialties was also comparable (Gini index, 0.83; 99% CI, 0.80 to 0.86; $P = 0.22$). The substantial inequality of cases among ORs and specialties is important conceptually because the incidence of infections equals the count of infections divided by the count of cases. Because the numbers of cases differ substantially among OR and specialty combinations, the combinations of ORs and specialties with the most infections will differ from the combinations with the greatest incidences of infection. Estimates of the coefficients of quartile variation show also large inequality among combinations not only for the infections but also for cases and OR minutes (Table 3).

Discussion

In a resource-constrained environment, interventions to reduce surgical site infection should be preferentially targeted to reduce OR contamination and the OR and specialty combinations with the most infections. Our results show that such inequality of surgical site infections among ORs is due not only to inequality in the incidence of infections but also to inequality in the total minutes of cases. In contrast, among OR and specialty combinations, the cause of the inequality is principally inequality in the total minutes of cases. Thus, considering what ORs and OR and specialty combinations to target is not only an issue of incidence, but also population size in units of minutes or hours.

With respect to efforts to reduce surgical site infections, our results indicate that a policy to apply measures equally among all ORs and specialties would be inconsistent with the substantive inequality of infections among ORs and among OR and specialty combinations. To appreciate the magnitude of these inequalities, they are comparable to and exceed, respectively, the inequality of household income in the USA.^{29,B} Thus, one should not treat ORs as equally important from the perspective of reducing overall postoperative infections. Our results also indicate that when targeting specific ORs, a contributing factor is cases of moderately long duration (e.g., 3.3 to 4.8 hr). Longer case durations increase the incidence of surgical site infections despite longer duration cases being associated with fewer cases per day.

These results pertaining to individual ORs are important because there are multiple interventions that could reduce surgical site infection that are applied according to the OR (e.g., capital equipment or ultraviolet-C germicidal lights used nightly).^{3,8–18} Even at a large teaching hospital with

^C Among the 11,958 combinations of date and room with at least one case lasting 196–290 min, those date and room combinations had a median [interquartile range (IQR)] of 2 [2–3] cases, 11.7% with one case. In contrast, among the 15,398 combinations with at least one case of the preceding quartile of duration (126 to 195 min), there were a median [IQR] of 3 [2–3] cases, 7.48% combinations with one case. Among the 10,025 combinations with at least one case longer than 290 min, there were a median [IQR] of 2 [1–2] cases, 45.7% with one case. Bacterial or viral transmission cannot be measured between successive cases in an OR on a given day when there is only one case that day.

^D There may be interest in categorizing cases using more factors than OR and specialty. Nevertheless, for intervention, the OR must be specified, and the next logical factor for administrative purposes would be specialty. Our use of 160 weeks of data were for scientific purposes, not practical administratively. Only 7% of the combinations of OR and specialty had even 25 observed infections (99% confidence interval, 3 to 9). See also Table 3.

Table 3 Coefficients of quartile variation in counts of surgical site infection, cases, and minutes of operating room time

Count variable	Median [interquartile range]	Coefficient of quartile variation (99% confidence interval)
Cases per week per operating room ($n = 57$)	10.0 [8.0–11.2]	17% (8 to 35)
Hours per week per operating room ($n = 57$)	26.9 [19.2–32.4]	26% (16 to 40)
Infections per week per operating room ($n = 57$)	0.26 [0.15–0.45]	50% (36 to 67)
Cases per week per observed combination of operating room and specialty ($n = 557$)	0.11 [0.02–0.44]	89% (85 to 94)
Hours per week per observed combination of operating room and specialty ($n = 557$)	0.27 [0.06–1.19]	91% (87 to 95)
Infections per week per observed combination of operating room and specialty ($n = 557$)	0.006 [0.000–0.019]	100%
Cases per week per combination of operating room and specialty averaging at least one case every other week (i.e., at least 80 observed cases) ($n = 131$)	2.12 [1.02–5.34]	68% (58 to 79)
Hours per week per combination of operating room and specialty averaging at least one case every other week (i.e., at least 80 observed cases) ($n = 131$)	6.74 [2.61–13.67]	68% (56 to 82)
Infections per week per combination of operating room and specialty averaging at least one case every other week (i.e., at least 80 observed cases) ($n = 131$)	0.062 [0.025–0.156]	72% (62 to 84)

The coefficient of quartile variation equals the difference between the 3rd and 1st quartiles divided by the sum of the quartiles.²²

Fig. 2 Relationship between observed count of surgical site infections and the numbers of cases and hours of operating room time. The sample sizes are 57 operating rooms among 160 weeks. The Spearman rank correlation coefficients equal -0.11 for the left panel ($P = 0.43$) and 0.68 for the right panel ($P < 0.001$). These data are limited to elective (scheduled) cases. The hours of operating room time exclude turnover times. The solid black lines were drawn using the STATA *lowess* function, using a bandwidth (span) of 0.99. Regarding the three operating rooms each averaging > 1.0 infections per week, they are physically adjacent to one another, mostly used by

the same specialty. They are outliers with respect to the count of infections because they are in the upper quartiles both of operating room minutes and infection rates (i.e., infections per case). Nevertheless, they are not outliers for their incidences of infection.³⁰ The upper inner fence (i.e., the lower limit for mild outliers) = 3^{rd} quartile + $1.5 \times (3^{\text{rd}}$ quartile $-$ 1^{st} quartile) = $5.74\% + 1.5 \times 4.18\%$, which is greater than the maximum observed incidence.³⁰

Table 4 Spearman rank correlation coefficients among characteristics of the 57 operating rooms over the studied 160 weeks

	Infections	Cases	Minutes	Incidence
Cases	−0.11 $P = 0.43$			
Minutes	0.68 $P < 0.001$	0.07 $P = 0.61$		
Incidence, overall infections per case	0.80 $P < 0.001$	−0.52 $P < 0.001$	0.43 $P < 0.001$	
Duration, overall minutes per case	0.58 $P < 0.001$	−0.64 $P < 0.001$	0.63 $P < 0.001$	0.77 $P < 0.001$

These calculations depend on sufficiently large sample sizes within operating rooms. There were 160 weeks of data. Among the 57 operating rooms, the 10th (25th) percentiles for infections, cases, and minutes were 18 (24), 569 (1,275), and 128,589 (184,171), respectively. Sample sizes for the 577 combinations of operating room and specialty were not as large (Table 3). The associations were not linear enough to use Pearson correlation coefficients, and there was substantial heteroscedasticity (Figs 2–3).

many specialties that regularly operate in only a few ORs, targeting ORs and targeting specialties are not the same.^C The results by OR and specialty combination are needed for purposes of selecting how to use *Staphylococcus aureus* within and between case transmission as a marker for contamination exceeding critical levels of contamination.^{2,5,6}

Achievable reductions in surgical site infection have economic value. For example, consider the three ORs at the studied hospital with the most infections being those from one specialty (Fig. 2). Those ORs had approximately 170 infections and 1,700 cases annually. In an elegant study, Shepard *et al.* quantified the cost of surgical site infection in units of hospital days and reported a mean adjusted effect of approximately 3.449 days.³¹ The equivalent USD value could then be obtained for the relevant region (e.g., American Hospital Association survey reports the mean cost per day for a nonprofit hospital in Iowa in 2018 was USD 1,524).³² From the randomized-controlled trial of a bundle of interventions (e.g., improved hand hygiene and cleaning of the anesthesia machine surfaces after intubation), the hazard ratio for surgical site infections was 0.12 ($P = 0.004$) and the incidence risk ratio for the primary endpoint of reduced transmission was 0.56 ($P < 0.001$). Using this latter, more conservative choice as the estimate of future reduction in surgical site infections, the estimated value of the one-year reduction in surgical site infections would be $(1 - 0.56) \times (170 \text{ infections}) \times (\text{cost in units of hospital days } 3.449) \times (\text{USD } 1,524 \text{ cost per hospital day}) = \text{USD } 393,170$. In comparison, a bundle of supplies (e.g., intravenous catheter hub cleaning) costs the hospital approximately USD 13.69 per case. Monitoring of bacterial transmission for the one specialty and using 125 case pairs over the intervention year³ to provide feedback costs approximately USD 60,000.^{4,5} Thus, total cost to prevent the infections, USD

$13.69 \times 1,700 \text{ cases} + \text{USD } 60,000 = \text{USD } 83,270$, is approximately 21% of the estimated direct cost saving. The bundle would be expected to be net cost savings provided the incidence risk ratio is less than 0.91, where $0.91 = 1 - (\text{USD } 83,270) / (170 \times 3.449 \times \text{USD } 1,524)$.

Limitation: surgical site infection monitoring

Our paper does not inform as to how to monitor for surgical site infections. Nevertheless, we used data from surgical site infections estimated from postoperative ICD-10-CM diagnosis codes, and thus the validity of those data remains relevant.

Our 3.67% surgical site infection incidence compares with the 3.6% rate from a prospective observational study from Dartmouth-Hitchcock Medical Center and UMass Memorial Medical Center during a clinical trial of an intraoperative hand hygiene device used by anesthesia providers.^{1,2,8} In addition, our studied period included the dates (20 September 2018 to 20 September 2019) of the single-hospital randomized trial with some of the hospital's surgeons receiving conventional care *vs* use of a bundle of measures to prevent surgical site infection plus feedback on bacterial and viral transmission using *Staphylococcus aureus* as the monitored marker.³ Those surgeons who chose to participate in that study (e.g., vascular, general, and orthopedic surgeons)^E had a prospectively measured incidence of postoperative

^E The trial included surgeons in a subset of specialties and only patients having surgery in the inpatient surgical suite (i.e., subset of rooms). Therefore, if the study affected our results, it would have decreased the Gini index over time. No suggestion of a decrease was observed. From Table 2, the estimated Gini indexes among ORs was 0.42 during the first 40 weeks *vs* 0.43 during the last. Similarly, the estimated Gini indexes among OR and specialty combinations were 0.87 and 0.88, respectively.

Table 5 Relative marginal effect of cases of different durations on the inequality of surgical site infections among operating rooms, quantified using the Gini index

	1 to 125 min	126 to 195 min	196 to 290 min	291 to 1365 min
Gini index for inequality of surgical site infections among cases with listed operating room durations	0.305	0.498	0.570	0.47
Correlation: case duration category and total (overall) Gini index	0.475	0.900	0.961	0.798
Share of total surgical site infections from cases with the listed operating room durations	24.1%	24.3%	25.3%	26.3%
Share of the inequality of surgical site infections among operating rooms	8.8%	27.4%	34.9%	29.0%
Relative marginal effect of 1% more cases of the case duration category on the total (overall) inequality	−15.3%	3.1%	9.6%	2.6%
99% confidence interval	−24% to −8%	−1% to 7%	5% to 14%	−5% to 13%

Each row and entry in this table is explained in the Appendix. The categories of case durations were selected to achieve the smallest possible mean absolute error from 25.0% in the percentage shares of total surgical site infections. The calculations were performed without rounding using minutes; corresponding dividers were 2.1, 3.3, and 4.9 hr. The median [interquartile range] of durations in each of the four categories were 1.2 [0.8–1.6], 2.6 [2.3–2.9], 3.9 [3.5–4.3], and 6.2 [5.4–7.5] hr, respectively.

surgical site infection of 4.66% (11/236 cases).³ The two incidences did not differ significantly ($P = 0.49$ by exact Chi square test, StatXact-12, Cytel, Cambridge, MA, USA), indicating validity.

Although our study's 3.67% infection incidence did not differ significantly from the previously measured 4.66% incidence, the estimated odds ratio of 0.78 (99% CI, 0.36 to 1.70) was less than 1.00, meaning smaller. Our method for estimating surgical site infection was limited to ICD-10-CM diagnosis codes (Table 1) because we included every surgical case. That differed from the Center for Disease Control's National Healthcare Safety Network process that includes selected, monitored procedures.^F In addition, it differed from the National Surgical Quality Improvement Program that includes randomly selected cases. The number of different data sources used for surgical site infection surveillance is positively associated with greater incidences.³³ Therefore, as expected, our use of ICD-10-CM diagnosis codes alone resulted in a comparable but potentially slightly less infection rate than in the randomized trial.^A

There is another method of comparison of our data that also suggests validity. Previously, we examined the inequality of the incidence of surgical site infection among ORs.^{1,8} The impact of that inequality was that cluster statistical designs at individual hospitals to study surgical site infections and interventions involving individual ORs were futile compared with matched cohort designs.^{1,8} Cluster designs depend on the

intracluster correlation, a measure similar to the coefficient of quartile variation in Table 3, but for the incidence of infection.³⁴ We previously used State of California surgical site infection data to quantify the intracluster correlation among 24 procedure categories' incidences of surgical site infection.¹ We calculated the coefficient of quartile deviation among those procedure categories as 42%. We then repeated it using the US national data for 2018, summing infection counts and procedures between adults and pediatric cases.³⁵ The coefficient of quartile deviation among the procedure categories was 48%. In comparison, among the 57 ORs of the current study, the coefficient of quartile variation for incidence was comparable at 57% (99% CI, 39 to 83). A somewhat greater inequality among ORs would be expected because the Center for Disease Control's National Healthcare Safety Network's monitored procedures do not include those procedures with negligible incidences of infection.

Additional limitations

Although it would have been appealing to include supplemental content with all calculations by OR repeated for OR and specialty combination, this was impractical because of the sample sizes. Despite studying 160 weeks of data and detecting no changes over time, the sample sizes were too small for many combinations of OR and specialty to reach meaningful conclusions.^D Nevertheless, those combinations with small total minutes of cases cannot be excluded because they contribute to the total. Adding additional hospitals would not have helped because that would have just added more combinations of OR and specialty with low counts. Still,

^F Procedures monitored by the National Hospital Safety Network included 14% of our studied cases and 33% of the infections. We found it useful to discuss with administrators that ongoing programs for monitoring selected procedures and cases provide high-quality risk-adjusted assessments of incidence, not cases per year.

Fig. 3 Relationship between observed counts of surgical site infections and the numbers of cases 3.3 to 4.8 hr long. Among the 3,148 cases with infection, the operating room durations were divided into quartiles. The 3rd quartile, 3.3 to 4.8 hr long, contributed to the inequality of surgical site infections among operating rooms

(Table 5). On the left, all surgical site infections are shown, and to the right infections among cases with durations 3.3 to 4.8 hr are shown. The Spearman rank correlation coefficients are 0.72 for the left panel and 0.82 for the right panel (both $P < 0.001$, $n = 57$ operating rooms over 160 weeks).

this limitation was functionally irrelevant for purposes of answering the question studied in this paper – whether inequality of infections differs from inequality of infection incidence among combinations of ORs and incidences. The reason is that incidence equals infections divided by cases. Therefore, our having shown marked inequality of cases among combinations answers the question.

Analyses by OR are needed for tactical implementation of infection preventive measures because capital equipment investments and case scheduling changes to reduce infections are determined by OR.^{8–18} Nevertheless, the necessity of also considering the combination of OR and specialty is unknown, given that the effect of specialty on *Staphylococcus aureus* transmission has been heterogeneous among studies.^{3–5,36,37} Studies showing an association of transmission with specialty all involved the hyper transmissible and more pathogenic strain characteristics of *Staphylococcus aureus*, specifically phenotype H or sequence type 5.^{4,36,37} Nevertheless, that would only be known *after* monitoring bacterial transmission. Furthermore, such strain characteristics are not necessary for benefit of a bundle of environmental and anesthetic interventions and transmission feedback, because phenotype and transmissibility were not measured as part

of the randomized trial, nor was specialty found to be a significant covariate for transmission.³

Although surgical site infections after elective surgery have multiple causes, the interventions by OR and monitoring of *Staphylococcus aureus* transmission disproportionately affect and involve anesthesiologists. Time series analyses of changes over time showed large initial decreases in pathogen transmission from incremental reductions in contamination tightly associated with development of surgical site infections.⁵ For example, patient antisepsis (e.g., nose and oral) is applied in the preoperative area.^{3,17,38} The anesthesia workspace is modified to reduce contamination.^{3,17,38} The surfaces of the anesthesia machine that are often contaminated (e.g., adjustable pressure limiting valve) are wiped as early as feasible after surgical incision.^{3,7,17,38} Germicidal lights or modified surfaces of the anesthesia machine likely are principally targeting the anesthesia work environment.^{15,16} Because anesthesiologists work in multiple ORs (i.e., those not selected for targeted efforts to reduce infection), there may be a crossover effect of the feedback from monitoring pathogen transmission on infections and transmission in other ORs and specialties.

Conclusions

Capital expenses to mitigate surgical site infections have greater cost savings when applied selectively. Tactical use of evidence-based surveillance of *Staphylococcus aureus* transmission to reduce surgical site infections has the benefit of reducing sampling time and laboratory costs. This can be achieved by targeting ORs and OR specialty combinations that have the most surgical site infections. Inequality of surgical site infections among ORs is substantial and caused not only by inequality in the incidence of infections but also inequality in the total minutes of cases. Inequality in infections among OR and specialty combinations is principally due to inequality in the total minutes of cases. Application of the Gini index to quantify the extent of inequality in infections among ORs provides a means to assess the importance of targeting specific listed ORs, or combinations of ORs and specialties, thereby mitigating this undesirable postoperative complication.

Author contributions Franklin Dexter helped with conceptualization, methodology, software, data curation, statistical analysis, writing, and editing. Richard H. Epstein helped with validation, writing, and editing. Randy W. Loftus helped with conceptualization and writing.

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APPENDIX Gini index, its decomposition, and explanations for each row of Table 5

Let Y_{ot} represent the number of surgical cases performed in the o^{th} OR ($o = 1, 2, \dots, N$) during the t^{th} 40-week period, $t = 1, 2, 3$, or 4 (Table 2). The Gini index is presented in terms of the mean absolute pairwise differences among the ORs:

$$G_t = \frac{\sum_{o=1}^{o=N} \sum_{i=1}^{i=N} |Y_{ot} - Y_{it}|}{2N \sum_{o=1}^{o=N} Y_{ot}} \quad (1)$$

For example, suppose that every OR had the same number of cases. Then, the numerator would equal zero (i.e., the minimum value of the Gini index equals 0). In contrast, suppose that $Y_{1t} > 0$ and all other ORs had no cases. Then, $G_t = (N - 1)/N$. Thus, for $N = 57$ ORs, the Gini index can be as large as 0.982. This Appendix is written in precisely the same sequence as our earlier study of the effect of changes in healthcare insurance, patient age distribution, and patient willingness to travel on the distribution of surgical cases among hospitals throughout the State of Iowa.²⁸

Let Y_{ot}^k represent the count of surgical site infections among cases performed in the o^{th} OR and of cases of the k^{th} duration interval, $k = 1, 2, 3$, or 4:

$$Y_{ot} = \sum_{k=1}^{k=4} Y_{ot}^k \quad (2)$$

There are four categories of OR times in Table 5. Y_{ot}^3 corresponding to the third column of numbers in Table 5 would equal the count of surgical site infections, from the o^{th} OR and during the t^{th} period, among cases 196 to 290 min long. The first row of numbers in Table 5 is the Gini index limited to cases of each of the four categories of case durations. For comparison, the overall Gini index equalled 0.397. We are including the t^{th} period in these equations, although time is pooled in Table 5, because we segmented the Gini index by periods in Table 2.

The second row of numbers in Table 5 is the Gini correlation coefficient R_t^k among ORs between a) the number of surgical site infections from cases of the k^{th} duration category and b) the count of surgical site infections of all case durations combined. The Gini correlation is a measure of monotonicity, like the Spearman rank correlation coefficient.²⁶ Table 5 shows that there is a substantively lower Gini correlation for cases of durations 1 to 125 min vs the others, reflecting the markedly lower surgical site infection among cases of brief duration (Table 4).

The third row of numbers in Table 5, S_t^k , is the percentage share among all ORs of the cases of the k^{th} duration interval. We selected the categories in five-minute

increments that resulted in the smallest mean absolute error from equal 25% shares. Thus, this third row has been included for completeness, but adds no extra information.

These efforts are being made to decompose the Gini coefficient of equation (1)²⁴:

$$G_t = \sum_{k=1}^{k=4} G_t^k R_t^k S_t^k \quad (3)$$

For example, using the entries in Table 5 from left to right, $0.305 \text{ Gini index} \times 0.475 \text{ correlation} \times 24.1\% \text{ share} + 0.498 \times 0.900 \times 24.3\% + 0.570 \times 0.961 \times 25.3\% + 0.547 \times 0.798 \times 26.3\% = 0.397$, the value reported in the Results, rounded to 0.40. Equation (3) shows that more cases of durations of the k^{th} category would reduce the inequality of the counts of surgical site infections among ORs if the correlation R_t^k were negative. In contrast, in Table 5, the minimum observed value of R_t^k was $R_t^1 = 0.475$.

The percentage contribution of the surgical site infections of the cases of the k^{th} duration category to overall inequality in infections equals:

$$(G_t^k R_t^k S_t^k) / G_t \quad (4)$$

These K percentage shares sum to equal 1; shown by equation (3). Examining the equation, if all ORs had the same number of cases of the k^{th} duration category (i.e., $G_t^k = 0$), then the contribution of the k^{th} category to overall inequality would equal zero.

For example, consider the category of 196 to 290 min in the 3rd column of numbers in Table 5. The row 4 value of $34.9\% = (0.570 \text{ Gini index for surgical site infections among cases 196 to 290 min from row 1}) \times (0.961 \text{ correlation from row 2}) \times (25.3\% \text{ of infections were among cases with that duration category}) / (0.397 \text{ overall Gini index})$.

Although equation (4) may seem easy to interpret, it is not an appropriate endpoint.³⁹ Suppose that $G_t^k = 0$. That would mean that all ORs had the same number of surgical site infections among cases of the k^{th} category. Suppose too that the number of cases of the k^{th} category duration were increased slightly and identically for all ORs. Then, after the change, the new count of surgical site infections at each OR would be $(1 + e_t^k) Y_{or}^k$. The degree of total inequality of surgical site infections among ORs G_t must have been reduced. Yet, equation (4) would still equal zero.³⁹ Consequently, what is relied upon is the relative effect on the overall Gini coefficient of a marginal percentage change in the number of cases of the k^{th} category duration, $(\partial G_t / \partial e_t^k) / G_t$.³⁹ Several pages of derivation show that the corresponding right-hand side equals^{24,25}:

$$\frac{\partial G_t / \partial e_t^k}{G_t} = \frac{G_t^k R_t^k S_t^k}{G_t} - S_t^k \quad (5)$$

Using economic terminology, this is the elasticity of the Gini index with respect to a uniform percentage change in the number of cases of the k^{th} duration category during the t^{th} period.

The sum of the four relative marginal effects equals 0.0%.²⁴ For example, referring to the last row of Table 5, from left to right, $-15.3\% + 3.1\% + 9.6\% + 2.6\% = 0.0\%$. The negative marginal effect of 15.3% shows that increases of those cases would reduce the inequality of surgical site infections among ORs. The positive marginal effects of 3.1%, 9.6%, and 2.6% show that an equal percentage increase in cases of these durations in all ORs would increase the heterogeneity in the counts of surgical site infections among ORs.

OR = operating room.

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