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The surgical-interventional cleavage in cardiovascular medicine: A brazilian health care system analysis

A clivagem cirúrgica-intervencionista na medicina cardiovascular: Uma análise do sistema de saúde brasileiro

La escisión quirúrgico-intervencionista en medicina cardiovascular: Un análisis del sistema de salud brasileño

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Abstract
This study aims to compare in-hospital mortality, costs, and length of stay between traditional cardiovascular surgery and interventional cardiology in SUS (2009–2023), evaluate temporal trends in technological substitution, and quantify long-term effects using risk-adjusted models. An ecological design analyzed aggregated data from 2,303,648 procedures. ARIMA models and negative binomial regression adjusted temporal trends and mortality risk. Results revealed accelerated technological substitution (-1.27% annual decline in surgeries; $p < 0.001$), with initial mortality advantage for interventional procedures (RR = 0.43; 95% CI: 0.11–0.76). However, synthetic projections showed benefit inversion by 2023 (+72.38 excess deaths), linked to an inverse learning curve for interventions (+0.83% mortality per 1% volume increase; $p < 0.001$). Cost savings (R$5,524/case) and shorter hospitalization (-5.07 days) coexisted with rising complexity in surgical cohorts, increasing baseline mortality risk by 0.59% annually ($p < 0.001$). The study concludes that technological substitution in SUS achieved economic efficiency but requires parallel investments in training and risk stratification for clinical sustainability.
Keywords: Cardiovascular diseases; Cardiovascular surgical procedures; Hospital mortality; Unified Health System; Health inequities.

Resumo
Este estudo tem como objetivo comparar a mortalidade intra-hospitalar, os custos e o tempo de permanência entre a cirurgia cardiovascular tradicional e a cardiologia intervencionista no SUS (2009–2023), avaliar as tendências temporais na substituição tecnológica e quantificar os efeitos a longo prazo usando modelos ajustados ao risco. Um projeto ecológico analisou dados agregados de 2.303.648 procedimentos. Os modelos ARIMA e a regressão binomial negativa

ajustaram as tendências temporais e o risco de mortalidade. Os resultados revelaram substituição tecnológica acelerada (-1,27% de declínio anual nas cirurgias; p < 0,001), com vantagem de mortalidade inicial para procedimentos intervencionistas (RR = 0,43; IC 95%: 0,11–0,76). No entanto, as projeções sintéticas mostraram inversão do benefício até 2023 (+72,38 óbitos em excesso), atrelada a uma curva de aprendizado inversa para intervenções (+0,83% de mortalidade por aumento de 1% no volume; p < 0,001). A economia de custos (R$ 5.524/caso) e o menor tempo de internação (-5,07 dias) coexistiram com o aumento da complexidade nas coortes cirúrgicas, aumentando o risco de mortalidade basal em 0,59% ao ano (p < 0,001). O estudo conclui que a substituição tecnológica no SUS alcançou eficiência econômica, mas requer investimentos paralelos em capacitação e estratificação de risco para a sustentabilidade clínica.
Palavras-chave: Doenças cardiovasculares; Cirurgia cardiovascular; Mortalidade hospitalar; Sistema Único de Saúde; Desigualdades em saúde.

Resumen
Este estudio tiene como objetivo comparar la mortalidad intrahospitalaria, los costos y la duración de la estancia entre la cirugía cardiovascular tradicional y la cardiología intervencionista en el SUS (2009-2023), evaluar las tendencias temporales de la sustitución tecnológica y cuantificar los efectos a largo plazo utilizando modelos ajustados por riesgo. Un diseño ecológico analizó datos agregados de 2.303.648 procedimientos. Los modelos ARIMA y la regresión binomial negativa ajustaron las tendencias temporales y el riesgo de mortalidad. Los resultados revelaron una sustitución tecnológica acelerada (-1,27% de disminución anual en cirugías; p < 0,001), con ventaja de mortalidad inicial para los procedimientos intervencionistas (RR = 0,43; IC 95%: 0,11-0,76). Sin embargo, las proyecciones sintéticas mostraron una inversión de beneficios para 2023 (+72,38 muertes en exceso), vinculada a una curva de aprendizaje inversa para las intervenciones (+0,83% de mortalidad por 1% de aumento de volumen; p < 0,001). El ahorro de costos (R$ 5.524/caso) y la menor hospitalización (-5,07 días) coexistieron con el aumento de la complejidad en las cohortes quirúrgicas, aumentando el riesgo de mortalidad basal en un 0,59% anual (p < 0,001). El estudio concluye que la sustitución tecnológica en el SUS logró eficiencia económica, pero requiere inversiones paralelas en capacitación y estratificación de riesgos para la sostenibilidad clínica.
Palabras clave: Enfermedades cardiovasculares; Procedimientos quirúrgicos cardiovasculares; Mortalidad hospitalaria; Sistema Único de Salud; Inequidades en salud.

1. Introduction

Cardiovascular Diseases (CVDs) remain the leading cause of mortality in Brazil, accounting for 27.3% of all deaths in 2017, with standardized rates of 178 deaths per 100,000 inhabitants for coronary artery disease (Oliveira et al., 2020). This epidemiological burden reflects profound socioeconomic inequalities, evidenced by regional disparities in access to healthcare and outcomes. For instance, in less developed regions like the North and Northeast, limited access to supplementary health insurance (covering only 24% of the population) correlates with higher cerebrovascular mortality (Villela et al., 2019; Schultz et al., 2018). Public health initiatives such as Hiperdia and Mais Médicos have reduced hospitalizations for stroke but had minimal impact on acute myocardial infarction (AMI), underscoring the need for complementary strategies (Santos et al., 2021). Over the past two decades, traditional cardiovascular surgery—historically aligned with international mortality benchmarks—has been progressively replaced by minimally invasive interventional cardiology, driven by economic advantages (e.g., cost reductions of R$5,524 per case) and shorter hospital stays (-5.07 days) (Bernardi et al., 2024). Previous studies, such as the analysis of 105,599 cardiovascular surgeries in Brazil, demonstrate that data-driven initiatives improve surgical outcomes (Souza e Silva et al., 2018). However, critical gaps persist on to know how large-scale technological substitution affects case complexity and clinical sustainability in public healthcare systems.

Longitudinal analyses are scarce, particularly within Brazil's Unified Health System (SUS), where regional disparities in technology adoption and workforce training may distort direct mortality comparisons (Bernardi et al., 2024). For example, the inverse learning curve paradox identified in this study reveals that a 1% increase in interventional procedure volume raises mortality by 0.83%, contradicting classical volume-outcome principles (Souza e Silva et al., 2018). This phenomenon suggests systemic strain, where rapid expansion of minimally invasive techniques outpaces infrastructure and training capacity, compromising long-term outcomes (Schultz et al., 2018). Furthermore, the migration of low-risk patients to interventional cohorts concentrates complex cases in traditional surgeries, artificially inflating their mortality rates (Villela et al., 2019). This selection bias is exacerbated by the lack of national data on clinical severity, necessitating proxies like length of stay for risk adjustment (Oliveira et al., 2020). Programs such as the National Program for Improving Access and Quality of Primary Care aimed to mitigate inequalities but were limited by insufficient integration with procedural complexity metrics (Santos et al., 2021).

This study aims to compare in-hospital mortality, costs, and length of stay between traditional cardiovascular surgery and interventional cardiology in SUS (2009–2023), evaluate temporal trends in technological substitution, and quantify long-term effects using risk-adjusted models. The transition to interventional methods aligns with global guidelines prioritizing economic efficiency, such as the American Heart Association's recommendations for cost reduction in CVD management (Schultz et al., 2018). However, the Institute for Health Metrics and Evaluation warns that scalability without parallel investments in training may exacerbate inequalities, as seen in Brazil's regional mortality disparities (Villela et al., 2019). By integrating cost-effectiveness analyses with population risk dynamics, this study advances policy models for universal health systems.

2. Methodology

This ecological study is of quantitative nature (Pereira et al., 2018) using descriptive statistics with mean value, standard deviation, minimum and maximum (Shitsuka et al., 2014), and statistical analysis (Vieira, 2021) and we analyzed 2,303,648 cardiovascular procedures recorded in SUS by hospital information system between 2009–2023. We compared population-level outcomes between traditional cardiovascular surgery and interventional cardiology using three routinely collected metrics: mortality rate (deaths per 100 procedures), total hospitalization costs (Brazilian Reais, R$), and length of stay (days) (Morgenstern et al., 1995).

Data Source and Inclusion Criteria

The study included all hospitalizations for cardiovascular procedures funded by SUS during the study period, without exclusions. Mortality was defined as death occurring during the initial hospitalization, with no follow-up beyond discharge. As an ecological design, analyses used aggregated annual data rather than individual patient records.

Variables and Limitations

Primary Outcome: Absolute in-hospital mortality counts per procedure type.

Economic Metrics:

Total procedural costs (adjusted for inflation to 2023 values)

Mean length of stay (days) per hospitalization

Proxies for Unavailable Data:

Temporal trends in procedure volumes served as proxy for adoption rates

Length of stay interpreted as inverse proxy for procedural complexity

Mortality-to-cost ratios estimated resource efficiency

Analytical Approach

Variables and Adjustments

Primary outcomes were procedure-specific mortality rates and hospitalization costs. We adjusted for severity using length of stay (proxy for clinical complexity) and temporal trends (annual changes in patient selection). Mortality counts were calculated as (Mortality Rate × Procedure Volume)/100. To address confounding by indication, we developed a severity-adjusted model incorporating procedure type, hospitalization duration, and calendar year.

Temporal Trend Analysis

Initial linear regression models identified significant residual autocorrelation (Breusch-Godfrey test: p = 0.0073), prompting adoption of ARIMA (1,0,1) models for proportions of surgeries. Year was centered at 2016 (study midpoint) to reduce multicollinearity. A log transformation stabilized variance when heteroscedasticity was detected (Breusch-Pagan test: p = 0.0733).

Mortality Risk Modeling

Negative binomial generalized linear models (GLMs) replaced initial Poisson regressions due to severe overdispersion (Pearson χ^2/df > 9). These models used exposure-adjusted mortality counts, where procedure volume served as the exposure variable rather than an offset, preventing double-logarithmic distortion. For interventional procedures, we modeled the volume-outcome relationship as:

Log (Expected Deaths) = Baseline + β·log(Procedure Volume) + log(Procedure Volume)

This specification separates the learning curve effect (β) from the baseline volume-mortality relationship.

Causal Inference

Granger causality tests with 2-year lags assessed whether interventional adoption preceded surgical declines. Stationarity was verified using augmented Dickey-Fuller tests ($p < 0.05$ required for differencing). Conflicting test results (SSR χ^2 p = 0.019 vs. parameter F-test p = 0.150) were resolved using AIC/BIC comparisons favoring linear substitution trends.

Synthetic Projections

We simulated the consequences of replacing 10% of surgeries with interventional procedures annually. This conserved total case volumes by redistributing 10% of surgical patients to interventional cohorts each year, recalculating mortality as:

New Surgical Volume = 0.9 × Original Surgical Volume

New Interventional Volume = Original Interventional Volume + 0.1 × Original Surgical Volume

Mortality differences between observed and synthetic populations quantified long-term substitution effects.

Sensitivity Analyses

Model Robustness: Compared linear vs. quadratic temporal models using AIC/BIC.

Severity Adjustment: Tested interactions between procedure type, length of stay, and year.

Economic Impacts: Mixed-effects models with year as a random intercept evaluated cost differences.

Software

Analyses used Python 3.10 with statsmodels (v0.14.0) for GLMs/ARIMA and pandas (v2.0.3) for data management.

Ethical Considerations

As a secondary analysis of anonymized aggregate data, collected from a public database, no individual consent was required.

3. Results

The longitudinal analysis of 2,303,648 cardiovascular procedures reveals a transformative yet complex shift in clinical practice, marked by the systematic replacement of traditional surgeries with interventional cardiology. Temporal trends from

Table 1 demonstrate a consistent annual decline of 1.27% in surgical volumes (β = -0.0127, $p < 0.001$), with interventional techniques surpassing surgeries by 2021. While the linear regression model captures 97.4% of temporal variance ($R^2 = 0.974$), residual autocorrelation ($p = 0.0073$) and marginal heteroscedasticity ($p = 0.0733$) point to unmodeled dynamics, such as regional disparities in technology adoption or evolving patient selection criteria. These unaccounted factors gain clarity in severity-adjusted analyses of Table 2, which reveal an annual 0.59% increase in baseline mortality risk ($p < 0.001$), signaling a progressive concentration of higher-risk patients in surgical cohorts as interventional methods expand. This risk redistribution underscores the limitations of direct outcome comparisons, as surgical cohorts increasingly represent a residual population with elevated comorbidities or contraindications for minimally invasive approaches.

Table 1 - Temporal Analysis of the Proportion of Cardiovascular Surgeries in Brazil’s Unified Health System between 2009–2023.

Variable	Coefficient	Standard Error	p-value
Intercept	0.4729	0.004	< 0.001
Centered Year (2016)	-0.0127	0.001	< 0.001
Quadratic Year	0,000086	0.000	0.606
Validity Tests			
R²	0.974	-	-
Breusch-Godfrey Test	p = 0.0073	-	-
Breusch-Pagan Test	p = 0.0733	-	-

Source: Own elaboration.

The Table 1 highlights a consistent annual decline in surgical procedures, as indicated by the negative coefficient for the centered year variable (-0.0127, $p < 0.001$). The high R^2 value (0.974) demonstrates that the model captures a significant portion of the temporal variance. However, it should be noticed the Breusch-Godfrey and Breusch-Pagan tests, which point to residual autocorrelation ($p = 0.0073$) and marginal heteroscedasticity ($p = 0.0733$). These results suggest that additional unmodeled factors, such as regional disparities or institutional differences, could be influencing the trends.

Table 2 - Severity-Adjusted Risk Model.

Variable	Coefficient	Standard Error	p-value
Intercept	-15.0479	2.455	< 0.001
Procedure (Interventional)	-0.5945	0.053	< 0.001
Length of Stay	0.0456	0.010	< 0.001
Year	0.0059	0.001	< 0.001

Source: Own elaboration.

The Table 2 demonstrates how procedure type, length of stay, and year influence baseline mortality risk. The findings show a robust mortality advantage for interventional procedures (coefficient = -0.5945, $p < 0.001$) and a significant annual increase in baseline mortality risk (coefficient = 0.0059, $p < 0.001$). It should observe how these variables interact: as interventional techniques expand, surgical cohorts increasingly represent higher-risk patients, emphasizing the importance of risk stratification when interpreting outcome comparisons.

Mortality outcomes initially favor interventional cardiology, with a 57% lower risk compared to surgery (RR = 0.43, 95% CI: 0.11–0.76; p < 0.001), as seem at Table 3. However, substantial overdispersion (9.99) highlights significant unmeasured confounding, likely reflecting gradients in case complexity. When adjusted for severity (Table 2), interventional procedures retain a robust 59.45% mortality advantage (p < 0.001), but the systemic annual rise in baseline risk emphasizes the evolving patient demographics within surgical groups. This dynamic is further contextualized by synthetic projections (Table 4), where early mortality reductions (-151.88 deaths in 2009) invert by 2023 (+72.38 deaths), suggesting that the initial benefits of interventional adoption diminish as the technique expands to broader, higher-risk populations. The inversion implies a saturation of efficacy, where procedural scalability outpaces the ability to maintain mortality gains in increasingly complex cases—a phenomenon compounded by economic pressures to prioritize cost-efficient interventions, which may inadvertently incentivize premature scaling.

Table 3 - Comparative Mortality Risk.

Method	Risk Ratio (RR)	95% CI	Overdispersion
Negative Binomial Model	0.43	(0.11 – 0.76)	9.99

Source: Own elaboration.

The Table 3 compares the mortality risk between interventional cardiology and cardiovascular surgery. The risk ratio (RR = 0.43, 95% CI: 0.11–0.76, p < 0.001) highlights a 57% lower mortality risk for interventional procedures. However, the substantial overdispersion (9.99) suggests the presence of unmeasured confounders, likely related to case complexity. Focus on how the severity of cases impacts these outcomes and recognize that interventional procedures' mortality advantage may diminish as their use expands to broader and higher-risk populations.

Table 4 - Substitution Analysis with Synthetic Data.

Year	Actual Deaths	Simulated Deaths	Difference
2009	5,846.06	5,694.18	-151.88
2018	6,820.13	6,845.47	+25.34
2023	7,391.54	7,463.93	+72.38

Source: Own elaboration.

The Table 4 presents simulated projections of deaths associated with interventional cardiology and cardiovascular surgery from 2009 to 2023. The data show an initial reduction in deaths (-151.88 in 2009) due to interventional adoption but reveal a reversal by 2023 (+72.38 deaths). Focus on how procedural scaling impacts mortality outcomes, noting that as interventional volumes grow, the benefits of reduced mortality may be offset by increased case complexity and strained resources.

A critical paradox emerges in the learning curve analysis demonstrated at Table 5. Surgical mortality decreases by 1.83% per 1% volume growth (β = -1.83, p = 0.042), aligning with classical volume-outcome principles. Conversely, interventional mortality increases by 0.83% per 1% volume growth (β = +0.83, p < 0.001)—a finding that defies expectations and underscores systemic strain. This inverse relationship likely reflects institutional overextension, where rapid interventional adoption (Table 1) outpaces the development of operator expertise, infrastructure readiness, or patient selection protocols. The divergence in learning curves is exacerbated by the economic efficiencies of interventional care (Table 6), which reduce hospitalization by 5.07 days ($p < 0.001$) and achieve annual per-case savings of R$ 5,524 (Standard Deviation = R$ 877.29). While these savings drive procedural substitution, they may also create perverse incentives to prioritize volume over quality, diluting expertise as adoption accelerates. The synthetic data projections (Table 4) corroborate this risk, showing that initial mortality benefits erode as interventional volumes grow, ultimately leading to net increases in deaths by 2023.

Table 5 - Comparative Learning Curve (Interventional vs. Cardiovascular Surgery) in Brazil's Unified Health System between 2009–2023.

Variable	Coefficient	Standard Error	p-value
Interventional Cardiology			
Intercept	-6.7224	1.882	0.003
Log (Quantity)	0.8327	0.167	< 0.001
R^2	0.657	-	-
Cardiovascular Surgery			
Intercept	26.6259	9.044	0.011
Log (Quantity)	-1.8289	0.809	0.042
R^2	0.282	-	-

Source: Own elaboration.

The Table 5 illustrates the contrasting learning curves for interventional cardiology and surgery. While surgical mortality decreases by 1.83% per 1% volume growth ($p = 0.042$), interventional mortality increases by 0.83% per 1% volume growth ($p < 0.001$). Pay attention to this paradox, which likely reflects challenges in scaling interventional procedures, such as insufficient operator training or inadequate infrastructure, despite their cost and efficiency advantages.

Table 6 - Annual mean differences between Interventional Cardiology and Cardiovascular Surgery Brazil's Unified Health System between 2009–2023.

Variable	Mean	Standard Deviation	Minimum	Maximum
Cost (R$)	-5,524.75	877.29	-6,897.93	-4,151.58
Length of Stay (day)	-5.07	0.51	-5.87	-4.28

Source: Own elaboration.

The Table 6 showcases the economic and logistical benefits of interventional cardiology compared to surgery. On average, interventional procedures reduce hospitalization costs by R$ 5,524.75 ($p < 0.001$) and shorten hospital stays by 5.07 days. It should be observed on to how these efficiencies contribute to the growing preference for interventional techniques while also noting the potential trade-offs, such as the strain on infrastructure and the learning curve effects discussed elsewhere.

Causal inference models from Table 7 confirm that interventional adoption precedes declines in surgical volumes, with Granger causality tests supporting substitution dynamics (SSR Chi^2: $p = 0.0194$; Likelihood Ratio: $p = 0.0459$). However, conflicting F-statistics ($p = 0.1501$) and sensitivity analyses described at Table 8 reveal that these relationships are sensitive to temporal granularity and model assumptions. The linear substitution trend (AIC = -94.76) proves more robust than quadratic alternatives (AIC = -93.14), reinforcing the dominance of interventional growth. Yet, this substitution interacts critically with the learning curve paradox: as interventional volumes surge, their associated mortality penalty creates a self-limiting cycle where early gains are offset by declining outcomes at scale. This tension is magnified by shifting risk pools, where severity-adjusted models (Table 2) and residual autocorrelation suggest that surgical cohorts increasingly absorb high-risk patients, inflating their apparent mortality rates through residual confounding.

Table 7 - Granger Causality Test.

Test	Statistic	p-value
SSR Chi²	7.8870	0.0194
Parameter F	2.4268	0.1501
Likelihood Ratio	6.1643	0.0459

Source: Own elaboration.

This table evaluates the causal relationship between interventional adoption and the decline in surgical volumes. The significant SSR Chi² ($p = 0.0194$) and Likelihood Ratio ($p = 0.0459$) suggest a substitution dynamic, where growth in interventional cardiology precedes reductions in surgical volumes. Readers should note the sensitivity of these results to temporal granularity and modeling assumptions, as highlighted by the conflicting F-statistics ($p = 0.1501$). This underscores the need for careful interpretation of causality in procedural trends.

Table 8 - Temporal Sensitivity Analysis.

Model	AIC	BIC	Quadratic Coefficient (Variation)
Linear	-94.76	93.34	-
Quadratic	-93.14	91.02	0,0000086 (stable across years)

AIC: Akaike Information Criterion; BIC: Bayesian Information Criterion. Source: Own elaboration.

The Table 8 compares linear and quadratic models for analyzing temporal trends in procedural substitution. The linear model (AIC = -94.76) proves more robust, with stable results across years, as opposed to the quadratic alternative (AIC = -93.14). Readers should focus on the implications of these findings for modeling substitution dynamics, emphasizing the need for simplicity and consistency in analyzing long-term trends.

The interplay of these factors underscores a central tension between efficiency and efficacy. While interventional cardiology reduces immediate mortality (Table 3) and costs (Table 6), its rapid adoption introduces delayed risks, including inverse learning effects and diminishing returns at scale. These dynamics highlight the need for nuanced volume-outcome monitoring, where procedural growth is coupled with investments in training, risk stratification, and infrastructure. For instance, the paradoxical interventional learning curve may reflect insufficient operator experience as volumes expand—a variable not captured in mortality models but implied by overdispersion. Similarly, the annual rise in baseline surgical mortality may mask the role of interventional techniques in "skimming" lower-risk patients, leaving surgical teams to manage increasingly complex cases without proportional increases in support.

Ultimately, the data paint a picture of clinical progress tempered by systemic fragility. Procedural substitution drives measurable benefits in cost, hospitalization, and short-term outcomes, but these advantages are contingent on sustaining institutional capacity and rigorous patient selection. The inversion of mortality gains in synthetic projections serves as a cautionary signal: without parallel investments in training and risk-adjusted protocols, the very efficiencies that enable interventional growth may undermine its long-term viability. This analysis calls for integrated monitoring frameworks that track not only procedural volumes and mortality but also operator experience, case complexity, and temporal trends in risk stratification—ensuring that the shift toward minimally invasive care does not outpace the ecosystem required to sustain its benefits.

4. Discussion

This longitudinal analysis of over 2.3 million cardiovascular procedures in Brazil's Unified Health System (SUS) reveals a multifaceted narrative of medical progress, where the rapid adoption of interventional cardiology—despite its immediate benefits—unintentionally strained systemic resilience, creating a paradox of efficiency at the expense of long-term efficacy. The study's core finding lies in the tension between procedural substitution and outcome sustainability: while interventional techniques systematically replaced traditional surgeries (annual decline of 1.27%, $p < 0.001$), their expansion introduced cascading challenges, including risk redistribution across patient cohorts, inverted learning curves, and diminishing mortality gains. Initially, interventional cardiology demonstrated a robust 57% mortality reduction (RR = 0.43), aligning with global trends favoring minimally invasive care. However, by 2023, synthetic projections revealed a troubling inversion (+72.38 excess deaths), signaling that scalability without parallel investments in expertise and infrastructure risks eroding early advantages. This phenomenon mirrors the concept of "indication creep," where procedural overextension into higher-risk populations dilutes efficacy, compounded by economic incentives that prioritize cost savings (R$ 5,524 per case) over risk-adjusted outcomes (Riggs & Ubel, 2014).

The mortality advantage of interventional cardiology, while statistically significant, is contextualized by critical limitations. Severity-adjusted models uncovered an annual 0.59% rise in baseline mortality risk ($p < 0.001$), reflecting a progressive concentration of high-risk patients in surgical cohorts—a dynamic termed "residualization" (García et al., 2019). As interventional methods absorbed healthier patients, surgical teams faced increasingly complex cases without proportional increases in institutional support, artificially inflating surgical mortality rates. This risk redistribution underscores the fallacy of direct outcome comparisons in evolving clinical landscapes. Even thought, it's known that for the long-term prognosis may be better a surgical approach as it get a more complete intervention (Martins et al., 2021). Meanwhile, the negative binomial model's substantial overdispersion (9.99) highlights unmeasured confounders, such as operator experience or regional disparities in technology access, which likely distorted mortality estimates. Residual autocorrelation ($p = 0.0073$) and marginal heteroscedasticity ($p = 0.0733$) further suggest unmodeled variables, such as uneven adoption rates across socioeconomic regions (Roth et al., 2019) or temporal shifts in referral patterns, which could bias national trends.

A striking contradiction emerged in the learning curve analysis: while surgical mortality improved with declining volumes (-1.83% per 1% growth, $p = 0.042$), interventional mortality worsened as volumes surged (+0.83% per 1% growth, $p < 0.001$). This inversion defies classical volume-outcome theory and points to systemic overextension. For surgeries, reduced caseloads likely concentrated expertise among fewer providers, enhancing outcomes through a "focusing effect" (Dolan & Metcalfe, 2010). Conversely, interventional growth—driven by economic imperatives—appears to have outpaced the development of operator proficiency, patient selection protocols, and infrastructure readiness. The Granger causality tests, which confirmed procedural substitution (SSR Chi^2 $p = 0.0194$), also revealed sensitivity to model assumptions (F-statistic $p = 0.1501$), emphasizing that substitution dynamics are nonlinear and context-dependent. The synthetic data's mortality inversion (Table 5) further illustrates how early gains (-151.88 deaths in 2009) devolve into net losses (+72.38 deaths by 2023) when scaling occurs without mitigating systemic strain. Although it should be reviewed by the point that the value of experience in cardiovascular medicine is contradictory, as some describe no difference between less experienced surgeons (Caldonazo et al., 2025), even using other surgical technologies such as robotic (Jonsson et al., 2023), and others reinforce the influence of experience (Burt et al., 2015) (Bernardi et al,. 2024). That is probably due to the difference of methodology as has been show that the group experience matters more than the attending surgeon or fellows (Elbardissi et al., 2013).

Economically, the shift to interventional cardiology achieved significant efficiencies, reducing hospitalization by 5.07 days and costs by R$ 5,524 per case. However, these savings may have inadvertently incentivized volume-driven care, exemplifying Goodhart's Law—when metrics like cost reduction become targets, they often corrupt the system they aim to improve (Hennessy & Goodhart, 2023). The prioritization of procedural throughput over sustainable outcomes created a self-reinforcing cycle: cost savings justified further substitution, which amplified volume-related mortality penalties, yet the economic rationale persisted. This paradox underscores the need for reimbursement models that reward risk-adjusted outcomes rather than raw procedural volume, as it is known that both interventions aggregated may reduce costs and readmissions along with increasing survivability (Ali Khan et al., 2024). That was also perceived at other country as the expenditure for the treatment of AMI did not change the quality of care or outcome (Wadhera et al., 2019).

The study's limitations caution against overinterpretation. Synthetic projections assume linear substitution trends, potentially underestimating threshold effects, such as infrastructure saturation or policy interventions. Additionally, the absence of operator-level data (e.g., years of experience, mentorship exposure) obscures the human factors behind the inverse learning curve. Regional disparities—a likely contributor to heteroscedasticity—were not explicitly modeled, leaving gaps in understanding how urban-rural divides or resource allocation influenced outcomes, as it is literature demonstrated in multiple context (Roth et al., 2019) (Spitzer et al., 2022), especially because there is evidence that clinical factors may impose less mortality than social factors (Graham, 2016). That get even more explicit as the same intervention with the difference of surgical and transcatheter approach had been influenced by socioeconomic status of the patient (Li et al., 2024).

Theoretical implications extend beyond cardiovascular care. The findings align with complexity theory, where healthcare systems behave as adaptive ecosystems: rapid procedural innovation disrupts equilibrium, generating emergent risks like inverted learning curves (Hidalgo, 2021). They also challenge innovation diffusion theory, which posits that later adopters benefit from accumulated knowledge; here, late-stage interventional expansion lacked the ecosystem (e.g., trained operators, risk protocols) to sustain outcomes (Guo et al., 2024). For SUS, the lessons are clear: procedural substitution requires balanced integration—coupling technological adoption with investments in training, risk stratification, and infrastructure. Proposed solutions include tiered adoption protocols to limit high-risk interventions until expertise matures, centralized hubs to concentrate expertise, and outcome-linked reimbursement to align economic incentives with clinical goals, such as happened with QualiSUS Cardio, except with more specific and data driven goals (Ministry of Health, 2023). Finally, it has to be underlined that it all relies on to the quality and quantity of public reporting data of quality indicators (Renzi et al., 2014).

5. Conclusion

The transition from traditional cardiovascular surgery to interventional cardiology in Brazil's SUS achieved significant economic efficiencies, reducing costs by R$5,524 per case and shortening hospital stays by 5.07 days. However, rapid adoption without proportional investments in training and infrastructure led to systemic strain, evidenced by an inverse learning curve (0.83% mortality increase per 1% volume growth in interventions) and rising baseline mortality in surgical cohorts. While initial mortality benefits favored interventional methods (RR = 0.43), synthetic projections revealed net mortality increases by 2023, highlighting diminishing returns at scale. These findings underscore the necessity of balancing technological substitution with risk-adjusted protocols, centralized expertise hubs, and outcome-linked reimbursement models. Policymakers must prioritize integrated monitoring frameworks that track procedural complexity, operator experience, and regional disparities to ensure equitable and sustainable cardiovascular care.

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