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Geographic Concentration and Resource Context of Cardiac, Chest and Vascular Surgery Department Activity Across Saudi Ministry of Health Clusters in 2024: A National Ecological Analysis

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Abstract **Background:** Cardiac, chest and vascular surgeon specialisation patterns of activity can differ from patterns of infrastructure and the health worker force. The geographical concentration and relations between resource variables were explored in the cardiac, chest and vascular surgery department group within Ministry of Health (MoH) health clusters in 2024. **Methods:** Ecological study examined activity statistics from official registers, resource stock measures, workforce statistics and referrals data. Health clusters were the main units of observation, and harmonised cluster and branch health units were used for workforce and frontier benchmarking. Cluster denominators were proxy: populations of health-region proxy denominators were scaled to the 2024 population estimate based on unchanged regional population shares, and Riyadh and Jeddah clusters were split according to their rounded proxy beneficiary shares. The analysis included concentration measures, regression modelling, scaling, referral networks and exploratory frontier benchmarks. **Results:** 717,238 operations were recorded in MoH hospitals and 16,500 interventions in particular category of "Cardiac, Chest and Vascular" department. The three clusters of Madinah, Makkah and Riyadh Second comprised 36.7%. Rate estimates using the proxy denominators ranged from 12.2 to 103.7 per 100,000 persons. The spatial Gini index equaled 0.290 (95% interval 0.283–0.299, conditional upon the selected denominators, cluster borders and activity observations), while it equaled 0.319 for all surgery operations. The Hoover index was 21.9%, and between-region inequality accounted for 61.0% of Theil index. In 17 health unit's cardiothoracic consultants per 100,000 population showed an exploratory ecological association with activity (incidence rate ratio 1.34 per standard deviation of the variable, 95% confidence interval 1.11–1.60; q = 0.017). It means the association and not causation that the more consultants per population unit the higher activity rate. The variable-returns data envelopment analysis frontier estimated 2,435 additional interventions under the model assumption, a benchmark value rather than demonstrated ability to conduct interventions. MoH's share of the activity reported by the government in this category was 24.3%. **Conclusion:** The activity of MoH was geographically heterogeneous but relatively more even by the population proxy than by overall MoH surgical rate. Workforce composition and referral system of the whole government sector should be taken into account in addition to beds. Ecological associations and frontier benchmarks without adjustment do not reflect access, unmet needs, surgical quality or efficiency.

Key Words Saudi Arabia, Cardiac Surgery, Thoracic Surgery, Vascular Surgery, Geographic Inequality, Health Clusters, Ecological Study, Routinely Collected Data

INTRODUCTION

In 2024, 717,238 operations were recorded in the hospitals of Ministry of Health (MoH) in Saudi Arabia [1], among which there were 16,500 interventions in particular department of "Cardiac, Chest and Vascular". The latter number is related to official figures about the number of hospitals, their beds, and workers but does not identify cardiac, thoracic or vascular surgery. Mid- year 2024 population estimate of Saudi Arabia equals 35,300,280 [2]. It should be kept in mind that the issue of potential patient

population in relation to the location of services should be kept in mind when thinking about cluster-based planning, since health cluster may be characterized with large national contribution volume but few interventions per person. The geographical heterogeneity of observed surgical activity should not be confused with inequality in surgical access. For example, high activity rate may be associated with large referral inflow, and low activity rate does not itself reflect unmet need.

According to the health sector transformation program, access and integration and resource allocation are the priority issues in Saudi Arabia now [3]. Health Holding Company implements a health services organization strategy in 20 health clusters in Saudi Arabia [4]. Specialized surgical service requires a number of factors such as surgical workforce, intensive care and referral capacity. Distribution, access and system capacities are essential elements of surgical planning, both according to the global surgery 2030 and international surgical-volume approaches [5,6]. Recent research on cardiac surgical volume revealed substantial geographical inequalities as well [7,8]. But procedure-specific volumes used in those studies cannot be substituted by the general department category of the yearbook.

The previous Saudi Arabia studies have shown a significant difference in hospital beds between different regions and different sectors of public and private healthcare institutions, while recent study has analyzed resource equity and nursing workforce inequalities [9-12]. They provide the national framework for resource allocation planning, but only number of beds do not allow one to understand the specialization and actual surgery service of this resource. None of them analyzed surgical activity of specific category of department in relation to population, resources and referral process. Thoracic surgery has its own workforce, and it constitutes another reason to analyse department separately [13]. Thus, the department-level study requires a separate estimation of absolute concentration, distribution in relation to population, workforce composition and resources around activity. Department level can show place of recorded activity and relationship with resources, but not procedures and patients.

The analysis of the cardiac, chest and vascular surgery department activity of MoH in 2024 within 20 health clusters in Saudi Arabia was performed. Goals of the study include the quantification of absolute concentration and population-related distribution, description of the surgical, critical care and specialist workforce context, activity–resources associations, referral network structure, exploratory frontier benchmarks and impact of geographic aggregation and population assumptions on results. Comparison of national governmentsector activity was made to put MoH activity into broader provider landscape. Description of absolute concentration and population-relative distribution of activity rate was the first objective of the study. The secondary and exploratory objectives were related to the analysis of the workforce, resource, referral, frontier and sensitivity.

METHODS

Study Design and Reporting Framework

A cross-sectional ecological study was performed based on the publicly available aggregate data of 2024 calendar year, following the STROBE and RECORD criteria for source identification, geographic harmonisation, variable definitions and sensitivity analysis [14,15]. In this analysis, the unit of observation was the reporting area, not the individual patients or hospital, therefore the findings can be considered as the associations between the area characteristic and the registered activity level; these associations do not reflect the exposure-outcome relations between these parameters for individuals [16]. All 20 MoH clusters were included, without any sampling or exclusions based on the surgical volume. Units of analysis varied according to the particular component: 20 clusters for the primary geographical analysis, 17 cluster-branch harmonized units for the workforce, workforce-scaling and DEA analysis, and 20 branches/offices, 23 reporting sub-units and 13 administrative regions for the sensitivity analysis (Section 2.2).

Data Sources and Geographic Harmonisation

Interventions by cluster and department (sheet 4-36), beds by specialty (2-9), intensive-care beds by type (2-12), emergency beds (2-13), health facilities and heart/cardiology centres (2-4), hospitals by specialty and bed-capacity class (2-7 and 2-8), admissions by nationality (4-22), hospital performance indicators (4-25), referrals (4-63), physicians by specialty and professional grade (2-29), beds by provider sector (2-3), and other-government surgical activity (4-37) were extracted from the MoH Statistical Yearbook 2024 Excel workbook [1]. GASTAT healthcare statistics were used as the context, national-level figures and not as duplicates of the MoH resources [17]. Before interpretation of the dataset, the cluster-row sums were controlled and cross-verified against the published totals and subtotals of the sheet, as well as counts of beds, hospitals and intensive-care; workbook version dated 08-10-2026 was analyzed [1]. The department category is an administrative categorization performed by the reporting hospitals, the yearbook does not define any procedure level department categories, and thus their validity could not be verified.

Primary geographic hierarchy consisted of 20 clusters. The Makkah, Asir and Al-Jouf sub-units were summed to cluster totals, the three Riyadh sub-clusters and two Jeddah sub-clusters remained separate. Physicians counts were available for 20 MoH branches/offices, where Riyadh and Jeddah were single branches, whereas Qunfudah, Bishah and Qurayyat were separate branches. Geographic harmonisation of the two hierarchies was necessary for the analysis of the activity and workforce; analysis was carried out with the 17 units, where the three Riyadh clusters were merged to one, two Jeddah clusters were merged to one, and the Holy Capital-Qunfudah, Asir-Bishah and Al-Jouf-Qurayyat branches were merged. In the course of each of the analyses, the activity, workforce, resource and population

were summed up to the same boundaries. The activity for sub-units (Holy Capital, Qunfudah, Asir excluding Bishah, Bishah, Al-Jouf excluding Qurayyat, and Qurayyat) is directly provided in the sheet 4-36 and not reconstructed. Further sensitivity analyses used the geographic hierarchy of 20 branches/offices, 23 sub-units (20 clusters plus three merged clusters) and 13 administrative regions. Published subtotals were never counted with their sub-components.

Population Construction

Anchored point for the population by geography was the Saudi Census 2022 [18]. We used the 2022 health-region counts in the MoH 2022 health indicators workbook, Table 1-11, and not similar cities or governorates as identical catchment areas [19]. The 20 health-region population counts summed to 32,175,224. The each health-region population was scaled by 35,300,280/32,175,224 = 1.097126 to obtain a proxy for 2024 with the total population equal to the national figure of 35,300,280 [2]. The health-regional shares remain constant at their 2022 values, therefore neither migration nor growth in population differential were estimated between 2022 and 2024.

The proxy population for the Riyadh region was distributed into proportions 3.900:3.800:0.829 million, and for the Jeddah region – 1.800:0.996 million, using the rounded HHC beneficiary counts in the web page [4]. These are the service beneficiaries rather than verified 2024 residents of a city or health region; they could include the users from other clusters and do not include the residents served elsewhere, therefore the split can be considered as the planning proxy. Several alternatives to the split were studied by allocating HHC beneficiary denominator in all clusters and omitting the intra-region splits (17 units; Table 6). Makkah health region was formed by merging the Holy Capital and Qunfudah health regions; Asir health region – by merging Asir and Bishah; Al-Jouf health region – by merging Al-Jouf and Qurayyat. Counts of the nationality in regions were validated using the tabulation of the census data by the Gulf Labour Markets, Migration and Population (GLMM) programme and the Governorate Profiles [20,21]. The denominator for the sensitivity analysis of Saudi nationals was the 2022 share of Saudi nationals of each health region population scaled to the national 2024 total of 19,635,258. Therefore, the reference population was changed without changing the recorded CVS events and the Saudi patient procedure rate was not estimated.

Activity Definitions and Descriptive Measures

The outcome was the count of interventions in the cardiac, chest and vascular surgery department in MoH hospitals; further we abbreviate it as CVS. The number of patients was not used in any case as the unique interventions are already counted in the workbook and not unique patients; the outcome also excludes the coronary artery bypass grafting interventions or other procedure codes. Repeat interventions of the same patients are also separately counted and the workbook does not distinguish the intervention and the patient count. "Interventions" and "activity" refers to the intervention counts. We calculated the volume shares of 2024 national total, their ranks, department volume shares, CVS per 100,000 proxy population, rate ratios, interventions per 1,000 admissions, per 100 surgical beds and per adult intensive care unit (ICU) bed (the CVS count divided by the cluster's all-specialty admissions, surgical beds or adult ICU beds, multiplied by 1,000, 100 or 1, respectively). Admission and beds were used as the context denominators to describe the activity relative to the whole cluster resources; these ratios do not measure any efficiency or appropriateness of use. Poisson confidence intervals of the rates were calculated [22]. Location quotients compared the proportion of CVS interventions in the total local surgery with the corresponding proportion in the reference group; uncertainty followed the framework of the log-normal delta method [23]. An LQ above one means that CVS interventions form a larger share of the local surgery than in the reference, but not increased demand or access. In case of nested CVS/total counts a/t within the reference counts A/T, the log-variance of the two shares' difference is $1/a-1/t-1/A-1/T+2a/(tA)$. The covariance between the shares is accounted in this way; the reference is MoH nationally in the comparisons of clusters and all government providers in the comparisons of agencies. Heart/cardiology centres were those listed in sheet 2-4; this term does not imply the cardiac surgical capacity on the site.

Concentration, Inequality and Specialty Profile

Concentration was measured using the volume shares of the top three and top five contributors, the Herfindahl-Hirschman Index (HHI; 10,000 times the sum of squared volume shares), its inverse effective number of clusters and the Gini coefficient of the counts [24,25]. Population-weighted spatial Gini coefficient was calculated by constructing the Lorenz curves for ordering the clusters according to CVS per capita; it allows us to disentangle the concentration of absolute counts from the inequalities in rate across the populations [26]. The Hoover index was the half of the sum of the absolute differences between activity and population shares [27]. The Theil T Index was the sum over clusters of the activity share multiplied by the logarithm of the activity share divided by the population share; it is decomposable into between-region and within-region components using the 20 clusters categorized into the 13 administrative regions [28]; terms with zero shares are zero. Also, we calculated the population-weighted coefficient of variation of the rates, highest-to-lowest rate ratio, and the population share of the half of activity. Higher HHI, Gini, Hoover and Theil indices imply the higher concentration or inequality; on the contrary, the effective number of clusters is high if the activity is evenly distributed. The population-weighted spatial Gini coefficient is the key inequality measure as it captures the inequality across the whole rate distribution; the Hoover (share mismatch) and decomposable Theil indexes are the complements. There was no cluster with zero CVS activity, zero resource counts were taken into account for the indices except the extremal ratios calculation.

Resource-gradient concentration curve was calculated by ordering the clusters by the resource density. Concentration index was based on the population-weighted fraction ranks, where the tied ranks are resolved using the weighted midrank [29]. It described the correlation of the geographic distribution of the activity and resource, the ratio of the index to the spatial Gini is not the explained variance proportion. Uncertainty of event-count indices was assessed using 10,000 parametric Poisson bootstrap replicas [30], where each cluster count is drawn as a Poisson variable with the mean equal to the observed count, assuming the independence of events and the fixed denominators. In the case of paired CVS-to-total-surgery comparison, the CVS and non-CVS events were modeled as disjoint components so that CVS would remain a subset of total activity. These confidence intervals are conditional on fixed populations, boundaries and coding, and describe only the stochastic variation of the event counts. They do not capture the census error, reporting error, denominator uncertainty and uncertainty of the geographic crosswalk and the reconstructed catchment areas, and cannot be considered as comprehensive uncertainty measure. Bootstrap replicas were generated using the NumPy's default random generator and the fixed seed (seed value to be inserted by author). Complete enumeration resource stocks were presented without sampling intervals.

The 20×12 cluster-by-department matrix was analyzed using Pearson's chi-square statistic and Cramér's V. Adjusted standardized residuals, r = (O-E)/sqrt (E*(1-p_c) *(1-p_d)), where E is the cluster total multiplied by the national department total divided by all interventions, and p_c and p_d are the cluster and department shares, respectively, were used to indicate over- and underrepresentation compared to the independence, not the difference in quality, need or outcome. The very high chi-square is explained by the 717,238 events, while Cramér's V summarizes the magnitude of association. A two-tailed Bonferroni threshold for alpha=0.05, $|r| > \Phi^{-1}(1-0.05/480) \approx 3.71$, was used as the significance threshold. Dendrogram of the Ward hierarchical clustering on the Euclidean distances between residuals' profiles produced descriptive row and column orders [31]. The dendrogram groupings were used to show the portfolio similarity but not to classify the clinical service types.

Funnel Plots, Scaling and Association Models

Funnel plots of the CVS population-based rates were compared to the national rate Poisson limits, and to the Poisson limits inflated by a between-cluster additive variance component [32]. Let z be the standardized Poisson rate deviation, and w be the inverse Poisson rate variance. As recommended, 10% most extreme in each tail z-scores were winsorized, and the Q is the sum of squared winsorized deviations. The dispersion statistic φ was Q/20 (a winsorized mean squared z-score, not the Pearson statistic divided by residual degrees of freedom), and the between-cluster additive variance was τ^2=max {0, (Q-19)/(sum(w)-sum²(w)/sum(w))}; the inflated Poisson limits are $\theta 0 \pm z^*\text{sqrt}(\theta 0/n+\tau^2)$, where θ0 is the national rate, and n the proxy population in 100,000s. Winsorization of the one score per tail was done as the robustness check, neither of the rules are uniquely correct. The limits were the descriptive flags based on the winsorization rule, not clinical performance standards.

Log-log ordinary least-squares models were used to study the relationship between the counts of CVS and adult ICU beds, surgical beds, population and the cardiothoracic-vascular physician count. Robust variance estimates HC3, which outperform the other estimators in small samples in terms of heteroskedasticity, and t-based 95% confidence intervals were used for scaling exponents. Scale adjusted residuals were log(observed)-log(fitted) activity; scaling framework was chosen to compare the units of different sizes [33]. The negative binomial models with the CVS count as outcome, a log population offset, the NB2 variance function (mean plus dispersion multiplied by squared mean), maximum-likelihood dispersion estimate and Wald 95% confidence intervals were used [34]. The incidence rate ratios (IRR) describe the response per sample standard deviation of a continuous predictor, after geographical aggregation, or per presence vs absence of the centre indicator. Two-term models were exploratory; with 20 clusters and 17 harmonised units the estimates are imprecise and unstable, further adjustment beyond one covariate is not feasible, the correlated predictors (population, beds, workforce and center presence) cannot be isolated, and non-significant associations do not imply irrelevance of the resource.

To check the sensitivity to shared denominators, further NB2 models were built using log population and log resource stocks as separate predictors, rather than the ratio of one to another [35]. Correlation coefficient was estimated together with its confidence interval by means of the approximate Fisher transformation using the Bonett-Wright standard error [36]. The two-sided P-value was adjusted by the Benjamini-Hochberg procedure separately in each panel and statistic [37] (families: Panel A correlations, 14 tests including the Mann-Whitney U test; Panel A IRRs, 14; Panel B correlations, 9; Panel B IRRs, 9; Panel C elasticities, 10); the residual heatmap uses the Bonferroni criterion. Models were interpreted with effect size, confidence interval, dispersion and goodness-of-fit, with $q<0.05$ as the exploratory screening threshold.

Frontier Benchmarking, Referrals and Sensitivity Analysis

DEA is based on 17 harmonised units, three inputs – the combination of cardiothoracic and vascular physician headcounts, surgical beds and adult ICU beds, and one output – annual count of CVS interventions. These are the only workforce, surgical-bed and critical-care measures available for all 17 units; the output is the combined department count, not the complexity- or outcome-adjusted measure, and thus constrains interpretation of the efficiency scores. No unit has zero inputs or outputs. Input-oriented

CCR and BCC models are used to estimate the technical efficiency and pure technical efficiency, respectively [38,39]. Scale efficiency is the ratio of the two models; two models were used since constant returns DEA benchmarks every unit to the most productive scale, while variable returns compares the units with their peers only. The frontier ranking was based on the input-oriented CCR Andersen-Petersen super-efficiency, where the unit being evaluated is omitted from the reference set [40]. Constant-returns output gaps are the output multiplied by the inverse technical efficiency score minus one. Output-oriented BCC gaps are the estimated expansion factor minus one. They were the deterministic projections using broad resource input, common among the peers, and do not estimate the causative productivity or the clinically feasible additional operations.

The 20x20 matrix of referrals, including the reverse referrals and all specialties [1] includes the diagonal element reflecting the within-cluster referrals. For each cluster, the intra-cluster referrals were the diagonal element, outbound referrals the off-diagonal row sum, inbound referrals the off-diagonal column sum, net balance the difference of inbound minus outbound, and outbound intensity outbound referrals per 100,000 proxy population. Reverse referrals were left intact as the recorded count. We looked for associations between the net balance and CVS volume, and between the outbound intensity and CVS rate. Sensitivity analysis included geographic aggregation, substitution of rounded HHC beneficiary denominator or Saudi-national regional population shares, omission of the most influential clusters, and stratification by the centre presence. Denominator scenarios (HHC beneficiaries, Saudi national shares) were distinguished from geographic-unit scenarios (17 units, 20 branches, 23 sub-units, 13 regions). Government-sector total was constructed with the common department labels in sheets 4-36 and 4-37; the private-sector ACHI (Australian Classification of Health Interventions) chapter counts were not pooled since they categorize the procedures by body systems rather than departments. Thus the government-sector total is not the full count of the national surgical activity. Independent numerical reconciliations were made with Python 3.12, NumPy 2.3.5 and SciPy 1.17.0; the extraction, population construction and verification code was kept along with the analysis. Analysis map: concentration and inequality (Table 2); resource setting (Table 3); workforce and DEA benchmarks for 17 facilities (Table 4); rank correlations and NB2 regressions for 20 clusters and 17 facilities, plus separate log-stock NB2 regressions (Table 5); scaling analysis (Figure 6); referral system (Figure 5); sector setting and sensitivity tests (Table 6).

RESULTS

Activity Distribution and Specialty Mix

The MoH hospitals undertook 16,500 CVS interventions, which made 2.30% of MoH interventions, and 46.7 per 100,000 proxy population (95% Poisson interval 46.0-47.5). For Madinah region, the number of interventions was 2,432; for Makkah, 2,043; and for Riyadh Second cluster, 1,588. Together, these represented 36.7% of CVS interventions despite containing 27.7% of proxy population. However, this is merely a descriptive comparison and does not provide evidence on unmet need elsewhere. Five largest clusters supplied 54.2% CVS activity. In addition, there were discrepancies in volume rank and in population ranks: the ninth cluster in volume ranks was Riyadh First, with 17.2 per 100,000 proxy population, and the nineteenth in rate rank. Rate estimates by proxy denominators, not the verified resident-specific procedure rates, were 103.7 per 100,000 in Madinah, and 12.2 in Jeddah First (ratio 8.48) (Table 1).

There were five clusters with location-quotient intervals exceeding one: Madinah 2.32, Riyadh Second 2.02, Makkah 1.85, Hail 1.23 and Eastern 1.19. In addition, there were nine clusters with interval below one. Having applied a more stringent residual Bonferroni criterion, the following CVS activities became statistically significantly over-represented in these five clusters and understated in eight clusters. The full portfolio comparison revealed chi-square 146,836.6 with 209 d.f. and Cramér's V 0.136. Largest positive CVS residual was in Madinah (+44.6) while largest negative CVS residual was in Jazan (−23.8). In split-reporting units, the Holy Capital sub-unit was responsible for 98.6% of CVS interventions in Makkah, as reported directly for the two sub-units; and the rate of CVS procedures in Bishah exceeds the rate in the remainder of the Asir region (74.5 versus 62.9 per 100,000 proxy population).

Concentration and Resource Gradient

For CVS interventions, HHI was 786, which corresponds to 12.73 equally contributing clusters. Count Gini was 0.400. For proxy population, HHI was 754, count Gini was 0.389. Relative to proxy population, CVS spatial Gini was 0.290 (95% conditional interval 0.283-0.299), which was lower than total-surgery spatial Gini (0.319) and admissions (0.319). Paired CVS and all-surgery difference was −0.029 (−0.036 to −0.020), thus representing a distributional difference and not evidence on equities of access. Hoover index was 21.9% (21.2-22.6); this is the fraction of activity that differs to have the shares of activity and population equal. Half of CVS activity occurred in 31.2% of proxy population, which means that this is the distributional statistic and not a measure of access. The variation in 13 administrative regions contributed 61.0% to the total Theil inequality; the same set of 20 clusters and weights was used for all comparisons (Table 2).

The adult ICU and surgical-beds spatial Ginis were 0.265 and 0.264, respectively. Cardiac centres were even more concentrated, the spatial Gini for those was 0.545 and Hoover index was 40.0%. The resource-gradient concentration indices of CVS activity were positive and varied from 0.151 (total MoH beds) to 0.175 (cardiac centres). Among 12 surgical departments, CVS activities had the second smallest value of spatial Gini and third smallest value of Hoover index; the smallest value of these two was obtained for neurosurgery spatial Gini 0.231. Spatial maps

Table 1: Cardiac, Chest and Vascular (CVS) Surgical Department Activity Across The 20 Ministry of Health Health Clusters, 2024

		CVS volume and share			Specialisation		Population-based intensity		Resource-normalised intensity				
Health Cluster	Proxy pop. (000s)	N	National Share, %	Rank	Cluster Surgery, %	LQ (95% CI)	Per 100,000 (95% CI)	Rate ratio	Per 1,000 Admissions	Per 100 Surgical Beds	Per Adult ICU bed	Centres, N	Saudi Share, %
Riyadh First	4,310.3	741	4.49	9	1.29	0.56 (0.52–0.60)	17.2 (16.0–18.5)	0.37	8.81	81.3	1.66	1	66.0
Riyadh Second	4,199.8	1,588	9.62	3	4.64	2.02 (1.93–2.11)	37.8 (36.0–39.7)	0.81	23.26	223.7	8.77	1	64.7
Riyadh Third	916.2	358	2.17	15	2.29	1.00 (0.90–1.10)	39.1 (35.1–43.3)	0.84	7.44	114.0	3.23	0	83.4
Makkah	3,234.4	2,043	12.38	2	4.25	1.85 (1.78–1.92)	63.2 (60.5–66.0)	1.35	12.96	252.2	5.63	2	69.6
Holy Capital	2,937.9	2,014	12.21	—	4.80	2.09 (2.00–2.17)	68.6 (65.6–71.6)	1.47	—	284.5	—	2	—
Qunfudah	296.5	29	0.18	—	0.47	0.21 (0.14–0.30)	9.8 (6.5–14.0)	0.21	—	28.4	—	0	—
Jeddah First	2,805.3	343	2.08	16	2.25	0.98 (0.88–1.09)	12.2 (11.0–13.6)	0.26	6.29	128.5	4.23	0	75.0
Jeddah Second	1,552.3	914	5.54	6	2.27	0.99 (0.93–1.05)	58.9 (55.1–62.8)	1.26	13.57	137.2	4.10	0	74.4
Taif	1,208.6	653	3.96	10	2.39	1.04 (0.96–1.12)	54.0 (50.0–58.3)	1.16	7.85	129.1	5.68	0	84.5
Madinah	2,345.6	2,432	14.74	1	5.33	2.32 (2.24–2.40)	103.7 (99.6–107.9)	2.22	14.98	369.6	8.16	1	77.9
Qassim	1,466.0	843	5.11	7	1.27	0.55 (0.52–0.59)	57.5 (53.7–61.5)	1.23	8.20	98.1	4.07	1	82.1
Eastern	3,899.2	1,435	8.70	5	2.73	1.19 (1.13–1.25)	36.8 (34.9–38.8)	0.79	5.62	199.9	7.10	1	82.9
Al-Ahsa	1,211.5	763	4.62	8	2.36	1.02 (0.96–1.10)	63.0 (58.6–67.6)	1.35	6.63	187.5	5.09	1	88.8
Hafr Al-Batin	512.4	131	0.79	20	0.88	0.38 (0.32–0.45)	25.6 (21.4–30.3)	0.55	2.06	48.0	1.93	0	83.6
Asir	2,220.9	1,437	8.71	4	1.86	0.81 (0.77–0.85)	64.7 (61.4–68.1)	1.38	15.44	180.3	5.73	1	85.0
Asir (excl. Bishah)	1,881.3	1,184	7.18	—	2.01	0.87 (0.83–0.92)	62.9 (59.4–66.6)	1.35	—	198.7	—	1	—
Bishah	339.6	253	1.53	—	1.37	0.60 (0.53–0.67)	74.5 (65.6–84.3)	1.59	—	125.9	—	0	—
Tabuk	972.1	501	3.04	12	2.17	0.94 (0.87–1.03)	51.5 (47.1–56.3)	1.10	7.37	121.0	3.43	0	77.6
Hail	818.9	647	3.92	11	2.82	1.23 (1.14–1.32)	79.0 (73.0–85.3)	1.69	10.28	179.2	7.52	1	90.2
Northern Borders	409.9	263	1.59	18	1.85	0.81 (0.72–0.91)	64.2 (56.6–72.4)	1.37	5.51	94.3	2.05	1	88.1
Jazan	1,541.5	417	2.53	14	0.80	0.35 (0.32–0.38)	27.1 (24.5–29.8)	0.58	2.70	70.1	2.29	0	83.3
Najran	649.8	492	2.98	13	1.90	0.82 (0.76–0.90)	75.7 (69.2–82.7)	1.62	6.72	178.9	5.02	1	70.8
Al-Baha	372.1	322	1.95	17	1.03	0.45 (0.40–0.50)	86.5 (77.3–96.5)	1.85	6.23	100.6	3.74	0	83.8
Al-Jouf	653.7	177	1.07	19	0.88	0.38 (0.33–0.44)	27.1 (23.2–31.4)	0.58	2.81	55.7	0.90	0	90.5
Al-Jouf (excl. Qurayyat)	439.7	119	0.72	—	0.88	0.38 (0.32–0.46)	27.1 (22.4–32.4)	0.58	—	56.7	—	0	—
Qurayyat	214.0	58	0.35	—	0.87	0.38 (0.29–0.49)	27.1 (20.6–35.0)	0.58	—	53.7	—	0	—
Saudi Arabia, MoH total	35,300.3	16,500	100.00	—	2.30	1.00 (reference)	46.7 (46.0–47.5)	1.00	8.79	157.8	4.56	12	79.9

Volume, Specialisation, Population-Based and Resource-Normalised Intensity (CVS: Combined Cardiac, Chest and Vascular Department. Populations are Constructed 2024 Proxies. Italic Sub-Units Are Included in Parent Totals; Ranks Concern 20 Clusters. Centres Are Yearbook-Designated Heart/Cardiology Centres. Saudi Share Concerns Admissions; LQ: Local/National CVS Share of Surgery, with Nested-Total Log-Normal Intervals [23]. Rate Intervals are Exact Poisson [22]; Rate Ratios use the National MoH Rate. Bed Denominators Cover All Specialties)

Table 2: Concentration and Population-Relative Inequality of CVS Activity Compared with MoH Service Volumes and Resource Stocks Across the 20 Health Clusters, 2024

	Count concentration					Population-Relative Inequality							
Distribution across clusters	Leading Cluster (Share, %)	CR3, %	CR5, %	HHI	ENC	Spatial Gini (95% CI)	Hoover, % (95% CI)	Theil T (95% CI)	Between Theil, %	Rate CV	Extremal Ratio	Pop. Hosting 50% of Total, %	Count Gini
CVS surgical interventions	Madinah (14.7)	36.7	54.2	786 (773–799)	12.73	0.290 (0.283–0.299)	21.9 (21.2–22.6)	0.139 (0.132–0.147)	61.0	0.523	8.48	31.2	0.400
All surgical interventions	Asir (10.8)	28.0	42.7	626 (624–627)	15.99	0.319 (0.317–0.320)	24.0 (23.9–24.1)	0.168 (0.167–0.169)	76.4	0.616	15.46	28.0	0.280
Hospital admissions	Eastern (13.6)	30.7	45.0	648 (647–649)	15.43	0.319 (0.318–0.320)	24.0 (23.9–24.0)	0.168 (0.168–0.169)	80.5	0.575	8.55	29.9	0.268
Population (2024)	Riyadh First (12.2)	35.2	52.3	754	13.27	Reference							0.389
MoH hospital beds	Riyadh First (8.5)	23.1	36.9	567	17.64	0.285	21.7	0.131	60.0	0.524	8.99	30.0	0.210
Surgical beds	Riyadh First (8.7)	24.7	39.2	588	17.00	0.264	20.0	0.112	59.2	0.488	9.04	31.6	0.237
Adult ICU beds	Riyadh First (12.3)	30.6	43.7	643	15.56	0.265	18.3	0.130	54.5	0.525	10.82	33.7	0.285
All ICU beds (NICU+PICU+adult)	Riyadh First (10.5)	27.1	40.7	601	16.64	0.292	21.3	0.143	55.1	0.540	9.87	31.3	0.249
Monitored ER beds	Riyadh First (10.4)	29.2	44.3	643	15.54	0.327	22.9	0.181	72.4	0.639	14.45	28.9	0.300
Hospitals ≥301 beds	Eastern (12.5)	27.5	42.5	650	15.38	0.308	21.8	0.170	54.3	0.631	15.08*	30.2	0.290
Cardiac centres	Makkah (16.7)	33.3	50.0	972	10.29	0.545	40.0	0.586	61.3	1.158	10.52*	17.5	0.492

CVS: Cardiac, Chest and Vascular Department; MoH: Ministry of Health; All Values are Calculated Indices, CR3/CR5: Combined Shares of the Three/Five Largest Contributors. HHI = 10,000×sum of Squared Shares, ENC = 10,000/HHI. Spatial Gini is Population-Weighted, Count Gini Weights Clusters Equally. Hoover and Theil Compare Activity Shares with Population Shares. Between-Region Theil uses 13 Administrative Regions. CV is the Population-Weighted Coefficient of Variation of Rates, Event-Count 95% Iintervals are Conditional Parametric Poisson-Bootstrap Intervals, 10,000 Replicates, with Populations and Boundaries Fixed [30]. Stocks Carry No Sampling Intervals. The Paired Spatial-Gini Difference, CVS Minus All Surgery, is −0.029 (−0.036 to −0.020). *Extremal Ratios Omit Zero-Resource Clusters: Nine Have No Centre and One Has no Hospital with at Least 301 Beds

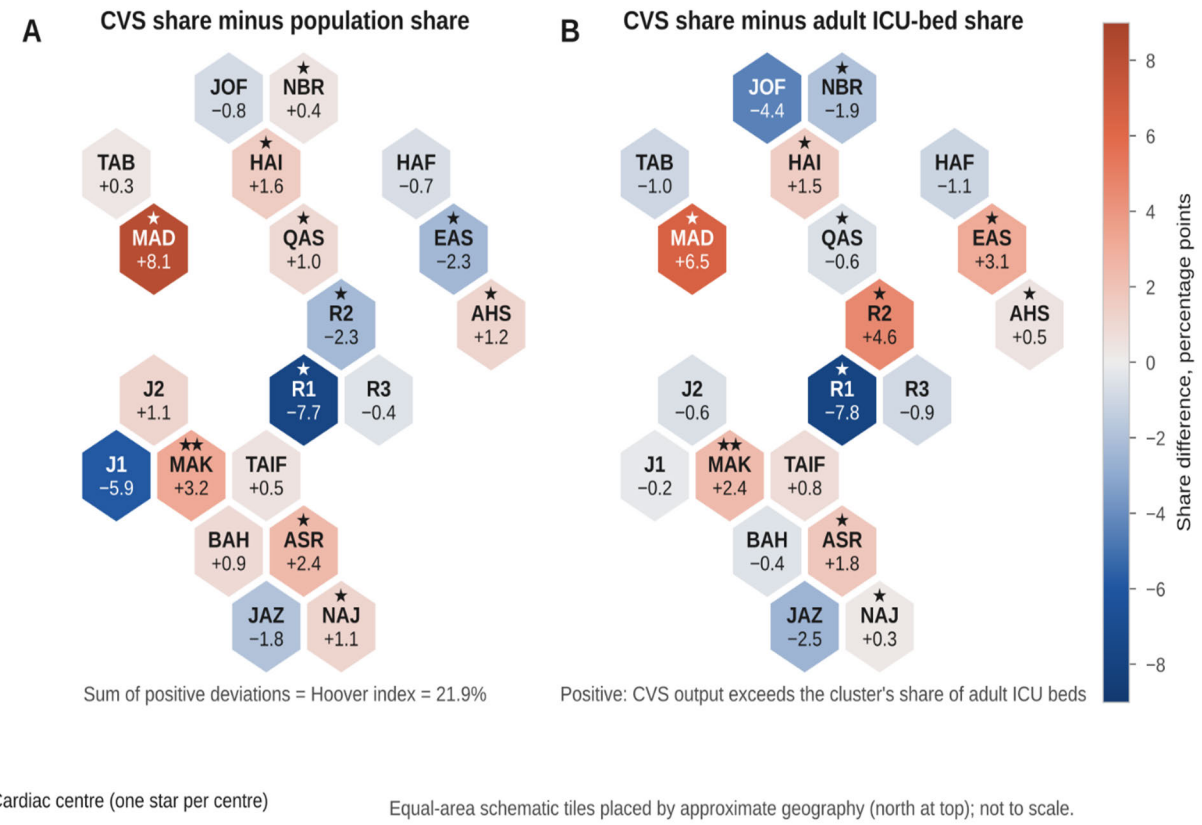


Figure 1: Spatial Balance of CVS Activity Compared to Population and Adult ICU Capacity in the 20 MoH Health Clusters, 2024

Values Calculated from Recorded Counts and Proxy Populations, Equal-Area Schematic Tiles for 20 Clusters in Geographic Order, Neither The Boundaries nor the Tile Sizes Represent Actual Catchments. (A) CVS Activity Volume Share Minus Population Proxy Share, (B) CVS Share Minus Adult ICU-Bed Share, In Percentage Points. Stars Indicate MoH Heart/Cardiology Centres. Positive Deviations from Population Shares Sum to the Hoover index. Codes: R1/R2/R3, Riyadh First/Second/Third, J1/J2: Jeddah First/Second, MAK: Makkah, MAD: Madinah, QAS: Qassim, EAS: Eastern, AHS: Al-Ahsa, HAF: Hafr Al-Batin, ASR: Asir, TAB: Tabuk, HAI: Hail, NBR: Northern Borders, JAZ: Jazan, NAJ: Najran, BAH: Al-Baha, JOF: Al-Jouf, TAIF: Taif
Source: MoH 2024, population proxy as in Table 1 [1]

and concentration curves reveal different features of CVS distribution which cannot be found from volume ranks only (Figures 1 and 2); cluster-by-department residuals are in Figure 3.

Infrastructure and Exploratory Outlier Assessment

There were 290 MoH hospitals in 20 clusters, with 46,905 beds, 3,619 adult ICU beds and 12 heart/cardiology centres (Table 3). There were eleven clusters which had at least one centre; and nine clusters with no centres. The adult ICU bed density varied from 2.89 per 100,000 proxy population in Jeddah First to 31.23 in Northern Borders. The general bed occupancy ranged from 38.6% in Northern Borders to 74.5% in Makkah. On the other hand, adult ICU bed occupancy was 24.8%-87.8% in Riyadh Third and Eastern cluster, respectively. The CVS-intervention density per adult ICU bed ranged from 0.90 in Al-Jouf to 8.77 in Riyadh Second; this demonstrates that rankings based on capacity-adjusted activities can differ from population rankings. Since adult ICU beds are shared across all specialties, the ratios in question do not measure CVS-related capacity.

Nineteen clusters were outside the Poisson 99.8% funnel; thus the variation in between-cluster CVS intervention rates is much larger than due to random noise, therefore the simple Poisson limit becomes useless. Winsorized mean squared z-score was 89.7; and the standard deviation of the between-cluster variations was 15.9 interventions per 100,000 proxy population. With the extended limit, Madinah (z = 3.56), Al-Baha (2.44) and Hail (2.00) lay above the 95% upper limit while Jeddah First (z = −2.16) lay below the 95% lower limit. Only Madinah fell outside the 95% upper extended limit. With application of winsorisation of one value per tail, the standard deviation rose to 20.6, and only Madinah was outside the 95% limits. Thus, the outlier detection was quite sensitive to the choice of the dispersion rules, especially for the borderline Hail cluster; all flags here are merely descriptive but do not identify poor performing or inefficient clusters (Figure 4).

Frontier Benchmark and Referral Context

The constant returns DEA frontier covered Makkah, Madinah and Asir clusters. The mean technical efficiency was 0.677, the mean pure technical efficiency was 0.913, the mean scale efficiency was 0.744. The constant-returns DEA projection resulted in the increase of the observed output by

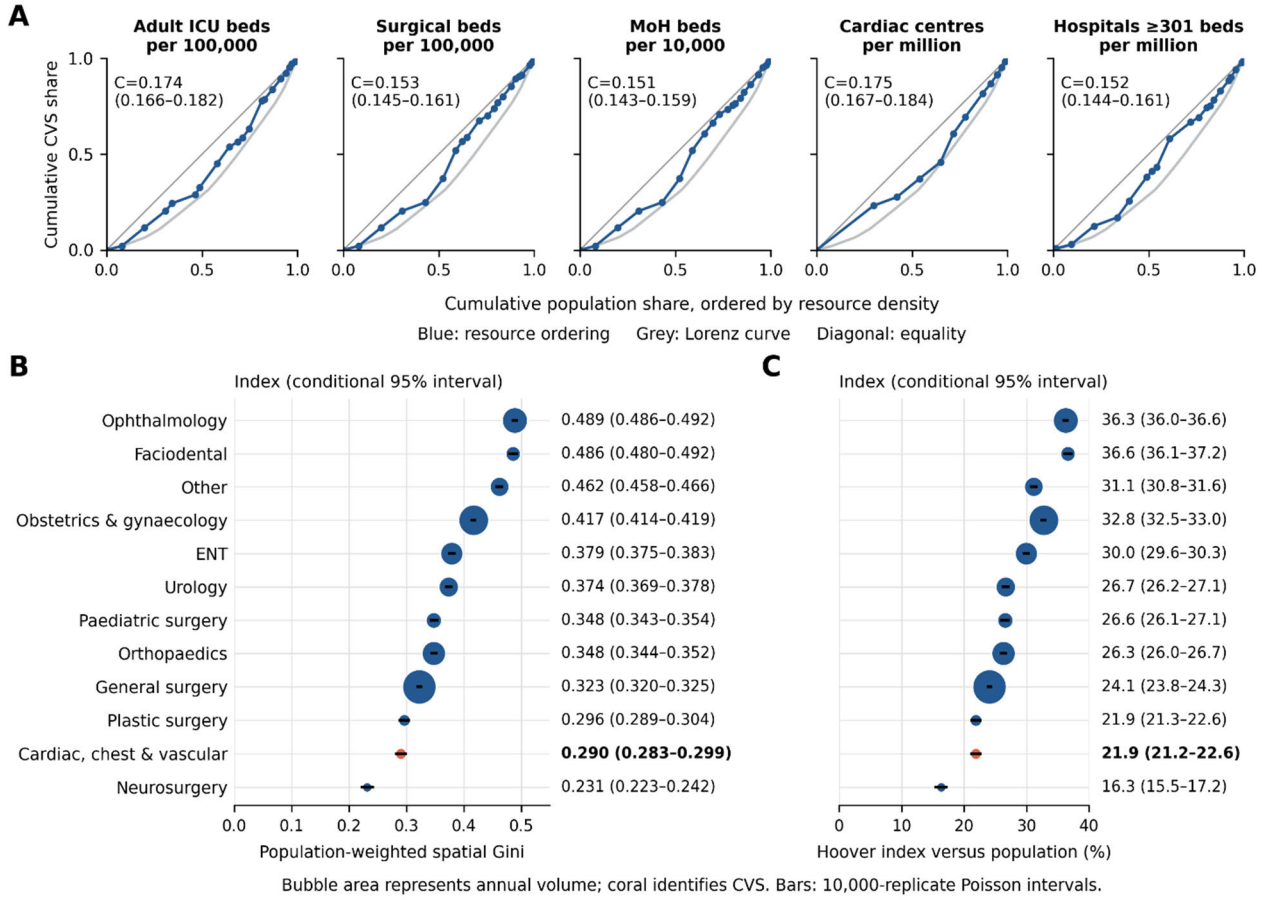


Figure 2: CVS Resource-Gradient Concentration and Geographical Inequality of 12 MoH Surgical Departments, 2024
CVS resource-gradient concentration functions, ordered by the density of each resource. Ties are calculated with a population-weighted midrank, and are shown as tied points in the graph. C is the concentration index with conditional 95% Poisson bootstrap intervals. The grey Lorenz curve is ordered by the CVS rate. (B,C) Spatial Gini and Hoover indices of 12 department categories, with population weight; the bubble size represents the activity volume. Intervals are the conditional 95% from 10,000 Poisson replicates. The Lorenz bound is a rank-ordering benchmark, not a variance-accounted-for measure
Source: MoH 2024 [1]

6,069 interventions (36.8% increase) whereas the output-oriented variable-returns DEA projection revealed gaps of 2,435 interventions (14.8% increase). These gaps were largest in Al-Jouf (533), Jeddah (508), Taif (238), and Jazan (236). The Riyadh and Hafr Al-Batin clusters were efficient under variable returns with extreme combination of scale and inputs (Table 4). These projections are model-derived estimates and not the observed capacity.

There were 341,365 referrals in the referral matrix, out of which 301,968 were intracluster referrals (88.5%) and 39,397 were off-diagonal referrals. Riyadh Second cluster got 11,251 inter-cluster referrals (28.6%); and Riyadh Second, Jeddah Second, Riyadh First and Makkah clusters received 69.1%. The correlation of net referral balance with CVS volume was 0.69 ($p<0.001$); this may largely be due to the size and importance of cluster as a medical referral center. On the other hand, the outbound referrals per capita did not correlate with the CVS rate (rho = -0.07, p = 0.762). These referrals were the referrals for all the specialties, not specifically CVS; thus, both correlations do not reflect the CVS-specific referral effectiveness or access to such treatment (Figure 5). This national context confirms the findings of the previous secondary data analysis about the Saudi electronic referral system [41].

Workforce, Associations and Scaling

There were 314 cardiothoracic physicians in the harmonised units, including 122 consultants, 160 registrars and 32 residents as well as 117 vascular surgeons. The cardiothoracic physician density was 8.9 per million national populations, which varied from 4.8 in Jeddah to 29.3 in Northern Borders. CVS interventions per combined cardiothoracic and vascular physicians ranged from 7.7 (Al-Jouf) to 55.3 (Asir); this is the ratio of department activity to the physicians' headcount and not the individual physician productivity. The independent scaling exponent of work-force density was 1.29 (HC3-t-based 95% confidence interval 1.02-1.56; P=0.038 against the exponent one); this log-log scaling exponent is derived from a different model and is not equivalent to consultant-density IRR below. The adult ICU bed, surgical bed and population scaling exponents were 1.01, 1.42 and 0.77; for each of these,

Table 3: Resource Context of the 20 MoH health clusters, 2024: Hospital Infrastructure, Critical-Care and Emergency Capacity, Cardiac Centres and Hospital Throughput

	Hospital Infrastructure					Critical Care			Emergency		Cardiac Centres		Hospital throughput				
Health cluster	Hosp., N	≥301 Beds, N	MoH Beds /10k	Surg. Beds /100k	Surg. Bed Share, (%)	Adult ICU /100k	Neo.+Ped. ICU /100k	ICU Bed Share, (%)	ER mon. /100k	ER Monitored (%)	N	Per Million	Admit. /1,000	Bed occ., (%)	ICU occ., (%)	ALOS, days	Turns /mo
Riyadh First	21	3	9.28	21.1	22.8	10.35	6.40	18.1	5.87	52.8	1	0.23	19.5	62.5	68.2	7.89	2.57
Riyadh Second	13	2	6.37	16.9	26.5	4.31	3.95	13.0	3.81	52.6	1	0.24	16.3	63.8	61.5	7.00	2.70
Riyadh Third	14	1	19.43	34.3	17.6	12.12	9.82	11.3	7.75	38.8	0	0.00	52.5	46.3	24.8	7.89	1.81
Makkah	15	3	9.57	25.0	26.2	11.22	6.96	19.0	7.42	69.4	2	0.62	48.8	74.5	46.5	5.83	3.89
Jeddah First	6	1	3.96	9.5	24.0	2.89	2.60	13.9	1.71	32.7	0	0.00	19.4	70.0	30.8	6.80	3.15
Jeddah Second	8	3	15.33	42.9	28.0	14.37	15.85	19.7	3.93	55.0	0	0.00	43.4	67.4	33.4	8.08	2.75
Taif	16	3	21.84	41.9	19.2	9.52	17.38	12.3	8.11	36.4	0	0.00	68.9	55.2	52.7	7.20	2.54
Madinah	18	3	13.29	28.1	21.1	12.70	11.38	18.1	7.50	58.5	1	0.43	69.2	56.9	71.2	6.37	3.34
Qassim	19	2	22.67	58.6	25.8	14.12	15.28	13.0	9.07	37.3	1	0.68	70.1	55.0	56.1	5.10	2.89
Eastern	21	5	8.86	18.4	20.8	5.18	3.31	9.6	2.54	29.5	1	0.26	65.5	67.2	87.8	4.83	3.22
Al-Ahsa	10	2	16.96	33.6	19.8	12.38	13.95	15.5	8.67	59.0	1	0.83	95.0	65.1	73.7	4.73	3.89
Hafr Al-Batin	7	0	19.52	53.3	27.3	13.27	10.15	12.0	2.73	10.9	0	0.00	124.4	44.1	65.4	5.89	2.78
Asir	28	2	15.31	35.9	23.4	11.30	9.82	13.8	8.65	52.3	1	0.45	41.9	57.2	79.9	5.48	2.68
Tabuk	12	1	19.75	42.6	21.6	15.02	18.11	16.8	6.69	28.5	0	0.00	69.9	51.4	65.1	5.60	2.68
Hail	14	2	23.69	44.1	18.6	10.50	17.22	11.7	18.93	58.5	1	1.22	76.8	48.0	70.2	5.44	2.69
Northern Borders	11	1	35.62	68.1	19.1	31.23	22.93	15.2	18.79	49.0	1	2.44	116.4	38.6	66.9	5.87	2.81
Jazan	22	2	18.91	38.6	20.4	11.81	13.30	13.3	14.01	62.8	0	0.00	100.2	67.7	61.8	4.63	4.18
Najran	11	1	21.54	42.3	19.6	15.08	14.00	13.5	16.93	55.3	1	1.54	112.7	66.5	54.6	4.23	3.72
Al-Baha	10	2	34.80	86.0	24.7	23.11	23.92	13.5	24.72	53.2	0	0.00	139.0	51.1	44.3	6.75	3.30
Al-Jouf	14	1	29.68	48.6	16.4	30.14	22.64	17.8	10.10	35.1	0	0.00	96.2	49.6	42.8	5.24	3.27
Saudi Arabia, MoH total	290	40	13.29	29.6	22.3	10.25	9.32	14.7	6.89	48.0	12	0.34	53.2	57.9	57.9	6.00	3.00
Max ÷ min across clusters	4.7×	0–5†	9.0×	9.0×	1.7×	10.8×	9.2×	2.1×	14.4×	6.3×	0–2†	0.00–2.44†	8.5×	1.9×	3.5×	1.9×	2.3×

ALOS: Average Length of Stay, ER: Emergency Room, Mon.: Monitored, NICU/PICU (Neo+Ped.): Neonatal/Paediatric ICU, occ.: Occupancy; Turns/Mo: Bed Turnover Per Month, 10k/100k: 10,000/100,000. Hospitals ≥301 beds combine the 301–400, 401–500 and >500 classes. Cardiac centres follow the yearbook designation, which does not verify surgical capability; National Occupancy, ALOS and bed-turnover entries are the published MoH indicators in sheet 4-25, rather than arithmetic or bed-weighted cluster means. These indicators describe whole-cluster services. †A range is shown when the minimum is zero

Table 4: Cardiothoracic and Vascular Surgical Workforce, Partial Productivity and Data Envelopment Analysis Efficiency Across 17 Harmonised Cluster–Branch Units, 2024

			Specialist Workforce							Partial Productivity			Data Envelopment Analysis					
Harmonised Unit	Proxy pop. (000s)	CVS, n	CT, n (C/R/Res)	Vasc. n	CT /1m	CT C, %	Cardio. /1m	Anaes. /100k	ICU MD /100k	CVS / CT+V	CVS / CT C	CVS / aICU	TE (CRS)	PTE (VRS)	SE (RTS)	Super -TE	CRS gap, n	VRS gap, n
Riyadh (First–Third)	9,426.2	2,687	53 (26/18/9)	22	5.6	49.1	12.2	6.29	2.16	35.8	103.3	3.64	0.649	1.000	0.649 (DRS)	—	1,456	0
Makkah	3,234.4	2,043	27 (10/12/5)	10	8.3	37.0	25.4	7.33	3.96	55.2	204.3	5.63	1.000	1.000	1.000 (CRS)	1.011	0	0
Jeddah (First–Second)	4,357.6	1,257	21 (9/10/2)	11	4.8	42.9	10.3	5.16	2.46	39.3	139.7	4.13	0.712	0.730	0.975 (IRS)	—	509	508
Taif	1,208.6	653	19 (3/14/2)	7	15.7	15.8	29.0	10.59	2.48	25.1	217.7	5.68	0.696	0.754	0.923 (IRS)	—	286	238
Madinah	2,345.6	2,432	34 (12/14/8)	11	14.5	35.3	38.4	6.91	3.75	54.0	202.7	8.16	1.000	1.000	1.000 (CRS)	1.465	0	0
Qassim	1,466.0	843	15 (6/9/0)	3	10.2	40.0	36.8	10.98	3.14	46.8	140.5	4.07	0.847	0.939	0.902 (IRS)	—	152	72
Eastern	3,899.2	1,435	26 (11/11/4)	9	6.7	42.3	13.1	6.08	2.18	41.0	130.5	7.10	0.870	0.889	0.979 (IRS)	—	214	189
Al-Ahsa	1,211.5	763	17 (8/8/1)	4	14.0	47.1	28.9	12.55	4.87	36.3	95.4	5.09	0.670	0.880	0.761 (IRS)	—	376	222
Hafr Al-Batin	512.4	131	4 (1/3/0)	2	7.8	25.0	35.1	8.39	0.98	21.8	131.0	1.93	0.395	1.000	0.395 (IRS)	—	201	0
Asir	2,220.9	1,437	21 (9/12/0)	5	9.5	42.9	24.8	7.43	1.71	55.3	159.7	5.73	1.000	1.000	1.000 (CRS)	1.002	0	0
Tabuk	972.1	501	8 (4/4/0)	6	8.2	50.0	26.7	8.64	1.65	35.8	125.2	3.43	0.648	0.838	0.773 (IRS)	—	273	149
Hail	818.9	647	10 (5/5/0)	4	12.2	50.0	61.1	9.89	2.44	46.2	129.4	7.52	0.922	1.000	0.922 (IRS)	—	55	0
Northern Borders	409.9	263	12 (4/8/0)	2	29.3	33.3	73.2	13.66	1.46	18.8	65.8	2.05	0.342	0.981	0.349 (IRS)	—	506	123
Jazan	1,541.5	417	11 (2/8/1)	3	7.1	18.2	11.7	7.53	2.47	29.8	208.5	2.29	0.539	0.741	0.727 (IRS)	—	357	236
Najran	649.8	492	13 (5/8/0)	5	20.0	38.5	41.5	10.77	1.54	27.3	98.4	5.02	0.615	1.000	0.615 (IRS)	—	308	0
Al-Baha	372.1	322	7 (3/4/0)	6	18.8	42.9	45.7	20.69	4.03	24.8	107.3	3.74	0.459	0.913	0.502 (IRS)	—	380	165
Al-Jouf	653.7	177	16 (4/12/0)	7	24.5	25.0	56.6	13.61	1.84	7.7	44.2	0.90	0.151	0.859	0.175 (IRS)	—	998	533
Saudi Arabia, MoH total	35,300.3	16,500	314 (122/160/32)	117	8.9	38.9	22.2	7.58	2.57	38.3	135.2	4.56	Mean 0.677	Mean 0.913	Mean 0.744	—	6,069	2,435

DEA: Data Envelopment Analysis, CCR/BCC: Constant/Variable Returns-To-Scale Models, CT: Cardiothoracic, C/R/Res: Consultant/Registrar/Resident, V/vasc.: Vascular, CT C, %: Consultant Share, Cardio.: Cardiology, Anaes.: Anaesthesia, ICU MD: Intensivists, aICU: Adult ICU, 1m/100k: 1,000,000/100,000. Counts Include Residents, Harmonisation Follows Methods, DEA Inputs: CT+Vascular Headcount, Surgical Beds, Adult ICU Beds, Output: CVS. TE/PTE: Input-Oriented CCR/BCC Scores [38,39], SE=TE/PTE, IRS/DRS: Increasing/Decreasing Returns. Super-Efficiency Excludes the Evaluated Unit [40], CRS gap = CVS×(1/TE−1), VRS gap = CVS×(Output-Oriented BCC factor−1). Totals Use Unrounded Scores. These are Conditional Projections, National Scores are Unweighted 17-Unit Means

Table 5: Associations between Resource Density and CVS Activity: Rank Correlations, Negative Binomial Incidence Rate Ratios and Population-Adjusted Resource Elasticities

Panel A. Cluster level (n = 20): resource densities and hospital performance										
Predictor (SD)	N	Spearman ρ (95% CI)	p	q	IRR per SD (95% CI)	p	q	Dispersion α	Δα vs null, %	AIC
MoH beds per 10,000 (8.64)	20	0.38 (−0.09–0.71)	0.098	0.196	1.21 (0.96–1.51)	0.104	0.207	0.216	11.3	291.0
Surgical beds per 100,000 (18.2)	20	0.34 (−0.13–0.69)	0.139	0.243	1.22 (0.97–1.52)	0.084	0.207	0.212	12.9	290.6
Adult ICU beds per 100,000 (7.3)	20	0.38 (−0.09–0.71)	0.097	0.196	1.16 (0.90–1.49)	0.255	0.397	0.229	6.0	292.2
NICU + PICU beds per 100,000 (6.4)	20	0.45 (−0.01–0.75)	0.047	0.163	1.27 (1.02–1.58)	0.036	0.166	0.201	17.2	289.5
Monitored ER beds per 100,000 (6.2)	20	0.60 (0.17–0.84)	0.005	0.046	1.29 (1.04–1.58)	0.018	0.146	0.189	22.2	288.2
Hospitals ≥301 beds per million (1.13)	20	0.56 (0.13–0.82)	0.010	0.046	1.31 (1.04–1.64)	0.021	0.146	0.188	22.9	288.0
Cardiac centres per million (0.65)	20	0.56 (0.12–0.82)	0.010	0.046	1.23 (0.98–1.54)	0.073	0.207	0.208	14.4	290.3
Admissions per 1,000 (35.6)	20	0.29 (−0.18–0.66)	0.212	0.330	1.20 (0.95–1.51)	0.118	0.207	0.218	10.4	291.2
Bed occupancy rate, % (9.9)	20	−0.16 (−0.57–0.30)	0.490	0.532	0.93 (0.74–1.17)	0.526	0.566	0.239	1.9	293.2
Adult ICU occupancy, % (16.7)	20	0.20 (−0.27–0.59)	0.402	0.511	1.10 (0.88–1.39)	0.402	0.555	0.236	3.2	292.9
Average length of stay, days (1.16)	20	−0.16 (−0.57–0.30)	0.494	0.532	0.92 (0.73–1.16)	0.476	0.555	0.238	2.3	293.1
Non-Saudi admissions, % (7.8)	20	−0.22 (−0.61–0.25)	0.352	0.493	0.92 (0.73–1.16)	0.473	0.555	0.238	2.3	293.1
Inbound inter-cluster referrals per 100,000 (108.3)	20	−0.02 (−0.46–0.42)	0.920	0.920	1.00 (0.80–1.24)	0.998	0.998	0.243	−0.0	293.6
Cardiac centre present (yes vs no)	20	—	0.081†	0.196	1.42 (0.94–2.14) ‡	0.094	0.207	0.215	11.5	291.0
Multivariable model: Cardiac centre present	20	—	—	—	1.53 (1.03–2.27)	0.036	—	0.190	22.0	290.3; LR P = 0.072
Adult ICU beds per 100,000 (per SD)	20	—	—	—	1.22 (0.96–1.56)	0.103	—			
Panel B. Harmonised units (n = 17): specialist workforce and alternative-provider presence										
Predictor (SD)	N	Spearman ρ (95% CI)	p	q	IRR per SD (95% CI)	p	q	Dispersion α	Δα vs null, %	AIC
Cardiothoracic surgeons per million (7.0)	17	0.55 (0.06–0.83)	0.022	0.098	1.22 (0.98–1.53)	0.078	0.141	0.153	15.6	245.7
Cardiothoracic consultants per million (2.4)	17	0.68 (0.25–0.89)	0.003	0.023	1.34 (1.11–1.60)	0.002	0.017	0.115	36.4	240.8
Cardiothoracic + vascular surgeons per million (9.7)	17	0.46 (−0.05–0.78)	0.063	0.141	1.22 (0.98–1.51)	0.070	0.141	0.151	16.3	245.6
Cardiologists per million (18.1)	17	0.51 (0.01–0.81)	0.037	0.110	1.26 (1.03–1.56)	0.027	0.122	0.140	22.5	244.3
Anaesthetists per 100,000 (3.8)	17	0.27 (−0.25–0.67)	0.295	0.380	1.16 (0.94–1.42)	0.159	0.226	0.162	10.6	246.7
Intensivists per 100,000 (1.1)	17	0.31 (−0.21–0.69)	0.228	0.342	1.20 (1.00–1.46)	0.054	0.141	0.149	17.8	245.2
Other-government beds per 10,000 (2.9)	17	−0.33 (−0.71–0.19)	0.192	0.342	0.88 (0.72–1.08)	0.237	0.266	0.168	7.1	247.4

Table 5: Continued

Predictor (SD)	N	Spearman ρ (95% CI)	p	q	IRR per SD (95% CI)	p	q	Dispersion α	Δα vs null, %	AIC
Private beds per 10,000 (3.2)	17	−0.07 (−0.53–0.43)	0.801	0.801	0.91 (0.74–1.12)	0.373	0.373	0.173	4.2	248.0
MoH share of all hospital beds, % (20.7)	17	0.20 (−0.31–0.63)	0.433	0.487	1.16 (0.93–1.45)	0.176	0.226	0.164	9.3	247.0
Multivariable model: Cardiothoracic surgeons per million (per SD)	17	—	—	—	1.19 (0.95–1.50)	0.131	—	0.148	18.2	247.2; LR P = 0.170
Other-government beds per 10,000 (per SD)	17	—	—	—	0.93 (0.75–1.13)	0.454	—			
Panel C. Population-Adjusted Elasticities: log E[CVS] = β0 + β1·ln(population) + β2·ln(resource stock)										
Resource stock (log)	N	Resource elasticity β2 (95% CI)	p	q	Population Elasticity β1 (95% CI)	LR test P	Dispersion α	Δα vs population-only model, %	AIC	
Adult ICU beds	20	0.53 (−0.08–1.13)	0.086	0.096	0.55 (0.14–0.95)	0.103	0.200	11.8	291.4	
Surgical beds	20	0.98 (0.23–1.73)	0.010	0.014	0.35 (−0.07–0.78)	0.021	0.177	22.2	288.8	
All MoH beds	20	1.01 (0.26–1.76)	0.008	0.014	0.41 (0.04–0.79)	0.021	0.177	22.1	288.8	
Monitored ER beds	20	0.53 (0.20–0.86)	0.002	0.006	0.59 (0.30–0.88)	0.007	0.161	29.1	286.8	
Cardiothoracic surgeons	17	0.69 (0.16–1.22)	0.011	0.014	0.44 (0.06–0.82)	0.020	0.122	26.5	243.8	
Cardiothoracic consultants	17	0.64 (0.32–0.95)	<0.001	<0.001	0.44 (0.16–0.72)	0.001	0.093	44.1	239.0	
Cardiothoracic + vascular surgeons	17	0.77 (0.18–1.35)	0.010	0.014	0.43 (0.04–0.81)	0.019	0.122	26.7	243.7	
Cardiologists	17	0.74 (0.30–1.17)	<0.001	0.005	0.47 (0.18–0.76)	0.004	0.103	38.0	241.0	
Anaesthetists	17	0.48 (−0.59–1.54)	0.379	0.379	0.54 (−0.19–1.27)	0.382	0.159	4.1	248.4	
Intensivists	17	0.56 (0.13–0.99)	0.011	0.014	0.22 (−0.31–0.75)	0.017	0.120	27.6	243.5	

CVS: Cardiac, Chest and Vascular; ICU: Intensive Care Unit; NB2: Negative Binomial Model with Quadratic Variance; P: Unadjusted; q: Benjamini–Hochberg False-Discovery-Rate-Adjusted p-value; Rho: Spearman Correlation with Approximate Bonett–Wright Intervals [36]. IRR: NB2 Incidence Rate Ratio for a One-Sample-SD Increase, with Log-Population Offset [34]; q: Benjamini–Hochberg Adjustment within Each Panel and Statistic [38]. SD is the Sample Standard Deviation. Δα: Reduction in Fitted NB2 Dispersion. Null α=0.243 for 20 Clusters and 0.181 for 17 Units. AIC: Akaike Information Criterion; LR: Likelihood-Ratio Test; †Mann–Whitney comparison for centre presence; median proxy rates 63.2 versus 39.1 per 100,000. ‡Presence-versus-absence IRR. Two-term models were exploratory, not preregistered. Bold identifies the matching statistics and predictors with q<0.05. Panel C Includes Log Population and Log Resource Stock Separately; Resource Elasticity is not an IRR per SD

Table 6: National Sector Context of MoH CVS Output and Robustness of the Concentration Estimates, 2024

Panel A. CVS surgical output by government sector and agency, 2024									
Sector / agency	All Surgery, N	CVS, N	CVS / Agency Surgery, %	Government CVS Share, %	Government Surgery Share, %	Lq (95% ci)			CVS / 100k National Pop.
Ministry of Health (all clusters)	717,238	16,500	2.30	24.33	66.37	0.37 (0.36–0.37)			46.7
Ministry of Defense	123,598	25,486	20.62	37.58	11.44	3.29 (3.26–3.32)			72.2
Ministry of National Guard	62,496	2,839	4.54	4.19	5.78	0.72 (0.70–0.75)			8.0
Ministry of Interior	28,557	654	2.29	0.96	2.64	0.36 (0.34–0.39)			1.9
King Faisal Specialist Hospital and Research Centre	47,590	16,775	35.25	24.73	4.40	5.62 (5.55–5.68)			47.5
King Khalid Eye Specialist Hospital	13,504	0	0.00	0.00	1.25	—			0.0
Royal Commission Hospitals	6,464	604	9.34	0.89	0.60	1.49 (1.38–1.61)			1.7
Saudi Airlines Medical Services	22,521	0	0.00	0.00	2.08	—			0.0
Ministry of Education	58,734	4,964	8.45	7.32	5.43	1.35 (1.31–1.38)			14.1
All government sectors	1,080,702	67,822	6.28	100.00	100.00	1.00 (reference)			192.1
Panel B. Robustness of CVS concentration to geography, denominator and influential units									
Specification	Units, N	HHI	ENC	Spatial Gini (95% CI)	Hoover, % (95% CI)	Theil T (95% CI)	Between Theil, %	Extremal Ratio	Pop. Hosting 50% of CVS, %
Primary: 20 clusters, census-anchored population (2024)	20	786	12.73	0.290 (0.283–0.299)	21.9 (21.2–22.6)	0.139 (0.132–0.147)	61.0	8.48	31.2
20 clusters, HHC beneficiary denominators	20	786	12.73	0.302 (0.295–0.310)	23.2 (22.6–23.9)	0.148 (0.141–0.156)	59.3	5.66	30.0
17 harmonised units, census population (no intra-city split)	17	956	10.46	0.250 (0.243–0.259)	20.8 (20.0–21.5)	0.106 (0.099–0.113)	80.1	4.06	31.2
20 MoH branches/offices, census population	20	930	10.76	0.259 (0.251–0.268)	21.4 (20.7–22.2)	0.112 (0.106–0.120)	75.2	10.60	30.5
23 reporting sub-units, census-anchored population	23	759	13.18	0.299 (0.292–0.307)	22.6 (21.9–23.3)	0.145 (0.139–0.154)	58.1	10.60	30.5
13 administrative regions, total population	13	1,405	7.12	0.221 (0.212–0.230)	15.8 (15.1–16.6)	0.085 (0.078–0.091)	—	3.83	34.5
13 administrative regions, Saudi population	13	1,405	7.12	0.190 (0.182–0.199)	13.4 (12.6–14.1)	0.064 (0.059–0.070)	—	4.47	37.4
Primary, excluding Madinah (largest volume)	19	782	12.79	0.263 (0.255–0.272)	20.3 (19.5–21.1)	0.116 (0.109–0.123)	45.1	7.08	32.6
Primary, excluding the three Riyadh clusters	17	953	10.49	0.256 (0.248–0.265)	18.4 (17.8–19.1)	0.115 (0.109–0.123)	55.7	8.48	34.4
Cardiac-centre clusters only (n = 11)	11	1,200	8.33	0.265 (0.257–0.275)	20.4 (19.6–21.2)	0.118 (0.111–0.127)	84.3	6.03	32.9
Clusters without a cardiac centre (n = 9)	9	1,432	6.99	0.306 (0.291–0.322)	24.3 (23.0–25.7)	0.157 (0.142–0.174)	27.1	7.08	30.1
Leave-one-cluster-out range (cluster whose omission gives min / max)	19	HHI 782–852 ENC 11.74–12.79		0.251–0.306 (Riyadh First / Makkah)	18.6–22.9 (Riyadh First / Riyadh Second)	0.108–0.152 (Riyadh First / Makkah)	—	—	—

ACHI: Australian Classification of Health Interventions, HHC: Health Holding Company, Panel B Values are Sensitivity Scenarios, Panel A: MoH sheets 4-36/4-37 [1], LQ Compares Agency/Government CVS Shares of Surgery. Structural-Zero Categories Receive no LQ, private ACHI Activity is Excluded. Labels may Differ in Scope; Panel B: Populations follow Table 1; HHC uses Undated Beneficiaries [4]. Saudi Denominators Retain all Events [2,20], These are not Saudi-Patient Rates, Intervals: Conditional 10,000-Replicate Poisson Bootstrap. HHI Minimum/Maximum Omit Madinah/Eastern, ENC Endpoints Reverse that Order. Other Leave-One-Out Cells Name the Omitted Cluster. Between-Region Theil is Inapplicable for 13 Regions

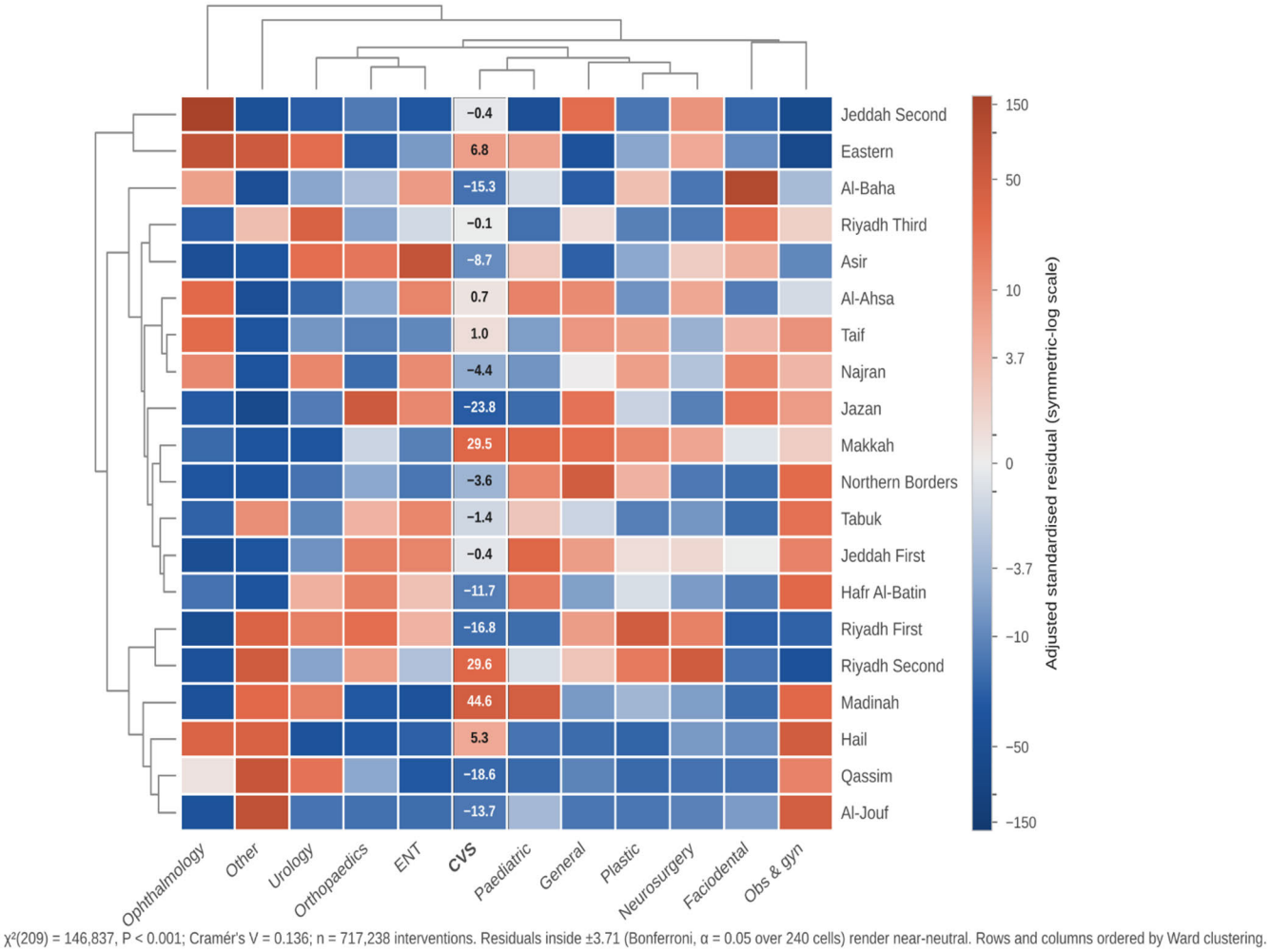


Figure 3: Specialty Mix Signatures: Adjusted Standardised Residuals of the Surgical Activity by Cluster and Department, 2024
Adjusted standardised residuals of the 20×12 cluster-by-department table [50]. Blue denotes fewer and salmon more interventions than expected in an independent clusters-departments model. A symmetric logarithmic color scale makes the small and large residuals comparable. The Bonferroni criterion corresponds approximately to ±3.71 in 240 cells. Rows and columns are ordered using Ward hierarchical clustering [32]; the outlined column is that of CVS, and shows residual values. The data contains 717,238 interventions but not patient outcomes
Source: MoH 2024 [1]

interval includes one. Madinah surpassed its fitted output by 0.73-0.94 log units under all three scaling laws, while Al-Jouf was 1.47 log units below the fitted value for adult ICU beds (Figure 6).

In cluster level, there were three correlations surviving after false discovery correction for clustering within panels: the monitored emergency-bed density (rho = 0.60); the large hospital density (rho = 0.56); and the centre density (rho = 0.56), q = 0.046 for each of them. None of the cluster-level NB2 IRR survived such adjustment. In seventeen harmonised units, the cardiothoracic consultant density correlated with CVS rate (rho = 0.68, q = 0.023) and had IRR 1.34 per SD unit increase (95% confidence interval 1.11-1.60; q = 0.017). Separate log-stock model estimated the consultant elasticity 0.64 (0.32-0.95), which implies 6.2% increase in CVS volume (1.10^β -1) per 10% growth of consultant stock with fixed population size, this is the ecological statistical association rather than causal effect. Other-government and private bed-density correlations were -0.33 and -0.07, respectively; none of them was statistically significant (Table 5).

Government Sector Context and Robustness

The total number of interventions in government sector was 67,822 interventions in the department category. The MoH accounted for 24.3% of this activity while delivering 66.4% of all government surgical activities. Ministry of Defense accounted for 25,486 CVS interventions, King Faisal Specialist Hospital and Research Center 16,775 interventions; altogether 62.3% of government activities. The activity in this category was 192.1 per 100,000 national population, whereas 46.7 per 100,000 for MoH-only sector; note that the national population denominators ignore agency-specific catchments, eligibility criteria, and referral role. The total in government is equal to the sum of MoH (Sheet 4-36) and other agencies (Sheet 4-37) row; the

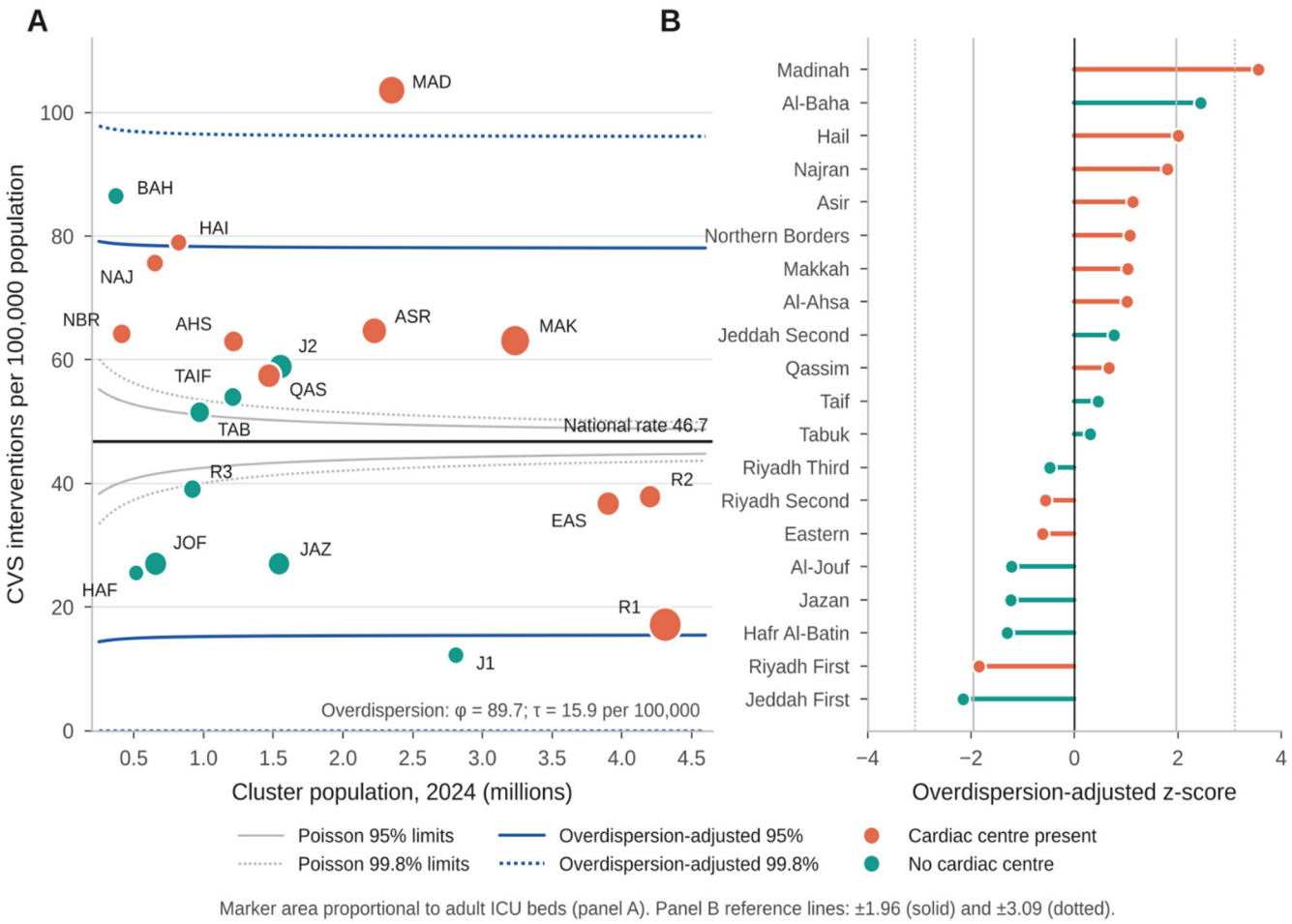


Figure 4: CVS Funnel Plot with Poisson and Overdispersion-Adjusted Control Limits, 2024
(A) CVS rates by proxy population, with Poisson 95% and 99.8% limits, and additive-variance limits [33]. The national average rate is 46.7 per 100,000. φ=89.7 is the mean squared winsorized Poisson z-score (Q/20), not the commonly used Pearson statistic divided by residual degrees of freedom. τ=15.9 is the standard deviation between clusters per 100,000. Bubble sizes indicate adult ICU beds; heart center status is determined from the yearbook sheet 2-4. (B) Standardised deviations with additive variance widening. Classifications are descriptive flags that depend on dispersion and population assumptions
Source: MoH 2024 [1]

smaller fraction of MoH activities is determined by the distribution of specialised services across defence, specialist, university and other providers, not under-performance of MoH. (Table 6).

The sensitivity analysis for spatial Ginis provided a range from 0.190 to 0.306, and from 13.4% to 24.3% for Hoover indices. The clustering into Riyadh and Jeddah clusters decreased the spatial Gini to 0.250 and increased the between-region Theil component to 80.1%. With 13-region specification, the total population Gini was 0.221; the specification with Saudi national population shares lowered the Gini further to 0.190. With HHC beneficiary population, it was 0.302. The leave-out-one-clusters Ginis varied between 0.251 (when Riyadh First was omitted) and 0.306 (when Makkah was omitted). Concentration measures excluding denominators were unchanged with replacement of population numbers. The lowest values arose with aggregating into 13 regions and from using Saudi national population; the highest values were from leaving out Makkah or restricting to the clusters without a cardiac centre, hence, the largest influence of geographical aggregation and population denominator choice. In every specification, CVS spatial Gini (maximum 0.306) remained below the principal all-surgery spatial Gini (0.319); omission of Madinah, Makkah or Riyadh clusters did not alter substantive conclusion.

DISCUSSION

Geographic Concentration Within a Wider Provider System

The main finding of this study is the difference between the degree of absolute concentration and relative inequality in relation to the population. CVS activities presented higher concentration than total number of MoH surgeries considering the latter as a reference value, but its spatial Gini is smaller if proxy population is taken as a reference benchmark. While Madinah, Makkah and Riyadh Second play an important role, relatively low level clusters like Al-

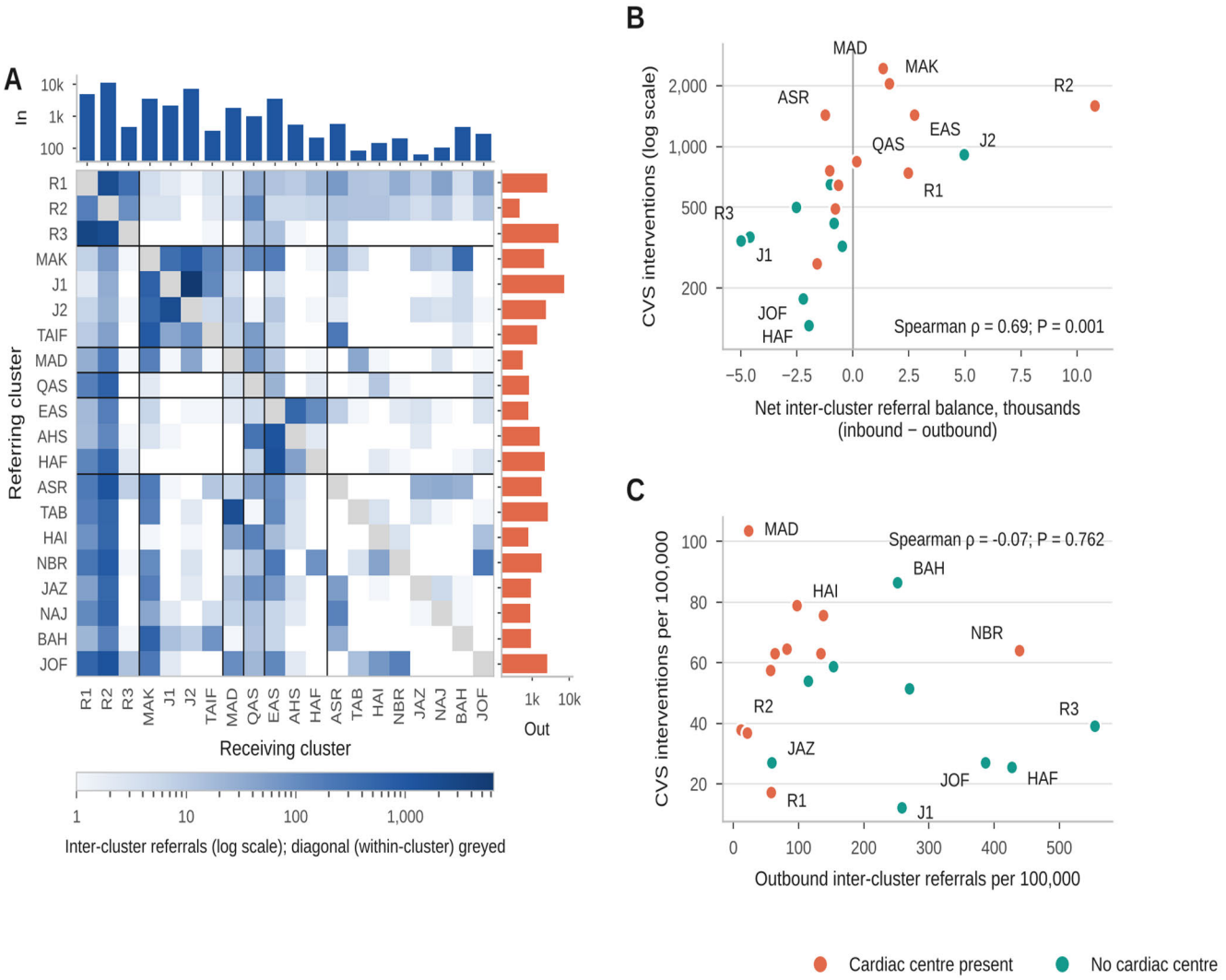


Figure 5: Inter-Cluster Referral Network and its Relation to CVS Activity, 2024

(A) Origin-destination matrix of all-specialty referrals, including reverse referrals, to general or specialised government hospitals. Diagonal elements are intra-cluster referrals, greyed; off-diagonal colors use a logarithmic scale. Inset bars represent off-diagonal sums; black bars separate the administrative regions. (B) Referral net balance against CVS volume. (C) Outbound referrals per proxy population against CVS rate. Counts are observed; Spearman correlations are unadjusted descriptive statistics. Figure B Reports p = 0.001 to three decimals; the full precision value is 0.000756. These flows cannot reveal CVS patients. Codes are those of Figure 1

Source: MoH 2024 sheet 4-63 [1]

Baha and Hail presented relatively high rates too. Therefore, it is clear that the interpretation of the policy is strongly affected by the type of the reference. Volume shares describe contribution to the total output of the MoH; rates describe relative activity in relation to an estimated catchment area; location quotients describe portfolio of the cluster. None of them presents resident access to services directly. The low spatial Gini coefficient therefore doesn't necessarily indicate equal access to specialised surgery, since needs of patients, eligibility criteria, travel time and cross-cluster treatments weren't assessed and high-rate clusters aren't superior, low-rate – inferior per se.

The existence of the second provider sector, the government one, has an important implication for the MoH clusters assessment. Almost three quarters of total government CVS department activities happened outside MoH clusters; hence the MoH rates reflect only a part of the provider system. The lack of activity in a population center might be complemented by the activities of defence, specialty or university hospitals. On the other hand, high MoH rate might happen due to the referral of patients there. Lack of the significant correlation with the density of alternative providers beds doesn't exclude substitution possibilities; the bed density is just a rough measure of surgical specialisation and differs in eligibility criteria and units of analysis. Clinical procedure registries, such as emerging Saudi CABG registry, allow us far more detailed comparison than just the department count [42].

Resources, Teams and the Meaning of Frontier Scores

The positive concentration indices imply that CVS activity was more concentrated among those clusters with denser

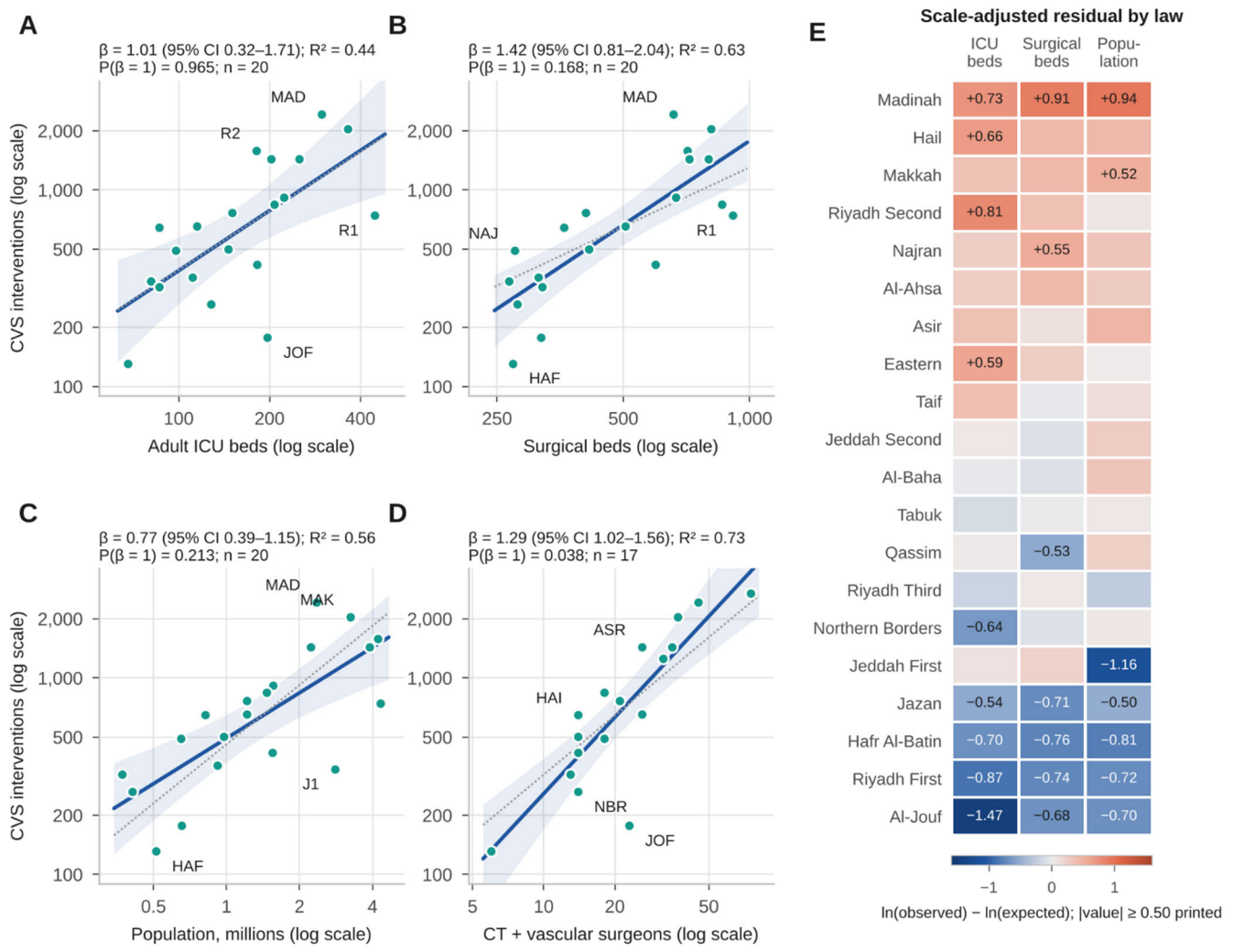


Figure 6: Scaling of CVS Output with Critical-Care, Surgery Bed, Population and Personnel Resources, and Scale-Adjusted Residuals, 2024

(A–D) Ordinary least squares regression of CVS activity versus adult ICU beds, surgical beds, proxy population (20 clusters) and total cardiothoracic–vascular physician headcount (17 units). Estimates β with robust HC3 covariance and t-based 95% confidence intervals. The dotted line represents the reference linear function with exponent 1 through the centroid. (E) Log observed vs. log predicted activity for the three cluster-level models; values whose absolute magnitude exceeds 0.50 are printed. Codes are those of Figure 1. Scaling exponents and residuals are model estimates describing ecological relations [34]

Source: MoH 2024 [1]

infrastructure. However, it is impossible to separate the contribution of the resource base because it is correlated with each other and the referral activity also affects both volume of activity and resource base. The consultant density demonstrated better statistical properties than total cardiothoracic staff after adjustment for multiple testing. It corresponds to the role of the staff composition, however consultants can be allocated in clusters with already high volumes or designated centres, hence the reverse causality, and referral and other resources such as the operating theatre could explain both variables. The population adjusted elasticity model helps to address the shared denominator problem, however it doesn't deal with the confounding and reverse causality problem.

The bed and physician counts neglect several resources required for conducting surgery. Guidelines on health system of perfusionists in cardiac surgery and the description of development of cardiology centres demonstrate the key importance of specialized team, perioperative processes and services organisation [43,44]. Yearbook doesn't provide us with information on perfusion staff, operating room capacity, complexity and allocation of ICU beds. The cluster could be equipped with lots of general surgery or ICU beds but mainly used by other specialties. Hence the low rate of activity to resources ratios in some clusters doesn't give grounds to the discussion of underutilization of beds and specialists. Any expansion of resources and workforce should be based on more detailed information about local needs, staffing models, procedures mix and patients' outcomes.

DEA approach divides the effect of the scale and the peer group frontier, however it doesn't help to interpret

managerial efficiency. The scores are dependent on the choice of inputs, comparable output and extremum points of the frontier. Relatively small size of the reference set (only 17 units), only three types of input and one heterogeneous output makes the scores extremely sensitive to possible differences in the reporting. The 2,435-intervention variable-returns gap is not the forecast of how much interventions can be safely and efficiently conducted using current resources, the same refers to the super-efficiency scores due to the small reference set and extreme units. Planners need to specify procedure mix, CVS resource base, demand, eligibility criteria and outcomes before setting any targets. Constant returns gaps are extremely sensitive to the scale alterations.

Concentration and Clinical Outcomes

Studies on the relationship between volume and performance of the hospital provide grounds for studying specialisation concentration, but not prove clinical superiority of the clusters. Birkmeyer et al discovered procedure-specific relationship between volume of operations and the hospital death rate in the USA [45]. Later studies on lung cancer showed associations between the higher surgery volume and the survival rate, LOS, readmissions and mortality [46,47]. Recently published metaanalysis revealed a dose-response relation between hospital volume and the outcome after abdominal aortic aneurysm repair [48]. All these studies consider both procedure and patients outcomes. Our aggregated data sets do not allow setting volume thresholds and benefiting from them.

In the same way the funnel limits should be treated cautiously. Wide variation compared with the simple Poisson model reflects the heterogeneity, but the reason of it can be legitimate heterogeneity in case mix, referral activity, eligibility criteria, coding and catchment area. Major change in the flagged clusters after adjusting winsorisation rule demonstrates sensitivity of classification to the statistical rule. The consistent high rate of Madinah helps in understanding the service organisation and referral demand; it is not a proof of clinical superiority. Jeddah First's low rate is exceptionally sensitive to the population partitioning and provider abundance.

Implications for Geographic Planning

Population proportional distribution represents a very transparent reference, however it is not optimal for allocation. Geographic equity is more complicated concept and takes into account needs, travel and consequences of decision making on the allocation [49]. Our Hoovers' index represents the discrepancy in the share, however doesn't suggest reallocation of 21.9% of interventions. The complex specialization could be equitable if referral routes and travel arrangements were good. Such kind of analysis highlights areas where the additional examination is required, especially the intra-metropolitan contrast in Riyadh and Jeddah, and contrast between the activity and general critical care beds. Moreover inequality and concentration measures are also dependent on the geographical units: aggregation of Riyadh and Jeddah sub-clusters reduced spatial Gini from 0.290 to 0.250 owing to smoothing of city contrasts (Table 6).

The most informative linkage between data sets would include the combination of the information about origin of patients, procedure code, treating hospital, specializations of staff and patients' outcomes across the provider sectors. This linkage would help to differentiate the local demand from referral activity, measure travel time to the treatment and check appropriateness of resource allocation to the procedures. At the moment the six tables and six figures present us a variety of complementary administrative views: activity intensity and concentration; resources and workforces; residuals of specialities, scaling and referral activities; sensitivity to the geographical units. Agreement of these results supports the descriptive patterns, disagreement indicates insufficient information. Procedure-specific registries and patient-origin, treatment, work force and outcome data linkage can validate these patterns.

Limitations

The observed outcome variable was an aggregated intervention count in the joint department. Patients, procedures, their emergency or elective nature, indication, multiple interventions and outcomes remain unknown. Different classification in the residual 'other' category was very variable, and even departments with similar names can have quite different classification system in different agencies. Private-sector data were not pooled because of different ACHI chapter classification system. Hence, the research could not compute national access to cardiac surgery, CABG utilization, disease adjusted unmet need and procedure-specific quality. Secondly, the populations of clusters were computed as proxies. Scaling assumes constant 2022 geographic proportions, and dated and rounded beneficiary counts were used for Riyadh and Jeddah partition. Populations of health regions are not the same as populations of similarly-named governorates. Cross-cluster care seeking, visitors, nationality-based eligibility and mobility may affect the rates. The national denominator was official, while cluster allocations were analytical. The results of sensitivity analysis provide an indication about the implications of alternative population allocation hypotheses, but they are no confirmation of any particular allocation as the actual 2024 catchment areas. Thirdly, workforce was counted as heads, including the residents, and not as clinical FTEs, and not taking part-time work, multiple appointments, non-clinical functions and distribution over facilities into account. Beds of general surgery and adult intensive care units were not assigned to CVS. Performance measures covered the whole cluster, the referrals covered all specialties. Targets of DEA were deterministic and were not modified for clinical complexities. Current online HHC description and 2026 literature were used for interpretation of the results but not used as measures of 2024 workforce and services. The fixed 2024 observation period did not allow assessment of further service changes. Conditional

bootstrap intervals exclude error of source data, denominator and catchment reconstruction uncertainty, and hence underestimate the overall uncertainty. Ecological design cannot prove patient-level relationship or causal effects, and with 17-20 unit's multivariable estimation is unstable.

CONCLUSION

During 2024, Saudi MoH hospitals had registered 16,500 interventions in the cardiac, chest and vascular department category. The recorded activity exhibited substantial variation between clusters, but its spatial inequality with respect to the proxy population was somewhat smaller than that of total MoH surgery activity (the spatial Gini ratio 0.290 versus 0.319), conditional on constructed cluster denominators. The association with the density of consultants is exploratory ecological relationship, but not proof of a causal workforce effect; DEA benchmark is an unvalidated measure of excess clinically appropriate operations. The results call for geographical analysis and linkage by procedure of data. These results do not prove access, unmet need, quality or efficiency of care provision, nor the locations to redistribute resources; linkage of procedure and patient-level data is required for assessment of access, referral pathway and outcomes, capacity.

Consent and Ethics

This analysis does not include any individual record or identifier and did not use human subjects. It does not require either ethics committee review or patients' informed consent.

Availability of Data and Code

The MoH Statistical Yearbook 2024 workbook [1], population sources [2,18,19] and HHC cluster list [4] are publicly available. The derived analytical dataset and the code for data extraction, population construction, geographical mapping, index calculation, statistical models and sensitivity analyses are provided with the archive. They contain only published aggregate data.

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