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Cost of ownership assessment for a da Vinci robot based on US real-world data

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Abstract

Background: Despite growth of robotic surgery, published literature lacks assessment of the cost of ownership (CoO) of a da Vinci robot by surgical service line and the associated benefit such data provides.

Methods: Based on real-world data (RWD) from 14 US hospitals and ≈6000 da Vinci robotic cases, CoO was assessed using all relevant fixed and variable cost components, calculated by surgical service line.

Results: At a representative hospital with an efficient robotic program (n = 424 cases), the weighted average fixed cost per case was $984. Weighted average variable cost per case was $8025 (range: $3325 for Cholecystectomy—multiport, to $16 986 for Rectal Resection). Assessing weighted average by case, main variable cost drivers were non-da Vinci supplies (49.5%), staff costs (28.6%), and da Vinci supplies (21.9%).

Conclusions: Case mix, annual robotic case volumes, and cut-to-close/patient-in-room time by surgical service line represent core variables influencing robotic program CoO, which help drive profitable program management.

KEYWORDS

cost of ownership, da Vinci robot, fixed and variable costs, real-word data

1 | INTRODUCTION

Despite the accelerated growth of robotic surgery in recent years, the published literature offers limited cost of ownership (CoO) assessment of this technology that includes all relevant cost categories. *Cost of ownership* is defined as initial equipment acquisition, variable supply and case costs by service line, and maintenance costs. Gaining insight into these costs can have a direct and positive effect on a robotic program's financial success and overall efficiency. Further, hospitals use a variety of approaches to robotic cost accounting, making it difficult, if not impossible, to determine accurate CoO assessments within a hospital and across hospitals. A recently published systematic review concluded that the methodological quality of studies evaluating costs of robotic surgery was low and insufficient to inform action by hospitals.[1] For example, cost accounting methods vary regarding the inclusion of capital cost of a robot and other indirect cost, such as administrative salaries, housekeeping, and many other nonrelated variables. Even within a given hospital, cost accounting methods may not be standardized for robotic and nonrobotic cases making comparisons difficult. Some look at direct costs only; others spread capital costs across department costs in different ways. These factors motivate the need for a more standardized approach to robotic CoO assessment.

The peer-reviewed literature has traditionally focused on the cost of robotic surgery by case rather than the CoO of the robot itself.[2-7] Additionally, when most US hospitals consider the cost of owning the da Vinci robot, they typically assess robotics differently than capital medical equipment used in laparoscopy, such as towers and generators, etc.[1] Why are there so many different cost accounting methods when it comes to assessing robotic vs laparoscopic costs?

In short, robotics emerged in the 2000s during the era of data capture and value-based medicine—both of which emerged more than a decade after the introduction of laparoscopy. While robotic surgical program performance data are now seen by most hospitals as critical to assessing whether and to what degree a program is "successful," very few such performance data assessments were performed on laparoscopy programs when this technology was introduced. Further complicating cost accounting matters is the fact that, although more data are now being collected than ever before, many hospitals' cost accounting data assessments are flawed due to data collection, auditing, and standardization errors combined with weak analytics.[8]

As of 2017, an estimated 2800 of 5500 US hospitals[9] (51%) have a da Vinci robot, with an estimated 644 000 annual robotic surgeries performed in the USA.[10] When a hospital or Integrated Delivery Network (IDN) is considering the acquisition of robotic technology for a new or existing robotic program, an accurate assessment of the total CoO should be an integral part of the technology acquisition equation. Beyond the fixed capital and service costs of the robot, the significant variable costs include the per procedure cost (supplies and multi-lived, so-called robotic "reposables"), case times, and associated cost of labor. Factors that contribute to these variable costs include case mix by service line and annual robotic case volume. Nevertheless, the published literature has yet to produce a detailed and standardized approach to calculating total CoO for the robot. This paper meets that need by analyzing the CoO of a da Vinci robot using anonymized, aggregated real-world data (RWD) from a range of robotic programs reflecting 14 US hospitals inclusive of an academic medical center (AMC), numerous mid-sized community hospitals, and a small, rural facility. All data were obtained from CAVA Robotics International (www.cava-robotics.com), an independent US-based firm that assists hospitals with optimization of da Vinci robotic program performance. The CAVA database captures and aggregates quality, operational, and financial robotic surgery and program data in connection with hospital engagements.

2 | MATERIAL AND METHODS

The CoO assessment included all relevant fixed and variable cost components: time, OR crew-related labor, capital, supplies, and service. Aggregated, anonymized data were collected from 14 US hospitals sourced from the facility Electronic Medical Records (EMR), supply chain, and cost accounting databases across 20 robotic case types within seven service lines, as summarized in Table 3. The various datasets for each hospital were curated and then synthesized, audited for gaps and errors by surgeons and administrative stakeholders, and then approved by the facility for accuracy. Fixed cost components, including purchasing costs and operational costs, were determined using current list prices for da Vinci robots.[11] Variable costs consisted of supplies for the robot, nonrobotic surgical supplies, case time, and labor.

2.1 | Fixed cost components

Currently, there are five versions of the da Vinci robot available; the most commonly used Xi and Si, as well as the X, SiE, and Single Port (SP), with an average sales price of $1.47 M. and a yearly average service contract cost of $154 K.[11,12] To calculate annual CoO, a service life of 5 years was used to estimate annual capital depreciation because in a real-world environment, robotic technology is often obsolete—or perceived as such—within this time frame, leading surgeons and facilities to move to next generation technologies.

To associate these fixed costs to a single robotic case, the yearly capital depreciation and service contract expense was divided by the average yearly number of robotic procedures performed per da Vinci robot at a given facility. This estimate (n = 424 cases annually) was obtained from data from Bellin Health (Green Bay, Wisconsin USA), selected as an example of an efficient robotic program given its excellent data management, analytics, and programmatic best practices. The average case mix by service line and case type is shown in Figure 1

2.2 | Variable cost components

Variable cost was calculated using RWD of $\approx$ 6000 da Vinci robotic cases from the 14 hospitals. These variable costs included disposable supplies such as drapes, trocars, sutures, and other commonly used surgical supplies. In addition, costs of mesh and single-use disposable laparoscopic instruments were included if surgeons utilized these additional costly supplies. Operating room time was included based on surgical case time, separated into cut-to-close time and patient-in-room time. Although the OR time cost assumptions in this analysis did not include the possible impact of *scheduled vs actual* case times, it should be noted that this differential can impact the cost of robotic ownership due to greater or lesser case efficiency and overall throughput. Associated OR personnel cost calculations were also included, based on aggregated CAVA data. Real-world da Vinci supplies, non-da Vinci supplies, and surgical times (inclusive of cut-to-close time and patient-in-room time) are presented in Table 1 by surgical service line and case type.

Time data were used to estimate operation room (OR) staff costs. Hourly costs were derived based on staffing data and CAVA expert opinion, inclusive of usual and customary OR personnel by surgical case type, and expected pre-, intra-, and post-op times by personnel type, including surgeon, anesthesiologist (ANES), registered nurse circulator (RNC), technical assistant (TA), and mid-level assistant (MLA). The personnel time intervals used in the cost calculation were determined as cut-to-close time for surgeon and TA and as patient-in-room time for ANES, RNC, and MLA. Table 1 illustrates the average time per case, and Table 2 includes OR personnel requirements per case. The related time information (Table 1) was combined with the number of staff required per case type (shown in Table 2) with hourly personnel costs of $418.40 for employed surgeons, $326.66 for ANES, $41.12 for RNC, $26.09 for TA, and $66.11 for MLA.[10]

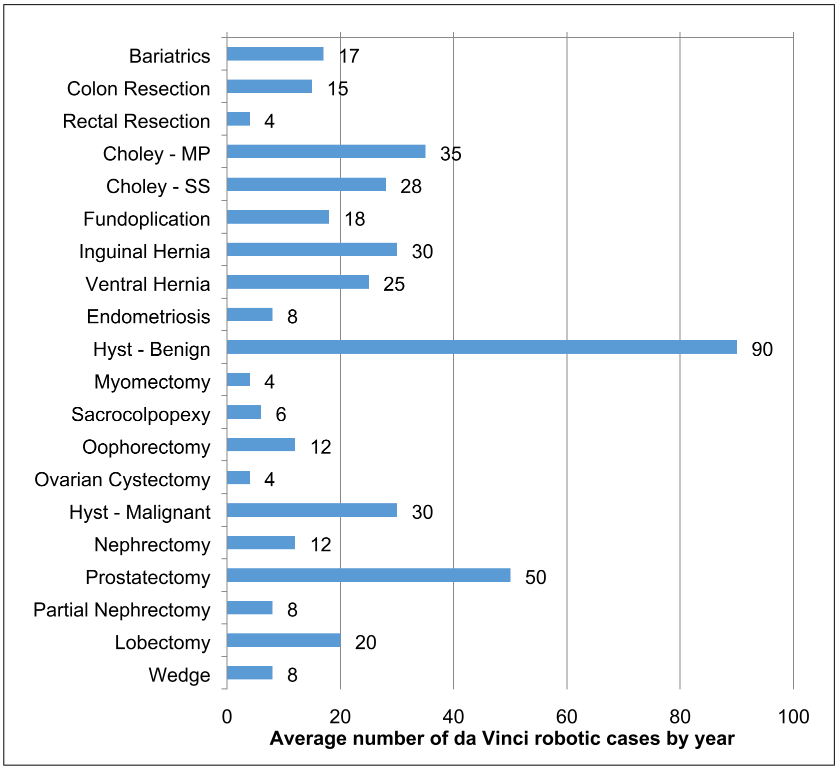

FIGURE 1 Annual real-world robotic cases, by case type, in Bellin Health Green Bay, Wisconsin (total n = 424). Abbreviations: Choley - MP: Cholecystectomy, Multi-Port; Choley - SP: Cholecystectomy, Single-Port; Hyst - Benign: Hysterectomy, Benign; Hyst - Malignant: Hysterectomy, Malignant; Wedge: Wedge Resection

The impact of surgeon learning curves is another cost variable that should be called out, given that learning curves can lead to cost per case being overstated. Average case times always included surgeon learning curves, training surgeons, and poor performing surgeons; these numbers can also be impacted by case complexity. While not included in the current model, such variables may merit subanalysis.

2.2.1 | Real-world cost categories considered

Variable RWD cost categories considered in the CoO assessment include da Vinci supplies (ie, reposable instruments, drapes, seals, and other disposable supplies); non-da Vinci supplies (ports, trocars, gowns, gloves, disposable nonrobotic energy and staple devices as well as other nonrobotic laparoscopic supplies); and personnel costs, based on RWD from the hospitals. For the base-case analysis, the mean values presented in Table 1 were applied, whereas the influence of the upper and lower estimates (informed by the 95% confidence interval limits presented in Table 1) was investigated in sensitivity analyses. For the sensitivity analyses on fixed costs, the case volume was varied between 250 cases (low estimate) and 600 cases (high estimate).

3 | RESULTS

CoO assessment of the da Vinci robotic surgery presents fixed costs, variable costs, and total costs by robotic case as total costs from the hospital perspective, and as weighted average per robotic case, weighted by the number of robotic cases performed by case type (presented in Figure 1). The sensitivity analysis of the CoO results per case is informed by higher and lower input value estimates (as described above), whereas the base case results reflects the outcomes if the mean values are applied.

3.1 | Base case results

Results of the CoO assessment for the da Vinci robot are presented in Table 3 by robotic case and in Table 4 for the total case mix, respectively. All costs are presented from the hospital perspective.

Assuming no financing costs (due to the extreme variation in payment and finance options available), and adding the yearly service contract costs (including 4 years in a 5-year period in order to reflect the 1-year warranty period), the result is in average yearly fixed cost of $417 200 ($294 000 purchasing costs and $123 200 service contract costs). Applying the efficient *Bellin Health* yearly robotic case number (n = 424 cases) yielded an average fixed cost of $984 per da Vinci robotic case.

Variable costs, however, are highly dependent on case type. The weighted average *variable cost* was $8025, ranging from $3325 (cholecystectomy, multiport) to $16 986 (rectal resection) as presented in Table 3. Looking at weighted average by case, the main variable cost drivers were the non-da Vinci supplies (49.5%), personnel costs (28.6%), followed by da Vinci supplies (21.9%). This cost distribution is case specific and is different for each surgery case type. *Total variable costs for the hospital*, using the efficient number of annual Bellin facility cases as the basis of the calculation (n = 424), were $3 402 560, as illustrated in Table 4.

The total weighted average cost by da Vinci surgical case (Table 3) is $9009, ranging from $4309 (cholecystectomy, multiport) to

TABLE 1 Overview of US hospital, based on CAVA real-world data on da Vinci robotic procedures by case type, used as basis of CoO assessment

		Cut to Close Time				Patient in Room Time				dV Supplies				Non-dV Supplies			
Service Line	Case Type	n	Mean	2.5%CI	97.5%CI	n	Mean	2.5%CI	97.5%CI	n	Mean	2.5%CI	97.5%CI	n	Mean	2.5%CI	97.5%CI
Bariatrics	Bariatrics	35	102.4	53.7	200.2	35	137.1	85.3	249.4	35	$3729	$1708	$8214	35	$7109	$2616	$10 570
Colorectal	Colon resection	452	172.2	65.3	356.0	452	214.4	99.3	408.7	439	$1644	$1060	$2596	452	$5804	$710	$12 752
	Rectal resection	8	357.5	192.7	500.2	8	405.9	229.9	542.5	8	$1601	$1200	$3406	8	$9802	$3369	$15 822
General	Chole—MP	224	83.9	38.6	212.0	224	117.8	67.6	271.8	224	$1153	$1016	$1479	224	$763	$203	$5260
	Chole—SS	90	51.7	34.7	80.6	90	80.4	59.2	119.3	90	$892	$865	$971	90	$2977	$2576	$3739
	Fundoplication	69	146.5	78.5	272.5	69	191.2	102.5	348.1	68	$1710	$1060	$4211	69	$4632	$259	$9607
	Inguinal hernia	482	80.3	24.0	173.0	482	113.1	55.0	220.9	482	$1439	$905	$2504	482	$1352	$420	$5189
	Ventral hernia	478	94.5	35.0	212.3	478	128.1	62.9	260.5	478	$1408	$1076	$2087	478	$1417	$377	$4407
Gyn	Endometriosis	240	101.9	33.0	248.0	248	129.3	57.0	271.8	252	$1300	$1016	$3701	252	$2633	$731	$7232
	Hyst—benign	1944	110.3	47.0	254.0	2246	144.2	78.0	290.0	2379	$1772	$937	$4781	2379	$3548	$593	$9253
	Myomectomy	120	153.7	45.0	320.7	124	183.7	77.2	346.7	128	$1351	$1021	$3497	128	$3274	$739	$8500
	Sacrocolpopexy	86	159.3	81.0	310.8	147	192.6	108.7	337.1	176	$1946	$1044	$3284	175	$6611	$1476	$12 514
	Oophorectomy	43	87.7	31.2	198.8	44	124.2	61.7	233.3	44	$1505	$1016	$2381	44	$4028	$783	$8066
	Ovarian cystectomy	117	138.0	42.5	261.3	124	167.5	71.1	300.6	125	$1242	$1016	$3670	125	$2445	$437	$7064
Gyn oncology	Hyst—malignant	218	194.2	95.4	348.6	443	199.4	114.1	379.0	561	$2274	$1016	$4418	561	$7051	$595	$11 019
Urology	Nephrectomy	22	212.4	105.1	340.0	41	284.6	157.0	429.0	52	$2102	$1016	$3995	51	$6110	$1060	$11 822
	Prostatectomy	218	247.3	144.1	419.9	258	295.6	179.0	484.2	284	$2238	$1016	$4846	284	$4399	$3222	$7386
	Partial nephrectomy	80	203.3	102.6	335.2	94	279.1	172.9	429.7	95	$1664	$1016	$4655	95	$5900	$1074	$11 544
Thoracic	Lobectomy	76	193.5	81.3	360.4	76	265.1	156.8	418.4	76	$1739	$1059	$3463	76	$6365	$800	$18 123
	Wedge	30	154.8	56.9	295.7	30	222.6	125.2	360.8	28	$1407	$993	$2207	30	$4745	$788	$20 620

Abbreviations: Choley - MP, Cholecystectomy, Multi-Port; Choley - SP, Cholecystectomy, Single-Port; Hyst - Benign, Hysterectomy, Benign; Hyst - Malignant, Hysterectomy, Malignant; Wedge, Wedge Resection.

TABLE 2 Overview of required full-time surgery staff by case type[a]

		Required Staff in Full-Time Equivalents				
Service Line	**Case Type**	**Surgeon (n)**	**ANES (n)**	**RNC (n)**	**TA (n)**	**MLA (n)**
Bariatrics	Bariatrics	1.00	1.00	1.00	1.00	1.00
Colorectal	Colon resection	1.00	1.00	1.00	1.00	1.00
	Rectal resection	1.00	1.00	1.00	1.00	1.00
General	Chole—MP	1.00	1.00	1.00	1.00	0.50
	Chole—SS	1.00	1.00	1.00	1.00	1.00
	Fundoplication	1.00	1.00	1.00	1.00	1.00
	Inguinal hernia	1.00	1.00	1.00	1.00	0.50
	Ventral hernia	1.00	1.00	1.00	1.00	1.00
Gyn	Endometriosis	1.00	1.00	1.00	1.00	1.00
	Hyst—benign	1.00	1.00	1.00	1.00	1.00
	Myomectomy	1.00	1.00	1.00	1.00	1.00
	Sacrocolpopexy	1.00	1.00	1.00	1.00	1.00
	Oophorectomy	1.00	1.00	1.00	1.00	0.00
	Ovarian cystectomy	1.00	1.00	1.00	1.00	0.00
Gyn oncology	Hyst—malignant	1.00	1.00	1.00	1.00	1.00
Urology	Nephrectomy	1.00	1.00	2.00	2.00	0.00
	Prostatectomy	1.00	1.00	2.00	2.00	0.00
	Partial nephrectomy	1.00	1.00	2.00	1.00	1.00
Thoracic	Lobectomy	1.00	1.00	1.00	1.00	1.00
	Wedge	1.00	1.00	1.00	1.00	1.00

Abbreviations: ANEAS, Anesthesiologist; Choley - MP, Cholecystectomy, Multi-Port; Choley - SP, Cholecystectomy, Single-Port; Hyst - Benign, Hysterectomy, Benign; Hyst - Malignant, Hysterectomy, Malignant; MLA, Midlevel Assist; RNC, Registered Nurse Circulator; TA, Technical Assistant; Wedge, Wedge Resection.

[a]Based on CAVA Expert Opinion.

$17 970 (rectal resection). Total cost from the hospital perspective (Table 4), using the *efficient number* of annual Bellin Health robotic cases (n = 424) as the basis of the calculation, was estimated at $3 819 760. (See *Discussion* for additional explanation on estimated average annual robotic case volume per robot.)

3.2 | Sensitivity analyses results

Sensitivity analyses for the CoO assessment are presented by robotic case for fixed, variable, and total costs in Table 5. For each category, the base case, low values, and high values are presented in US dollars; the variation from the base case is presented as a percentage change.

In general, the variation of fixed costs (based on between 250 and 600 robotic cases annually) was not as pronounced as the variation of variable costs, while the variation in variable costs was more pronounced for the high estimates, as demonstrated by a higher percentage deviation from the base case compared with the low estimates.

4 | DISCUSSION

Based on the authors' real-world experience providing consulting support at dozens of US hospitals with robotic programs, facilities may begin to experience robot access limitations at 250 to 325 cases annually—due to scheduling challenges, surgeon or crew skill challenges, or all three factors. This annual case volume represents between 30% and 45% of the robot's theoretical capacity (assumed as three cases per day × 5 days per week × 52 weeks a year = 780 cases, depending on case mix, with a dedicated robotic operating room).

Nevertheless, even a modest annual volume of 300 robotic cases commonly leads to a hospital beginning to experience robot case scheduling and access challenges, which in turn may cause hospital administrators to question the "robot value proposition" (ie, is it possible to get enough profitable robotic cases done annually on a robot, given the cost?). While there are a small number of very efficient robotic programs (doing 600 or more cases per year on a single robot), this is uncommon. The influence of annual case volume—high or low—on the fixed annual cost of robot ownership is highly significant, with more efficient and typically higher volume robotic programs achieving superior fiscal performance to lower efficiency, lower annual case volume programs when assessing reposable use, non-da Vinci supplies, and overall CoO. This component was not assessed in this paper, however, and is thus a limitation of the present analysis.

While case volume and efficiency are indeed related (ie, as a program's case volume increases, average case time typically decreases while per-case supply efficiency improves). However, case volume alone may not *always* be an indicator of a robotic program's efficient use of supplies or reposables (ie, a higher volume program can lose money due to excessive per-case supply consumption, if not well managed). As seen in the sensitivity analysis, variation in variable costs had much greater impact on the robotic program, especially for the high estimates, as demonstrated by a higher percentage deviation from the base case compared with the low estimates. This underscores the importance of programmatic standardization (case times, crew

TABLE 3 CoO results: Fixed and variable costs *by Robotic Surgery Case*[a]

Service Line	Average Fixed Costs[b]			Average Variable Costs				Total Costs
Case type	Pur-chase	Ser-vice	Total fixed	da Vinci sup.	Non-da Vinci sup.	Staff costs	Total VAR	Fixed and variable
Bariatrics (weighted average)	$693	$291	$984	$3729	$7109	$1750	$12 588	$13 572
Bariatrics	$693	$291	$984	$3729	$7109	$1750	$12 588	$13 572
Colorectal (weighted average)	$693	$291	$984	$1635	$6645	$3406	$11 687	$12 671
Colon resection	$693	$291	$984	$1644	$5804	$2826	$10 274	$11 258
Rectal resection	$693	$291	$984	$1601	$9802	$5583	$16 986	$17 970
Gen Surg (weighted average)	$693	$291	$984	$1283	$1981	$1484	$4748	$5732
Chole—MP	$693	$291	$984	$1153	$763	$1408	$3325	$4309
Chole—SS	$693	$291	$984	$892	$2977	$964	$4833	$5817
Fundoplication	$693	$291	$984	$1710	$4632	$2468	$8810	$9794
Inguinal hernia	$693	$291	$984	$1439	$1352	$1350	$4141	$5125
Ventral hernia	$693	$291	$984	$1408	$1417	$1626	$4451	$5435
Gyn (weighted average)	$693	$291	$984	$1694	$3639	$1866	$7198	$8182
Endometriosis	$693	$291	$984	$1300	$2633	$1690	$5622	$6606
Hyst—benign	$693	$291	$984	$1772	$3548	$1860	$7180	$8164
Myomectomy	$693	$291	$984	$1351	$3274	$2467	$7092	$8076
Sacrocolpopexy	$693	$291	$984	$1946	$6611	$2574	$11 130	$12 114
Oophorectomy	$693	$291	$984	$1505	$4028	$1411	$6943	$7927
Ovarian cystectomy	$693	$291	$984	$1242	$2445	$2049	$5735	$6719
Gyn oncology (weighted average)	$693	$291	$984	$2274	$7051	$2881	$12 206	$13 190
Hyst—malignant	$693	$291	$984	$2274	$7051	$2881	$12 206	$13 190
Urology (weighted average)	$693	$291	$984	$2149	$4864	$3867	$10 880	$11 864
Nephrectomy	$693	$291	$984	$2102	$6110	$3605	$11 818	$12 802
Prostatectomy	$693	$291	$984	$2238	$4399	$3954	$10 591	$11 574
Partial nephrectomy	$693	$291	$984	$1664	$5900	$3716	$11 280	$12 264
Thoracic (weighted average)	$693	$291	$984	$1644	$5902	$3181	$10 727	$11 711
Lobectomy	$693	$291	$984	$1739	$6365	$3351	$11 455	$12 439
Wedge	$693	$291	$984	$1407	$4745	$2756	$8908	$9892
All case types (weighted average)	$693	$291	$984	$1754	$3974	$2297	$8025	$9009

[a]Costs were determined by case using a weighted average on the basis of the average case mix presented in Figure 1 based on an annual case volume of 424 cases related to Bellin Health in Green Bay, Wisconsin.

[b]Based on an annual case volume of 424 cases, Bellin Health, Green Bay, Wisconsin USA.

performance metrics, and da Vinci and non-da Vinci supplies) as a means of reducing robot CoO. Costs may also be artificially constrained due to the arbitrary determination of reposable instrument lives; instrument use and surgeon instrument preferences are another contributor to cost and associated variability.[13,14] When a surgeon demonstrates high instrument variation, this also often leads to increased cost. Thus, robotic case standardization, based on high-utilizing surgeons' consistent use of supplies, can help drive more predictable instrument profiles for each case type. While unique cases may occasionally demand creative approaches to surgery, most cases should be accomplished with standard and predictable instrument profiles. This is also impacted by the overall experience of the surgeon, with surgeons in their learning curve or early in their robotic careers typically far more variable and excessive in instrument use.

4.1 | Misaligned cost accounting

Real-world cost of data obtained from the CAVA Robotics' data base includes capital costs for the robot. It is noted that these data are frequently amortized across all the robotic cases. However, at most hospitals when these same data are pulled for traditional laparoscopy, orthopedics, and other procedure-based service lines, the facility frequently follows different cost accounting methodologies. For example, a hospital may opt to roll up the capital cost of a da Vinci robot into its total robotic cost assessment, but not follow this same treatment of capital costs with other surgical technologies and service lines when attempting cost comparisons. Comparing the actual CoO of a da Vinci robot vs other surgical technologies is therefore challenging. Thus, when assessing robotic costs, a similarly designed

TABLE 4 CoO results: Fixed and variable total costs *For The Hospital*[a]

Service Line		Average Fixed Costs			Average Variable Costs				Total Costs
Case type	N	Purchase	Service	Total fixed	da Vinci sup.	Non-da Vinci sup.	Staff costs	Total VAR	Fixed and variable
Bariatrics (total cases)	17	$11 788	$4940	$16 727	$63 399	$120 854	$29 745	$213 998	$230 725
Bariatrics	17	$11 788	$4940	$16 727	$63 399	$120 854	$29 745	$213 998	$230 725
Colorectal (total cases)	19	$13 175	$5521	$18 695	$31 069	$126 263	$64 723	$222 055	$240 750
Colon resection	15	$10 401	$4358	$14 759	$24 666	$87 054	$42 389	$154 109	$168 869
Rectal resection	4	$2774	$1162	$3936	$6404	$39 208	$22 334	$67 946	$71 882
Gen Surg (total cases)	136	$94 302	$39 517	$133 819	$174 480	$269 438	$201 864	$645 782	$779 600
Chole—MP	35	$24 269	$10 170	$34 439	$40 363	$26 716	$49 284	$116 363	$150 802
Chole—SS	28	$19 415	$8136	$27 551	$24 965	$83 355	$26 997	$135 316	$162 867
Fundoplication	18	$12 481	$5230	$17 711	$30 782	$83 371	$44 422	$158 575	$176 287
Inguinal hernia	30	$20 802	$8717	$29 519	$43 171	$40 566	$40 508	$124 245	$153 764
Ventral hernia	25	$17 335	$7264	$24 599	$35 200	$35 430	$40 652	$111 282	$135 881
Gyn (total cases)	124	$85 981	$36 030	$122 011	$210 018	$451 239	$231 328	$892 585	$1 014 596
Endometriosis	8	$5547	$2325	$7872	$10 399	$21 061	$13 518	$44 979	$52 850
Hyst—benign	90	$62 406	$26 151	$88 557	$159 515	$319 307	$167 374	$646 195	$734 752
Myomectomy	4	$2774	$1162	$3936	$5403	$13 096	$9867	$28 367	$32 302
Sacrocolpopexy	6	$4160	$1743	$5904	$11 676	$39 665	$15 442	$66 782	$72 686
Oophorectomy	12	$8321	$3487	$11 808	$18 057	$48 331	$16 932	$83 321	$95 128
Ovarian cystectomy	4	$2774	$1162	$3936	$4967	$9778	$8196	$22 941	$26 877
Gyn oncology (total cases)	30	$20 802	$8717	$29 519	$68 227	$211 533	$86 432	$366 192	$395 711
Hyst—malignant	30	$20 802	$8717	$29 519	$68 227	$211 533	$86 432	$366 192	$395 711
Urology (total cases)	70	$48 538	$20 340	$68 877	$150 426	$340 476	$270 679	$761 580	$830 458
Nephrectomy	12	$8321	$3487	$11 808	$25 223	$73 325	$43 264	$141 813	$153 620
Prostatectomy	50	$34 670	$14 528	$49 198	$111 893	$219 947	$197 685	$529 526	$578 724
Partial nephrectomy	8	$5547	$2325	$7872	$13 309	$47 203	$29 729	$90 242	$98 114
Thoracic (total cases)	28	$19 415	$8136	$27 551	$46 038	$165 265	$89 066	$300 369	$327 920
Lobectomy	20	$13 868	$5811	$19 679	$34 779	$127 307	$67 016	$229 102	$248 781
Wedge	8	$5547	$2325	$7872	$11 259	$37 958	$22 050	$71 267	$79 139
All case types (total cases)	424	$294 000	$123 200	$417 200	$743 657	$1 685 067	$973 836	$3 402 560	$3 819 760

[a]Costs were determined combined all cases presented in the underlying average case mix presented in Figure 1.

model, as herein described, should be applied to obtain a true comparison with da Vinci robotics.

Why is there a common cost accounting method inequality between robotic and laparoscopic surgery CoO? There are several factors. A decade ago, when robotic surgery experienced significant volume growth and expansion of case mix, supply chain and finance departments of hospitals looked at robotics as *a new service* and wanted to evaluate the profitability of this service through a narrowly defined "cost" lens, but did not take into account an equitable comparison of the robotic costs vis a vis other Minimally Invasive Surgery (MIS) and non-MIS service lines. Amplifying this inconsistency is the fact that 20 years ago, had these same hospitals assessed the cost of laparoscopic surgery in the era of paper cost accounting with its limited ability to assess all the dimensions of surgical costs and provider performance metrics, many institutions may have seen weak or even negative financial performance. Robotics, on the other hand, emerged in the early big data era, at a time of heightened awareness of cost-effectiveness and value-based medical care—all of which did not exist in US hospital "C-suites" of the late 1980s and 90s.

Further complicating the assessment of robotic CoO is the lack of standardized cost accounting methodologies among US hospitals; attempting to compare the cost of a robotic system between hospitals or IDNs is currently affected by wide variation in cost accounting methodology. One example of this variation is the variety of ways that hospitals treat the cost of da Vinci reposable instruments: some hospitals place robotic surgery in the highest cost tier and add a first minute surcharge to the case to allow for the high instrument cost; some capitalize the cost of the instruments; some meticulously track the use of each instrument and capture the actual cost per use. In the model described herein, however, only hospitals that cost each reposable instrument have been used, an essential component to assure accuracy in the CoO assessment. It is advisable that these elements be

TABLE 5 Sensitivity analysis: Deviation of cost per da Vinci robotic surgery by case, using low and high estimates

Service Line	Fixed Costs					Variable Costs					Total Costs				
Case type	Low	%change	Base case	%change	High	Low	%change	Base case	%change	High	Low	%change	Base case	%change	High
Bariatrics (total cases)	$695	29.3%	$984	69.5%	$1668	$5338	57.6%	$12 588	75.3%	$22 070	$6033	55.5%	$13 572	74.9%	$23 738
Bariatrics	$695	29.3%	$984	69.5%	$1668	$5338	57.6%	$12 588	75.3%	$22 070	$6033	55.5%	$13 572	74.9%	$23 738
Colorectal (total cases)	$695	29.3%	$984	69.5%	$1668	$3958	66.1%	$11 687	89.8%	$22 187	$4653	63.3%	$12 671	88.3%	$23 855
Colon resection	$695	29.3%	$984	69.5%	$1668	$2972	71.1%	$10 274	103.8%	$20 941	$3667	67.4%	$11 258	100.8%	$22 609
Rectal resection	$695	29.3%	$984	69.5%	$1668	$7658	54.9%	$16 986	58.1%	$26 857	$8353	53.5%	$17 970	58.7%	$28 525
Gen Surg (total cases)	$695	29.3%	$984	69.5%	$1668	$2514	47.1%	$4748	119.9%	$10 440	$3209	44.0%	$5732	111.2%	$12 108
Chole–MP	$695	29.3%	$984	69.5%	$1668	$1957	41.1%	$3325	204.5%	$10 126	$2652	38.4%	$4309	173.7%	$11 794
Chole–SS	$695	29.3%	$984	69.5%	$1668	$4126	14.6%	$4833	27.7%	$6170	$4821	17.1%	$5817	34.7%	$7838
Fundoplication	$695	29.3%	$984	69.5%	$1668	$2642	70.0%	$8810	108.3%	$18 354	$3337	65.9%	$9794	104.4%	$20 022
Inguinal hernia	$695	29.3%	$984	69.5%	$1668	$1870	54.8%	$4141	152.4%	$10 451	$2565	49.9%	$5125	136.5%	$12 119
Ventral hernia	$695	29.3%	$984	69.5%	$1668	$2167	51.3%	$4451	123.5%	$9950	$2862	47.3%	$5435	113.8%	$11 618
Gyn (total cases)	$695	29.3%	$984	69.5%	$1668	$2506	65.2%	$7198	140.7%	$17 323	$3201	60.9%	$8182	132.1%	$18 991
Endometriosis	$695	29.3%	$984	69.5%	$1668	$2403	57.3%	$5622	162.1%	$14 737	$3098	53.1%	$6606	148.3%	$16 405
Hyst–benign	$695	29.3%	$984	69.5%	$1668	$2442	66.0%	$7180	150.9%	$18 013	$3137	61.6%	$8164	141.1%	$19 681
Myomectomy	$695	29.3%	$984	69.5%	$1668	$2651	62.6%	$7092	138.0%	$16 880	$3346	58.6%	$8076	129.7%	$18 548
Sacrocolpopexy	$695	29.3%	$984	69.5%	$1668	$3906	64.9%	$11 130	84.5%	$20 538	$4601	62.0%	$12 114	83.3%	$22 206
Oophorectomy	$695	29.3%	$984	69.5%	$1668	$2408	65.3%	$6943	92.3%	$13 349	$3103	60.9%	$7927	89.4%	$15 017
Ovarian cystectomy	$695	29.3%	$984	69.5%	$1668	$2203	61.6%	$5735	153.0%	$14 512	$2898	56.9%	$6719	140.8%	$16 180
Gyn oncology (total cases)	$695	29.3%	$984	69.5%	$1668	$3143	74.3%	$12 206	70.1%	$20 761	$3838	70.9%	$13 190	70.0%	$22 429
Hyst–malignant	$695	29.3%	$984	69.5%	$1668	$3143	74.3%	$12 206	70.1%	$20 761	$3838	70.9%	$13 190	70.0%	$22 429
Urology (total cases)	$695	29.3%	$984	69.5%	$1668	$5816	46.5%	$10 880	80.5%	$19 640	$6 511	45.1%	$11 864	79.6%	$21 308
Nephrectomy	$695	29.3%	$984	69.5%	$1668	$3925	66.8%	$11 818	81.1%	$21 406	$4620	63.9%	$12 802	80.2%	$23 074
Prostatectomy	$695	29.3%	$984	69.5%	$1668	$6526	38.4%	$10 591	77.7%	$18 824	$7221	37.6%	$11 575	77.0%	$20 492
Partial nephrectomy	$695	29.3%	$984	69.5%	$1668	$4219	62.6%	$11 280	95.8%	$22 084	$4914	59.9%	$12 264	93.7%	$23 752
Thoracic (total cases)	$695	29.3%	$984	69.5%	$1668	$3456	67.8%	$10 727	155.2%	$27 380	$4151	64.6%	$11 711	148.0%	$29 048
Lobectomy	$695	29.3%	$984	69.5%	$1668	$3595	68.6%	$11 455	138.2%	$27 282	$4290	65.5%	$12 439	132.7%	$28 950
Wedge	$695	29.3%	$984	69.5%	$1668	$3108	65.1%	$8908	210.1%	$27 627	$3 803	61.6%	$9892	196.1%	$29 295
All case types (total cases)	$695	29.3%	$984	69.5%	$1668	$3341	58.4%	$8025	109.5%	$16 813	$4036	55.2%	$9009	105.1%	$18 481

standardized so that robotic CoO can be universally performed in a reliable manner, and so robotic performance can also be compared correctly to lap and other service lines to achieve an equitable apples-to-apples assessment of CoO.

4.2 | Quality as a cost variable

Moreover, the *quality* of the robotic program itself—ie, the performance characteristics of the robotic surgeons, the efficiency of the crew, the management of supplies, etc.—further impacts the CoO equation. Quality, however, is rarely discussed as a factor in robotic CoO in the peer review literature, with wide variations in time metrics and supply utilization routinely observed in real-world settings. These variations—not strictly accounted for and a limitation of this analysis—are largely influenced by surgeon training and experience, crew training, case selection and case type, program performance policies, and governance.

4.3 | Cost of ownership for future robotic technologies

The current model also provides a base CoO framework which may be useful as a foundation for hospitals to evaluate new robotic systems as future technologies enter the market place. In this context, it is important for hospitals to standardize their cost accounting, as suggested herein, to achieve comparable analyses from the perspective of IDN to IDN/hospital to hospital, as well as from the perspective of assessing the CoO of robotic vs MIS technologies—fully burdened based on identical service line/case mix/case volumes, and all associated fixed and variable costs.

5 | CONCLUSION

Assessing the CoO of a robot using RWD makes it clear that there are many variables that directly and significantly impact CoO. Cost accounting, supply/reposable efficiencies, case mix, case volumes, and case times represent core variables that can drive up or reduce CoO. Robotics is thus often referred to as a "team sport," meaning that highly efficient management and work flow of all robotic stakeholders significantly impacts program quality and robotic CoO. Hospitals/IDNs that understand how robotic CoO is impacted by these variables hold the key to better controlling robotic costs, and thereby achieving improved financial performance of their robotic program. Moving forward, establishing this improved operational and financial approach is critical as new robotic vendors and technologies enter the global market, as administration and clinicians ask, *what does this new robotic technology really cost?*

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