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How can robot-assisted surgery provide value for money?

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ABSTRACT

Objectives To develop an interactive tool that estimates what potential benefits are needed for the robot to provide value for money when compared with endoscopic or open surgical interventions.
Design A generic online interactive tool was developed to analyze the (health) effects needed to compensate for the additional costs of using a surgical robotic system from a healthcare perspective. The application of the tool is illustrated with a hypothetical new surgical robotic platform. A synthesis of evidence from different sources was used combined with interviews with surgeons.
Setting Flexible tool that can be adapted to flexible settings.
Participants Any hospital patient group for which robotic, endoscopic or open surgical procedures may be considered as appropriate treatment alternatives (eg, urology, gynecology, and so on).
Intervention Robotically assisted surgical interventions.
Comparator Endoscopic or open surgical interventions.
Main outcome measures Thresholds of how much (health) effect is needed for robot-assisted surgery to provide value for money and to become cost-effective.
Results The utilization rate of the surgical robotic system and a reduction in complications appeared to be important aspects in determining the value for money. To become cost-effective, it was deemed important for new surgical robotic systems to have added clinical benefit and become less costly than the current system.
Conclusions This paper and its assisting interactive tool can be used by clinicians, researchers, and policymakers to gain insight in the benefit needed to provide value for money when using a (new) surgical robotic system or, when the effects are known or can be estimated, to assess the value for money for a specific indication. For robotic surgery to provide most value for money, we recommend assessing for each indication whether the necessary effects seem achievable.

Short summary

What is already known about this subject?

► Over the past decades, the number of robot-assisted procedures has increased tremendously, despite the high cost. Combined with the rising pressure on the sustainability of healthcare, this has led to a vicarious debate about its value for money.

What are the new findings?

► As different surgical robotic systems may have many different features and can be used for multiple indications, we developed an online tool that can be used to analyze the (health) effects needed to compensate for the additional costs of using a surgical robotic system, in order to become cost-effective. The model provides relevant stakeholders, such as surgeons, researchers, purchasers, and policymakers, the unique opportunity to gain insight in what is needed to provide value for money when using (new) surgical robotic systems.

How might these results affect future research or surgical practice?

► Our model offers guidance for future research as it can be estimated which indications have the potential to become cost-effective and therefore should be further investigated.

INTRODUCTION

Over the past decades, the implementation of robot-assisted surgery has increased tremendously. In 2000, about 1000 robot-assisted procedures were performed worldwide, whereas in 2018, that number had increased to more than 1 million.[1] Besides an increase in the number of robot-assisted procedures performed, an expansion in types of procedures is seen. The first robotic systems were mainly used in urology (prostatectomy) and gynecology (hysterectomy). Nowadays, we see a huge increase in application in other fields such as general, gastrointestinal, and thoracic surgery.[2] With the ever increasing pressure on sustainable healthcare, it is important to know how a surgical robotic system can be used most cost-effectively.

Currently, the da Vinci Surgical System of Intuitive is with 5114 installed systems worldwide the best known and most used system.[3] Ever since the introduction of da Vinci Surgical System there has been both enthusiasm and skepticism, followed by a vicarious debate on its value for money. Reported effects of robot-assisted surgery include less conversions, reduced blood loss, fewer perioperative complications, shorter hospital stays, faster recovery, and less positive tumor resection margins,[4–6] but these advantages are not confirmed in all studies and for all procedures. Moreover, these advantages come at a high financial investment.[1] Hospitals spend between $1000 and $4000 more per robot-assisted case compared with endoscopic minimally invasive or open procedures, in addition to the purchase and maintenance costs of the surgical robotic system.[7] Barbash and Glied estimated that if robot-assisted procedures replaced all conventional procedures, an additional $2.5 billion would be spent in annual healthcare costs in the USA.[7]

Sustainability of healthcare is an important issue in all countries. The increasing number of innovation entering the market demands healthcare providers to prioritize their investments in order to manage increasing costs and deliver the best possible outcomes for patients. Therefore, identifying which innovations provide most value for money is becoming increasingly important. As evidence regarding the cost-effectiveness of robot-assisted surgery is still lacking, the use of robotic surgery is becoming an important societal issue. In order to provide value for money, the increased costs of robot-assisted surgery need to be outweighed by the benefits. It is expected that in the coming years more providers (eg, Stryker, Johnson & Johnson, Medtronic and smaller companies) will increase their market share or enter the market with new surgical platforms leading to a further increase in robot-assisted surgeries in daily practice. With more providers of surgical robotic systems on the market, competing with Intuitive for new customers, it is expected that less expensive systems will become available and that robot-assisted surgery will be applied for a wider range of procedures.[7] However, the question remains whether such new systems will provide value for money.

As different surgical robotic systems may have many different features and can be used for multiple indications, we aimed to develop a generic online interactive tool that can be used to analyze the (health) effects needed to compensate for the additional costs of using a surgical robotic system, in order to become cost-effective. This tool can be used to explore under which circumstances a (new) surgical robotic system could provide value for money and to inform clinical research. In this paper, we will describe the tool and illustrate its application using a hypothetical new surgical robotic system. The tool enables adjustment of all input variables (ie, acquisition costs robotic system, number of procedures yearly performed) for different surgical robotic systems, and different hospital settings and indications.

MODEL CONSTRUCTION

Model structure

A health economic model was developed to estimate the thresholds of how much (health) effect is needed to outweigh the additional costs of a robot-assisted procedure compared with endoscopic and open procedures in a generic patient population over the life course of an individual. The costs and potential effects of these procedures are included in the model. In the model, robotic surgery can be compared with endoscopic or an open procedure, depending on the users' procedure of interest. The analysis was conducted from a healthcare perspective, including all relevant medical costs incurred for the health system. The model incorporates six aspects on which a robot-assisted procedure can potentially provide (health) effect for patients compared with an endoscopic or open procedure. These aspects were based on scientific literature and interviews with experts (n=4) operating in the field of urology, gynecology, thoracic and gastrointestinal surgery. These aspects are procedure time, conversion rate, complications, positive resection margins, length of stay and quality of life. The total costs, consisting of the fixed and variable costs, of a robot-assisted procedure and an endoscopic or open procedure can be calculated in the model. Subsequently, the additional costs of a procedure with a surgical robotic system are compared with the possible benefits that can be gained with a robot-assisted procedure. Besides possible benefits, also negative consequences of performing a robot-assisted procedure (eg, longer duration of procedure) can be entered into the model. The model allows for adjustments for specific procedures and specific populations, therefore one can use the model to calculate the benefits needed for a specific procedure and population. Where possible, we followed the Consolidated Health Economic Evaluation Reporting Standards (CHEERS) guidelines.[4]

The interactive model comprises an open web-based tool created with the Shiny package for R.[8] The online tool allows users to assess the extra costs and benefits of a surgical robotic system for a specific procedure of interest by entering data and/or costs for this specific procedure. A user manual is available to make sure that the tool can also be used without the background information in this article.

Costs procedure

The costs of a procedure are divided in fixed and variable costs. The fixed costs were defined as the acquisition costs for surgical devices, that is, a surgical robotic system or an endoscopic tower. The annual capital costs of the surgical robotic system and endoscopy tower were calculated by dividing the initial costs for equipment acquisition by an annuity factor, taking into account the useful life years of the equipment and the interest rate.[5] To calculate the total annual capital costs, the yearly costs for maintaining the equipment were added. To calculate the costs per procedure the total annual capital costs were divided by the number of yearly performed procedures with a surgical robotic system or endoscopy. The variable costs consist of the additional costs for disposables. The equations for cost calculation can be found in the online supplemental appendix II. Costs are presented in euros.

Potential benefits

In order to compare the potential effects of a robot-assisted procedure with the additional costs of the procedure, each aspect in the model is associated with a monetary value. Procedure time was defined as the operating room costs per minute based on cost calculations of a university medical center (Radboudumc), including three operating room assistants, an anesthesiologist and a surgeon. Despite the widespread adoption of endoscopic and robotic surgeries, there are still patients who require conversion to laparotomy during surgery. When compared with endoscopic surgery, a robot-assisted procedure may result in a lower percentage of conversions. The costs of a conversion are procedure specific and can be entered into the model for a procedure of interest. A robot-assisted procedure could also result in fewer complications, which are in the model divided into short-term complications (ie, within 30 days) and long-term complications (ie, after 30 days). The short-term complications, classified according to the Clavien-Dindo classification system, are subdivided into mild (Clavien-Dindo grade I/II) and severe (Clavien-Dindo grade III–V).[9] Long-term complications are defined as lasting complications for which prolonged treatment is required. As the costs for complications may vary widely for different indications these can be adapted in the model for the procedure of interest. Furthermore, performing a robot-assisted procedure may result in fewer positive tumor resection margins when compared with an endoscopic or open procedure. The consequences and, therefore, costs of a positive tumor resection margin are indication specific, which can also be entered into the interactive model for the procedure of interest. When compared with open surgery, patients undergoing robot-assisted surgery may be hospitalized for a shorter period. The reference costs for hospital stay per day were obtained from the Dutch costing manual.[5] Quality of life was operationalized by means of quality-adjusted life years (QALY), which are a measure combining quality of life and survival, where a QALY of 1 represents living 1 year in perfect health.[6] The cost-effectiveness threshold was set on €50.000 per QALY,[9] but can be changed in the model.

Analysis

The additional costs of a robot-assisted procedure were calculated by subtracting the total costs of the chosen comparator, an endoscopic or open procedure, from the total costs of the robot-assisted procedure. Threshold analysis for six aspects incorporated in the model is performed. This means that for every aspect the minimum effect that is needed to be achieved by performing a robot-assisted procedure to outweigh the additional costs is calculated, that is, the number of minutes of operating time or hospital days that need to be prevented to outweigh the extra costs; the rate of conversions, complications or positive margins that need to be prevented to outweigh the extra costs; the number of QALYs that need to be gained to become cost-effective. These thresholds were calculated by dividing the additional costs of a robotic procedure with the monetary value of each aspect.

We provided a hypothetical example for a procedure performed with a surgical robotic system compared with laparoscopy to illustrate how the model can be used. For this hypothetical example, we will calculate the required effects for a robot-assisted procedure to compensate the additional costs. Furthermore, to illustrate the use of the tool we showed three possible scenarios in which the surgical robotic system becomes cost-effective. Additionally, we assessed the impact of the acquisition price of the surgical robotic system and the number of procedures performed per year.

MODEL OUTPUT

The model can be used in two ways. First, the model shows the additional costs of performing a robot-assisted procedure and the effect needed on each aspect to compensate for these additional costs, for example, the number of hospital days that need to be prevented per procedure to offset the extra costs of a procedure with a surgical robotic system. Second, when the effects of a robot-assisted procedure are known, for example, a reduction in procedure time, they can be entered into the model. The model will show if the additional costs for a robotic procedure are compensated by the benefits. In case the (expected) benefits do not (yet) compensate for the additional costs of a robot-assisted procedure, it shows how much extra effect on each aspect is needed to outweigh the additional costs.

CLINICAL EXAMPLE

To illustrate how the model can be used, we will describe a hypothetical example for a procedure performed with a surgical robotic system compared with laparoscopy from a healthcare perspective. We would like to emphasize that the examples we used are all hypothetical to explain how the tool can be used, and do not represent real examples from clinical practice. For the costs of the robot-assisted procedure we assumed a new surgical robotic system will be used with an acquisition price of €1 million and a maintenance charge of €80 000 per year. For the endoscopic procedure, acquisition cost for the endoscopy tower of €100 000 and a maintenance charge of €8000 per year were assumed. For both devices, we assumed a useful life of 7 years and an interest rate of 4.2%.[5] An average of 200 procedures per year for both robot-assisted and endoscopic surgeries were used to calculate the fixed costs per procedure (table 1). We assumed variable costs of €1500 and €1000 for the robot-assisted and endoscopic procedures, respectively (table 1). The assumed costs of a conversion, complications and a positive surgical margin are presented in table 1. Since we used a hypothetical example to explain the model, the population is not relevant. When one uses the model to a specific procedure the population needs to be specified.

Table 1 Input costs for a hypothetical example of a procedure with a new surgical robotic system

Variable	Value	Source
Robot-assisted procedure		
Fixed cost		
New surgical robotic system	€1 000 000	Assumption*
Useful life surgical robotic system (in years)	7	Assumption*
Annual interest rate	4.20%	5
Annual maintenance cost	€80 000	Assumption*
Annual number of procedures	200	Assumption*
Fixed cost per procedure	€1239	
Variable cost		
Variable cost robotic system	€1500	Assumption*
Total cost	€2739	
Endoscopic procedure		
Fixed cost		
Endoscopy tower	€100 000	Radboudumc
Useful life endoscopy tower (in years)	7	Radboudumc
Annual interest rate	4.20%	5
Annual maintenance cost	€8000	Assumption*
Annual number of procedures	200	5
Fixed cost per procedure	€124	
Variable cost		
Variable cost endoscopic procedure	€1000	Assumption*
Total cost	€1124	
Benefit for potential effects		
Duration of operation (min)	€13.93	Radboudumc
Conversion	€1700	18–20*
Complication with Clavien-Dindo I/II	€5000	18–20*
Complication with Clavien-Dindo III–V	€16 000	18–20*
Lasting complication	€15 000	18–20*
Positive margin	€5000	18–20*
Hospitalization (day)	€668	5
QALY	€50 000	9

*We illustrated the use of the model with a hypothetical example, for which we used the input values given in this table. Even though these input values were based on existing literature, these do not reflect a specific indication.
QALY, quality-adjusted life year.

For this example, the total extra costs for a robot-assisted procedure compared with laparoscopy were €1615 (€2739 minus €1124). To compensate for these extra costs, robot-assisted surgery should result in either a shorter operating time of 116 min, or a reduction in conversions of 95%, or a reduction of 32% of Clavien-Dindo I/II complications, or prevent 10% of Clavien-Dindo III–V complications, or prevent 32% of lasting complications, or reduce positive margins with 32%, or a reduction of 2.42 hospital days, or gain 0.032 QALYs (table 2). This means that, for example, 0.032 QALYs should be gained with robotic surgery compared with laparoscopic surgery to compensate for the extra costs of €1615 per robot-assisted procedure (table 2), when assuming a willingness to pay of €50 000 per QALY (table 1).

A surgical robotic system may provide effect on more than one aspect at a time. Therefore, a combination of effects seen or expected for a procedure can be entered into the model to determine if these would compensate for the extra costs involved with a robot-assisted procedure or if extra benefit is still needed. Table 3 provides three scenarios for which the effects would outweigh the extra costs of the procedure when those effects can be

Table 2 Required effects for a robot-assisted procedure to compensate the additional costs if these effects would occur in only one variable at a time

	Effect needed to compensate the additional costs of €1615 per robot-assisted procedure compared with laparoscopy*
Duration of operation (min)	–116
Conversion	–95%
Complication with Clavien-Dindo I/II	–32%
Complication with Clavien-Dindo III–V	–10%
Lasting complication	–11%
Positive margin	–32%
Hospitalization (day)	–2.24
QALY	0.032

*The percentages in the table are absolute percentages, the percentage of patients in the total group of patients in which this must be prevented.
QALY, quality-adjusted life year.

achieved using the surgical robotic system. When a reduction of 25 min operating time, as well as a reduction of 10% for complications with Clavien-Dindo I/II, and 5% for a Clavien-Dindo III–V can be achieved using the surgical robotic system, the benefits of these effects will outweigh the extra costs of the procedure (scenario I). A reduction of one hospital day together with a QALY gain of 0.02 will also result in sufficient benefit to outweigh the extra costs of a robot-assisted procedure (scenario II). Scenario III shows an example in which a combination of effect on operating time, conversion, complications and positive margin could result in compensating the additional costs of a robotic procedure. Scenario IV provides an example in which besides positive consequences, also a negative consequence, a longer operating time of 15 min, for a robotic procedure is included.

Table 4 The additional cost per procedure with the surgical robotic system when either the acquisition costs for the surgical robotic system or the number of procedures per year is varied

	Extra cost per procedure when comparing the robot with laparoscopy
Acquisition of surgical robotic system of €500 000	€1086
Acquisition of surgical robotic system of €2 500 000	€2764
100 procedures per year performed	€4598
300 procedures per year performed	€1593

The additional costs for a robot-assisted procedure are dependent on various inputs such as the acquisition costs of the surgical robotic system and the number of procedures performed per year (online supplemental appendix I figures 1 and 2). The model can be used to assess the impact of such changes on the value for money. Table 4 shows the influence of the additional costs of a robot-assisted procedure when the acquisition costs of the surgical robotic system were varied from €500 000 to €2 500 000 and the number of procedures was varied from 100 to 300. In case the costs of the surgical robotic system are reduced to €500 000, the additional costs per procedure for our example were €1086 as compared with laparoscopy. The effects needed for each individual aspect to compensate for these extra costs are presented in table 5. The results show that a 7% reduction in complications with Clavien-Dindo III–V is sufficient to compensate for these additional costs. On the other hand, when performing 100 robot-assisted procedures per year the additional costs per procedure resulted in €4598 as compared with

Table 3 Hypothetical examples of combinations of effects that would outweigh the additional costs of a robot-assisted procedure when compared with laparoscopy

	Scenario I*	Scenario II*	Scenario III*	Scenario IV*
Duration of operation (min)	– 25	0	–5	+15
Conversion	0	0	–2%	0
Complication with CD I/II	–10%	0	–5%	–5%
Complication with CD III–V	–5%	0	–5%	–3%
Lasting complication	0	0	–5%	–3%
Positive margin	0	0	–3%	0
Hospitalization (day)	0	–1	0	–1
QALY	0	0.02	0	0

*The percentages in the table are absolute percentages, the percentage of patients in the total group of patients in which this must be prevented.
CD, Clavien-Dindo; QALY, quality-adjusted life year.

Table 5 Required effects with the robot to compensate the minimum and maximum additional costs (table 4) if these effects would occur in only one variable at a time

	Effect needed per variable to compensate the additional costs of €1086*	Effect needed per variable to compensate the additional costs of €4598*
Duration of operation (min)	−79	−335
Conversion	−64%	N/A (>100%)
Complication with Clavien-Dindo I/II	−22%	−92%
Complication with Clavien-Dindo III–V	−7%	−29%
Lasting complication	−7%	−31%
Positive margin	−22%	−92%
Hospitalization (day)	−1.63	−6.88
QALY	0.022	0.092

*The percentages in the table are absolute percentages, the percentage of patients in the total group of patients in which this must be prevented. N/A (>100%) means that more than 100% prevention is warranted to compensate for the extra costs of a robot-assisted procedure.
QALY, quality-adjusted life year.

laparoscopy. A reduction of 29% in complications with Clavien-Dindo III–V is then needed to compensate the additional costs of the procedure.

DISCUSSION

As far as we are aware, we are the first offering a generic and flexible insight in the potential cost-effectiveness of (new) surgical robotic systems. This is particularly important in the current era where many new systems are being developed while the affordability of healthcare is increasingly under pressure. The interactive model described in this paper provides relevant stakeholders, such as surgeons, purchasers, and policymakers, the unique opportunity to gain insight in what is needed to provide value for money when using (new) surgical robotic systems. It informs them on the effect that is needed to compensate the additional costs of a (new) surgical robotic system.

Earlier studies showed that surgical costs and effects for robot-assisted procedures may vary between indications.[10 11] Gkegkes *et al*, for example, found ranges from €2539 to €57 002 and from €7888 to €16 851 for robot-assisted and endoscopic procedures, respectively.[10] The costs used in our analysis, €2739 for a robot-assisted procedure and €1124 for an endoscopic procedure, seem low compared with these costs. This can be explained by the fact that the current surgical robotic system is more expensive than the costs we assumed for the new hypothetical surgical robotic system in the present study. Furthermore, we only included the fixed and variable costs of the equipment used and did not include other costs such as operating theater costs and anesthesia.

Some potential limitations of our model should also be discussed. First, less blood loss is often mentioned as a benefit for robot-assisted procedures, which we did not take into account in our model as we only focused on patient-related outcomes. However, blood loss may impact complications, which were incorporated in the model. Second, we also did not include potential ergonomic benefits for the surgeon in the model. Studies have shown that the ergonomics for the surgeon associated with robotic surgery is better compared with laparoscopic surgery.[12–14] Ergonomic problems may affect a surgeon's physical workload and potentially may even lead to absenteeism. As the costs of absenteeism of a surgeon are estimated at €1129 per day,[5] while the extra costs per procedure with the robot are €2345, a saving of more than 2 days of absenteeism per procedure performed is needed to compensate the extra costs. However, although it is very relevant, this issue is difficult to quantify. Quality of life of the surgeon can be one of the reasons, next to value for money, for using or purchasing a surgical robotic system. Third, we did not include learning curve effects and a potential increase in procedures that can be performed with future robotic systems that cannot be performed endoscopically yet. Especially for procedures that are performed with open surgery, robotic systems might affect the costs as well as the volume of procedures, since more patients could be treated on 1 hour. Furthermore, due to advances in technology, it is expected that in the future the duration of learning curves will reduce for robot-assisted surgery.[15] Furthermore, we only focused on including costs from a healthcare perspective. Productivity gains for patients who can return to work more rapidly were not taken into account. Also, we did not look at the reimbursement hospitals will receive from insurers for the additional hospital spending for robotic surgery. Therefore, we cannot provide insight in the value for money of robotic surgery from a societal or hospital perspective.

We aimed to follow the international CHEERS reporting guideline. However, as we did not conduct a standard cost-effectiveness study, some aspects were not applicable for our model. One should be aware that when using our model to perform a cost-effectiveness analysis, it is advised to follow all components of the guideline.

The clinical implication of our model is that more studies into the effectiveness of new surgical robotic systems seem warranted as these systems might become cost-effective, but only if they indeed also have added clinical benefits and if future systems become less costly. The many hospitals that already adopted a surgical robotic system can use the model to explore how the system should be used to provide most value for money by changing the costs and effects to their specific setting. As there is a lot of variation between indications, our model can also easily be used to assess if the expected effects for an indication will provide sufficient benefit to provide value for money. In this way, the model can be used to prioritize research.

Hospitals may also have other reasons for investing in costly new advanced technology, for example, scientific purposes, patient demand, fear of missing out, and competition between hospitals.[16 17] On the other hand, we believe that in the current era of rising healthcare costs, hospitals and other relevant stakeholders have to educate patients and society that new is not always better, and that money should be spent wisely. Our interactive model helps them in this discussion.

The utilization rate of a surgical robotic system showed a large influence on the extra cost per procedure. Increasing the number of procedures in our example, from 100 to 300 per year, appeared to reduce the extra costs per procedure with €3005 when compared with laparoscopy. This might lead to the clinical implication that the number of procedures with the robotic system should be as high as possible. However, the additional variable costs per robot-assisted procedure have to be compensated by a minimum health gain, otherwise the total costs per year will increase even though the fixed costs per procedure will decrease when more procedures are performed. For this reason, it is important to study specific indications and to assess whether the variable costs are indeed compensated by a health gain for that specific indication. Setting the fixed costs in the tool to zero can help explore whether this is the case.

In conclusion, our model and interactive tool provide a unique opportunity for all stakeholders such as researchers, clinicians and policymakers, to gain insight in the benefit needed to outweigh the additional costs of a (new) surgical robotic system or, when the benefits are known or can be estimated, to assess the value for money for a specific procedure. To achieve the maximum value for money, we recommend assessing for each indication whether the necessary effects seem feasible. The online tool (see also: https://sejal.shinyapps.io/supplement_robot-assisted_surgery_article/) provides this information, and can be easily used by all stakeholders.

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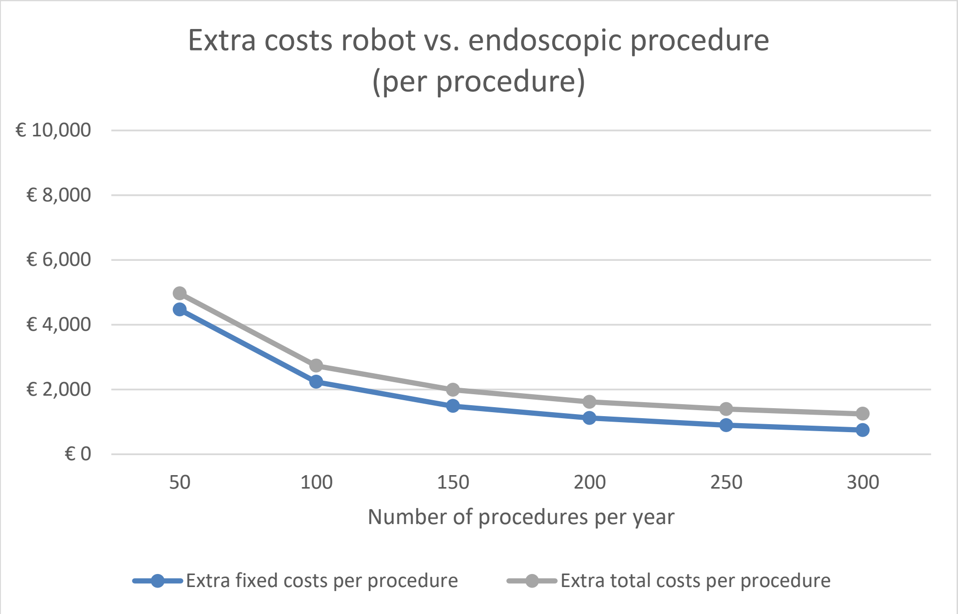
20 Widmar M, Strombom P, Keskin M, *et al*. Burden of surgical complications: contribution of long-term costs by Clavien-Dindo classification. *J Am Coll Surg* 2016;223:e90.

APPENDIX I

Figure 1. The influence of the number of procedures per year on the additional cost per robot-assisted procedure compared with endoscopic and open procedures.



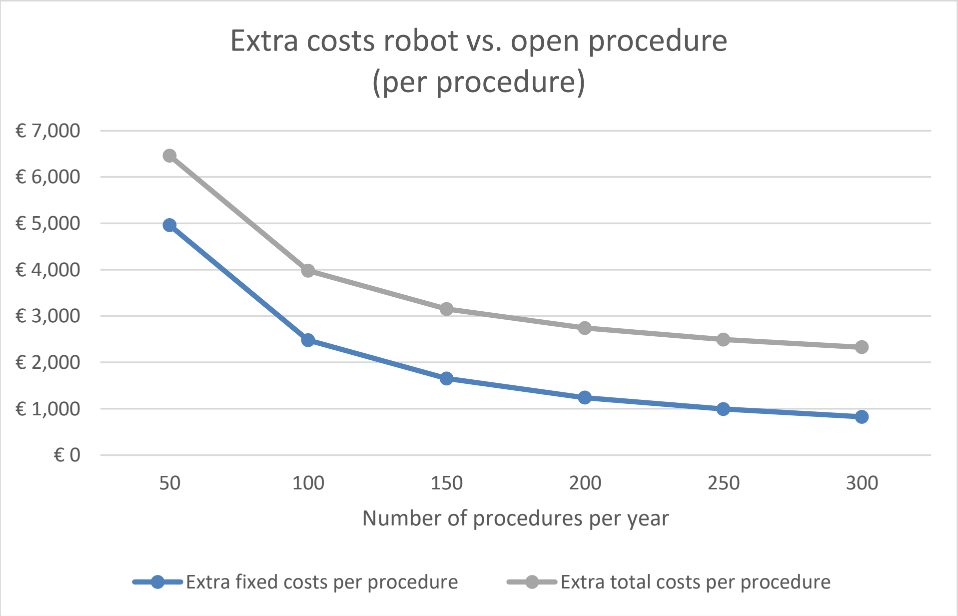
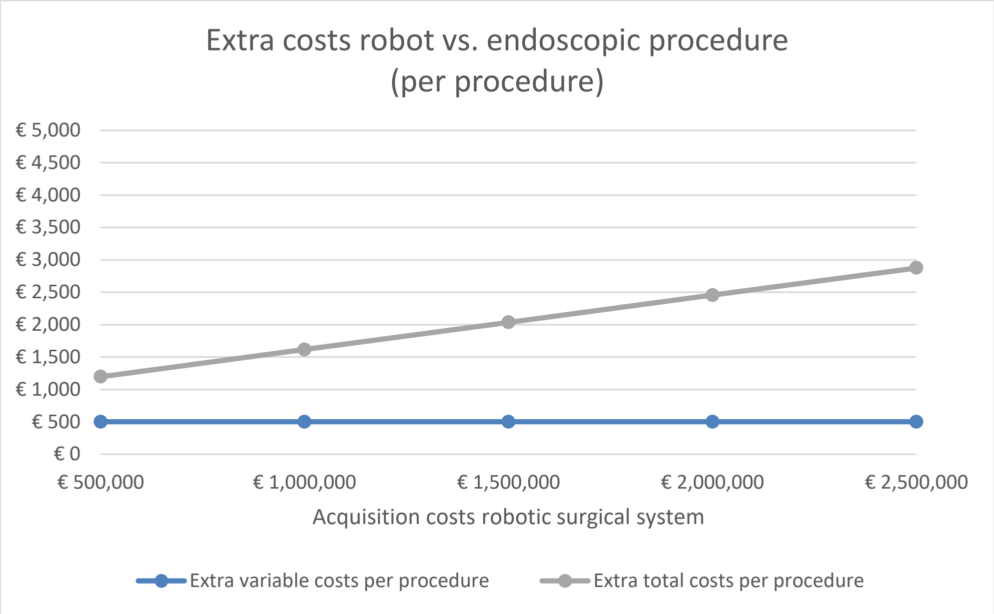
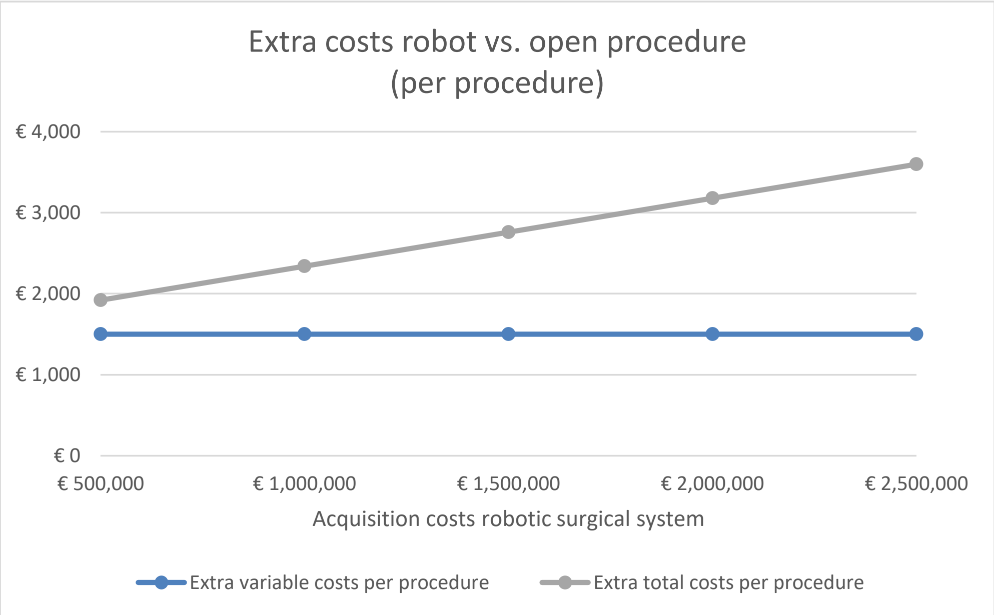


Figure 2. The influence of the acquisition costs of the surgical robotic system on the additional cost per robot-assisted procedure compared with endoscopic and open procedure.





APPENDIX II

Description of the calculations.

Calculation on the additional costs for the hybrid operating room:

= Total costs for a robot-assisted procedure - Total costs for a laparoscopic procedure

= ((acquisition costs robotic system * annuity + maintenance costs) / number of procedures) + variable costs) - ((acquisition costs laparoscopic tower * annuity + maintenance costs) / number of procedures) + variable costs)

Calculation on the value for money:

= Expected effects expressed in monetary value - Additional costs for a robot-assisted procedure

= ∑ (Cost effect * expected effect) - Additional costs for a robot-assisted procedure

Calculation on the effect required per variable (OR minutes, conversions, complications, hospital days, positive margin, QALY) to compensate for the additional costs:

= (expected effects - additional costs for robotic procedure) / (effect expressed in monetary value)

For example: (expected gain in operating time with robotic procedure – additional costs robotic procedure) / the costs on one operating minute

CHEERS checklist—Items to include when reporting economic evaluations of health interventions

Section/item	Item No	Recommendation	Reported on page No/ line No
Title and abstract			
Title	1	Identify the study as an economic evaluation or use more specific terms such as "cost-effectiveness analysis", and describe the interventions compared.	page 1, line 1
Abstract	2	Provide a structured summary of objectives, perspective, setting, methods (including study design and inputs), results (including base case and uncertainty analyses), and conclusions.	page 2, line 32 to 60
Introduction			
Background and objectives	3	Provide an explicit statement of the broader context for the study.	page 4, line 87 to page 5, line 135
		Present the study question and its relevance for health policy or practice decisions.	page 5, line 126 to 135
Methods			
Target population and subgroups	4	Describe characteristics of the base case population and subgroups analysed, including why they were chosen.	page 6, line 158 to 160 A surgical robotic system has many different applications. As it can be used for multiple indications, we aimed to develop a generic model that can be applied to different indications. Depending on for what procedure the tool is being used, the target population can differ. We used a general hypothetical example to explain how the tool can be used.
Setting and location	5	State relevant aspects of the system(s) in which the decision(s) need(s) to be made.	page 5, line 132 to 135; page The relevant aspects of the system are dependent on how the model is used. As the model can be used in different ways, one should specify the aspects that are relevant for that specific system.
Study perspective	6	Describe the perspective of the study and relate this to the costs being evaluated.	page 5, line 145 to 147; page 9, line 251 to 253; page 15, line 380 to 384
Comparators	7	Describe the interventions or strategies being compared and state why they were chosen.	page 5, line 144 to 145 In order to make the model flexible, robotic surgery can be compared to either endoscopic or open surgery. The user of the model can choose which comparator is relevant for the procedure of interest.
Time horizon	8	State the time horizon(s) over which costs and consequences are being evaluated and say why appropriate.	page 5, line 141 to 143 The benefits are calculated over the life-course of an individual. We included lasting complications and QALYs in the model, which both have impact over a patient's

Section/item	Item No	Recommendation	Reported on page No/ line No
			lifetime. These consequences were also included in the hypothetical example.
Discount rate	9	Report the choice of discount rate(s) used for costs and outcomes and say why appropriate.	Most consequences included in the model are short term consequences for which discounting is not relevant. Long term consequences, i.e. lasting complications and QALYs, should be discounted. In our example these are hypothetical, loosely based on discounted numbers from previous studies.
Choice of health outcomes	10	Describe what outcomes were used as the measure(s) of benefit in the evaluation and their relevance for the type of analysis performed.	page 5, line 140 to 143; page 6, line 164 to 167 In the tool the costs of health effects are compared to the extra costs of a robotic procedure, to provide insight in the value for money of robotic surgery. The outcome is the trade-off between the costs and the effects.
Measurement of effectiveness	11a	*Single study-based estimates:* Describe fully the design features of the single effectiveness study and why the single study was a sufficient source of clinical effectiveness data.	Not applicable, as this section refers to single study-based economic evaluation.
	11b	*Synthesis-based estimates*: Describe fully the methods used for identification of included studies and synthesis of clinical effectiveness data.	Page 5, line 147 to 152 The aim of this study was to develop a tool that can be used to provide insight in the benefits needed compared to the costs of robotic surgery. To illustrate how the tool works we used a hypothetical example, as we did not aim to assess whether the current robot is cost-effective. The numbers in the hypothetical example were loosely based on three studies from literature.
Measurement and valuation of preference based outcomes	12	If applicable, describe the population and methods used to elicit preferences for outcomes.	Not applicable
Estimating resources and costs	13a	*Single study-based economic evaluation:*Describe approaches used to estimate resource use associated with the alternative interventions. Describe primary or secondary research methods for valuing each resource item in terms of its unit cost. Describe any adjustments made to approximate to opportunity costs.	Not applicable, as this section refers to single study-based economic evaluation.
	13b	*Model-based economic evaluation:* Describe approaches and data sources used to estimate resource use associated with model health states. Describe primary or secondary research methods for valuing each resource item in terms of its unit cost. Describe any adjustments made to approximate to opportunity costs.	This paper illustrates a tool using a hypothetical example, therefore the resources are not relevant. We aimed to focus on how the tool can be used and not use real numbers. We did not aim to assess whether the robot is cost-effective. When the model is used for that purpose, it is important to state the information mentioned in this section of the CHEERS guidelines.

Section/item	Item No	Recommendation	Reported on page No/ line No
Currency, price date, and conversion	14	Report the dates of the estimated resource quantities and unit costs. Describe methods for adjusting estimated unit costs to the year of reported costs if necessary. Describe methods for converting costs into a common currency base and the exchange rate.	page 7, line 181 to 182; The costs are presented in Euros. Nevertheless, all costs in the model can be adjusted. As we used a hypothethical example for illustration purposes only, we did not convert costs.
Choice of model	15	Describe and give reasons for the specific type of decision-analytical model used. Providing a figure to show model structure is strongly recommended.	page 5, line 140 to 169; See also our nline tool (https://sejal.shinyapps.io/supplement_robot-assisted_surgery_article/)
Assumptions	16	Describe all structural or other assumptions underpinning the decision-analytical model.	page 8, line 225 to 231; page 9, line 251 to 264; page 9, table 1 The model is flexible and therefore all assumptions can be changed.
Analytical methods	17	Describe all analytical methods supporting the evaluation. This could include methods for dealing with skewed, missing, or censored data; extrapolation methods; methods for pooling data; approaches to validate or make adjustments (such as half cycle corrections) to a model; and methods for handling population heterogeneity and uncertainty.	Equations are provided in the appendix.
Results			
Study parameters	18	Report the values, ranges, references, and, if used, probability distributions for all parameters. Report reasons or sources for distributions used to represent uncertainty where appropriate. Providing a table to show the input values is strongly recommended.	Page 9, line 251 to 264; page 9, table 1;
Incremental costs and outcomes	19	For each intervention, report mean values for the main categories of estimated costs and outcomes of interest, as well as mean differences between the comparator groups. If applicable, report incremental cost-effectiveness ratios.	Page 10, line 272 to 281; page 11, table 2; page 12, line 288 to 302; page 12, table 3, page 13, line 310 to 232; page 13, table 4 and 5
Characterising uncertainty	20a	*Single study-based economic evaluation:*Describe the effects of sampling uncertainty for the estimated incremental cost and incremental effectiveness parameters, together with the impact of methodological assumptions (such as discount rate, study perspective).	Not applicable, as this section refers to single study-based economic evaluation.
	20b	*Model-based economic evaluation:* Describe the effects on the results of uncertainty for all input	Not applicable. This paper illustrates a tool using a hypothetical example, therefore the resources are not relevant. We aimed to focus on how the tool can be used and

Section/item	Item No	Recommendation	Reported on page No/ line No
		parameters, and uncertainty related to the structure of the model and assumptions.	not use real numbers. We did not aim to assess whether the robot is cost-effective. When the model is used for that purpose, it is important to state the information mentioned in this section of the CHEERS guidelines.
Characterising heterogeneity	21	If applicable, report differences in costs, outcomes, or cost-effectiveness that can be explained by variations between subgroups of patients with different baseline characteristics or other observed variability in effects that are not reducible by more information.	Not applicable
Discussion			
Study findings, limitations, generalisability, and current knowledge	22	Summarise key study findings and describe how they support the conclusions reached. Discuss limitations and the generalisability of the findings and how the findings fit with current knowledge.	page 14, line 336 to page 17, line 427
Other			
Source of funding	23	Describe how the study was funded and the role of the funder in the identification, design, conduct, and reporting of the analysis. Describe other non-monetary sources of support.	Page 1, line 24; Information provided via the submission system
Conflicts of interest	24	Describe any potential for conflict of interest of study contributors in accordance with journal policy. In the absence of a journal policy, we recommend authors comply with International Committee of Medical Journal Editors recommendations.	Page 17, line 429 to 433; Information provided via the submission system

For consistency, the CHEERS statement checklist format is based on the format of the CONSORT statement checklist