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How well do software assistants for minimally invasive partial nephrectomy meet surgeon information needs? A cognitive task analysis and literature review study

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Abstract

Introduction

Intraoperative software assistance is gaining increasing importance in laparoscopic and robot-assisted surgery. Within the user-centred development process of such systems, the first question to be asked is: *What information does the surgeon need and when does he or she need it*? In this article, we present an approach to investigate these surgeon information needs for minimally invasive partial nephrectomy and compare these needs to the relevant surgical computer assistance literature.

Materials and methods

First, we conducted a literature-based hierarchical task analysis of the surgical procedure. This task analysis was taken as a basis for a qualitative in-depth interview study with nine experienced surgical urologists. The study employed a cognitive task analysis method to elicit surgeons' information needs during minimally invasive partial nephrectomy. Finally, a systematic literature search was conducted to review proposed software assistance solutions for minimally invasive partial nephrectomy. The review focused on what information the solutions present to the surgeon and what phase of the surgery they aim to support.

Results

The task analysis yielded a workflow description for minimally invasive partial nephrectomy. During the subsequent interview study, we identified three challenging phases of the procedure, which may particularly benefit from software assistance. These phases are I. Hilar and vascular management, II. Tumour excision, and III. Repair of the renal defects. Between these phases, 25 individual challenges were found which define the surgeon information

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needs. The literature review identified 34 relevant publications, all of which aim to support the surgeon in hilar and vascular management (phase I) or tumour excision (phase II).

Conclusion

The work presented in this article identified unmet surgeon information needs in minimally invasive partial nephrectomy. Namely, our results suggest that future solutions should address the repair of renal defects (phase III) or put more focus on the renal collecting system as a critical anatomical structure.

Introduction

Software assistance during laparoscopic surgery has been a major research focus in the past two decades and is contributing to transforming surgical procedures in various surgical domains [1]. We understand the term *software assistance* to include any system, which supports surgeons by intraoperatively providing relevant information either in the laparoscopic video view or on dedicated channels with the goal to make surgery safer, more effective, and efficient. This information is usually based on preoperative or intraoperative imaging data. The vast majority of research in this field is conducted with a focus on technical challenges and solutions, as well as the impact that these have on the clinical outcome. Little focus has been put on the user-centred aspects of computer-assisted surgery [2]. Neglecting this side of the development can severely affect the systems' efficacy in supporting the surgeon and diminish their clinical benefit or even lead to significant patient safety risks [3].

Malaka et al. [4] argue that the first question that should be asked in this context is: *What information does the surgeon need*? Answering that question requires a closer look at the surgical procedure at hand. Namely, these surgeon information needs depend on the state of the surgical procedure. This has motivated a field of research which aims to model and detect surgical workflow sequences to display useful information to the surgeons [5–7]. In complex procedures in which technical support might be particularly useful, Malaka et al.'s question can therefore be extended to ask: *What information does the surgeon need and at what point in the procedure does he or she need it*? [8]

One such surgical procedure that has gained extensive attention from the surgical software assistance research community is laparoscopic or robot-assisted partial nephrectomy (LPN/RPN) [9–12]. LPN/RPN is a minimally invasive procedure to surgically remove renal tumours. LPN/RPN is a complex procedure in which the surgeon pursues two potentially contradicting objectives: On the one hand, the surgeon needs to ensure that the tumour tissue is completely removed while, on the other hand, preserving as much healthy renal tissue as possible. This includes the protection of risk structures, which are critical to the renal function, such as the renal vasculature or the urinary collecting system. While multiple software assistance concepts have been proposed for this procedure, no systematic investigation into the users' needs has been published. Moreover, no research has been conducted into how existing computer assistance concepts for LPN/RPN address these information needs.

This article aims to answer these two research questions: 1. Which surgeon information needs do occur during LPN/RPN, and 2. How do current software assistants for LPN/RPN meet these information needs?

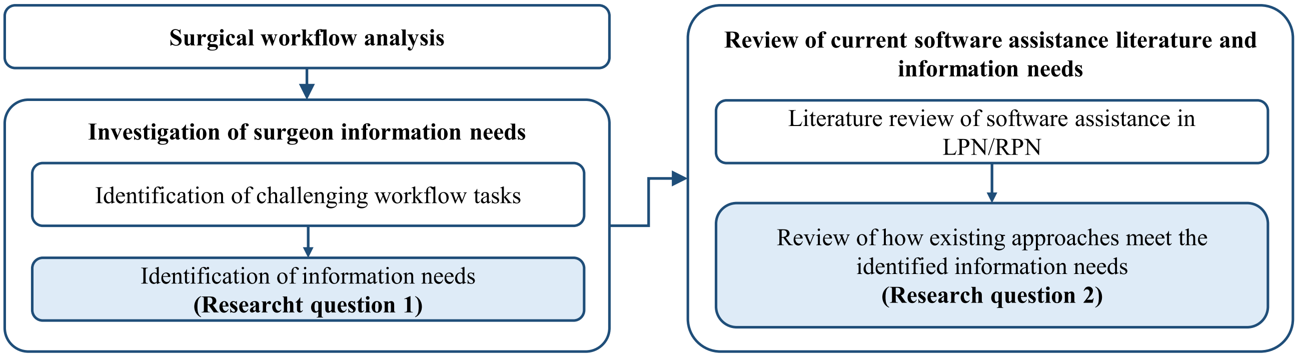

Fig 1. The research approach presented in this article.

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In this context, we understand *information needs* as any information that, if provided to the surgeon, can help make the procedure safer, more effective or more efficient, or that can help reduce the workload for the surgeon.

Research approach

The process we followed to answer these questions comprises three phases, and the article is structured accordingly (Fig 1): First, an investigation and documentation of the surgical workflow at hand (LPN/RPN) was conducted. This served to gain a basic understanding of the user task and as a basis for the information need investigation that followed. Second, we conducted a cognitive task analysis (CTA) based qualitative interview study on user information needs for software assistants intended for LPN/RPN. Within this study, we first identified particularly challenging parts of the workflow. We then identified information that may help surgeons conduct these challenging parts of the workflow, i.e., intraoperative information needs. This phase provided the data to answer research question 1. We then conducted a systematic literature review of LPN/RPN software assistants. This review focused on the information that researchers propose presenting to the surgeons and what phase of the surgery they aim to support. Finally, the results from the previous activities allowed us to review how the information presented to the surgeon in current systems address the user information needs we identified (research question 2).

Our contribution is twofold: We present novel results on surgeon information needs in LPN/RPN and review how these are met in the current literature. This information will fundamentally help the future development of effective intraoperative software assistants for LPN/RPN. Moreover, we demonstrate a research approach to obtain these data and discuss its applicability in other surgical procedures.

Related work on user needs and surgical workflow in LPN/RPN

Various informal descriptions of the surgical workflow in LPN/RPN exist. These descriptions are either published in the form of surgical educational literature (e.g. [13]) or published as reports of new surgical techniques (e.g. [14,15]). However, these procedure descriptions do not aim to systematically describe a generic workflow across various surgical strategies and schools of thought.

Much research has been conducted to systematically model surgical workflows and detect process phases automatically to inform intelligent assistance systems intraoperatively [5–7]. While a wide range of methods has been applied to model a broad field of surgical applications

[6], to our knowledge, no dedicated model or description of the workflow of partial nephrectomy exists.

A precise method for eliciting surgeons' user requirements for intraoperative computer assistance, the *workflow integration matrix*, has been previously proposed [8]. While this method has subsequently been successfully applied in a procedure within the field of interventional radiology, it does not seem to have been broadly adopted in the research community. To our knowledge, no investigation into the surgeons' information needs during partial nephrectomy has been conducted.

Related work on computer assistance in LPN/RPN

Several comprehensive literature reviews regarding computer assistance during LPN/RPN have been published in recent years. Hughes-Hallett et al. [10] conducted a review regarding augmented reality systems proposed for partial nephrectomy. Their review mainly focuses on solutions to the problems around image registration and tracking that have been proposed in the literature. Hekman et al. [12] conducted a broader review of software assistance solutions for partial nephrectomy. The review provides a comprehensive overview of the concepts proposed in literature and the associated technical challenges and solutions. However, the clinical purpose and visual data provided to the surgeon is not within this scope. Detmer et al. [11] provide an overview of the clinical purpose of various software assistants, but limit their review to virtual or augmented reality-based software assistance solutions. These reviews do not systematically report the information provided by the different software assistance approaches or when the information is provided to the surgeon.

Surgical workflow analysis

The first step to identify the user's information needs lies in understanding the workflow and the goals and tasks it comprises [8]. In our example, this workflow is the surgical procedure under investigation, i.e., LPN/RPN.

Materials and methods

A widely-used method for investigating and reporting workflows in human-machine systems is the hierarchical task analysis (HTA) [16]. This method has been used, modified, and extended over the past five decades. In 2006, Stanton [17] provided a comprehensive review of variations and extensions of the HTA approach. In the HTA method, the user's goals and activities are systematically deconstructed. One major challenge lies in identifying the stopping point for this deconstruction, i.e., in defining the desired granularity of goals and activities. Within the surgical domain, Sarker et al. [18] define the stopping point of task deconstruction such that the tasks and steps required for the achievement of the goal are well defined, but the individual technique and tools applied by the surgeon are not implied.

We investigated the LPN/RPN workflow based on surgical literature and documented it in the HTA format. An informal literature search was conducted on Google Scholar to identify eligible surgical procedure descriptions of LPN/RPN. The search terms "`laparoscopic partial nephrectomy`", "`laparoscopic partial nephrectomy segmental clamping`", and "`robot assisted partial nephrectomy`" were used in the search. The results were informally screened by one investigator (FJ). Forward and backward searches were applied for relevant results. The results of this literature search were combined with relevant scientific publications and surgical teaching literature that were already known to the authors.

Clinical publications and teaching literature were selected by the following inclusion criteria:

1. Publications, which describe the surgical procedure of LPN/RPN at a high level of detail, were included in the selection.
2. Both laparoscopic and robot-assisted procedures were included in the selection.
3. Different vascular management strategies (i.e., total clamping, selective clamping, and zero-ischaemia) were included in the selection.

We aimed for a minimal overlap in the authorship of the selected publications to prevent bias towards one surgical centre or school of thought. The surgical procedure described in each publication was reviewed and formalised into a separate HTA. The granularity of working steps was set to represent the tasks and steps required to achieve the respective sub-goals without implying the individual technique or tools. We did not explicitly list the sub-goals as they are implied in the surgical tasks we identified. The tasks and steps of each HTA were then compared to identify equivalences in order to avoid redundancies. Based on this, the HTAs were merged into one generic HTA, which included tasks and steps from all five HTAs with removed redundancies.

Additional publications were selected to validate this generic HTA. These followed the selection criteria as described above, except that no authorship overlap with any of the original publications or with each other was accepted. Separate HTAs were created for each of these publications. These HTAs were compared to the generic HTA to confirm if any additional tasks or working steps had been omitted in the generic HTA.

Results

Five clinical publications [13–15,19,20] were selected for the initial generic HTA. One author contributed to two of these [13,14]; no further authorship overlaps occurred. From these publications, 12 tasks comprising 43 surgical steps were identified constituting the initial generic HTA of the LPN/RPN surgical procedure (Table 1). Four publications were selected for validation [21–24]. Validation yielded no further surgical tasks, but three additional steps were identified, as highlighted in Table 1.

Generally, the steps do not necessarily have to be conducted in the order in which they are listed here. Some steps may be conducted only once; others may be conducted repeatedly. E.g., vessel cauterisation and tissue resection are performed continuously and iteratively during tumour resection.

Discussion

The performed HTA, as presented in Table 1, aims to depict a generic workflow of LPN/RPN. It is, to our knowledge, the first systematic workflow analysis for this particular procedure. Moreover, the performed HTA covers a range of surgical approaches as it is collated and validated based on a number of independent procedure descriptions. Thus, it includes steps that may only be applicable in some of these approaches (e.g., different clamping strategies will affect which exact steps of vascular management will have to be taken).

Our HTA does not formally describe in what order or how many times a step is conducted. This information is commonly represented as *plans* in HTA [17]. However, formalising these would somewhat complicate the workflow description, particularly in the context of using it as a basis for discussion in the subsequent interview study.

Table 1. Workflow of LPN/RPN in HTA format.

Surgical Task	Surgical Steps
1 Prepare operation	1.1 Preoperative planning 1.2 Patient preparation
2 Initiate operation	2.1 Stretch retroperitoneal space[1] (*only in retroperitoneal approach)* 2.2 Insufflate operative space 2.3 Place camera port 2.4 Place working ports
3 Navigate to operative site	3.1 Navigate to renal fascia 3.2 Mobilise kidney 3.3 Dissect hilum
4 Intraoperative examination and planning	4.1 Remove renal fat from tumour area 4.2 Examine tumour 4.3 Search for further tumours 4.4 Plan and mark excision site 4.5 Confirm plan with ultrasound 4.6 Position kidney for excision[1] 4.7 Confirm that all materials required during resection and renorrhaphy are prepared 4.8 Administer diuretics before clamping
5 Manage renal vessels	5.1 Clamp renal artery or segmental arteries 5.2 Clamp renal vein or segmental veins 5.3 Confirm that no relevant branches have been missed 5.4 Start clock to monitor ischaemia time
6 Excise tumour	6.1 Navigate within excision site 6.2 Cut renal tissue 6.3 Cauterise vessels 6.4 [if not clamped] Reduce blood pressure after renal cortex has been cut through 6.5 [if not clamped] Identify and clamp intrarenal vessels 6.6 [if not clamped] Monitor continued renal perfusion under reduced blood pressure 6.7 Place excised tumour next to kidney 6.8 Take biopsy from tumour bed[1]
7 Repair renal defects	7.1 Close entries to collecting system and major intrarenal vessels 7.2 Confirm lower repairs 7.3 Repair parenchyma
8 Unclamp	8.1 Administer diuretics 8.2 Open / remove clamps 8.3 Assess haemostasis 8.4 Repair remaining bleeding vessels 8.5 [if not removed in 8.2] Remove clamps
9 Extract tumour with specimen bag	
10 Conclude operation	10.1 Repair extrarenal defects 10.2 Place wound drain 10.3 Inspect operative site after deflation to confirm haemostasis 10.4 Remove trocars and close ports
11 Administer postoperative care	
12 Communication with other operation room staff	12.1 Communicate with assistant 12.2 Communicate with anaesthetist 12.3 Communicate with nurse staff

[1] These steps were identified during validation.

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Beyond literature-based workflow investigation, other methods are available to inform an HTA (e.g., observation, interviews, etc.). Depending on the purpose of the investigation and on the domain investigated, these may be helpful or even required to further inform the HTA. For example, some domains may not have the same level of detailed procedural literature as was available in this context.

Identification of surgeons' information needs

To further determine users' information needs for an assistance system, the challenging aspects of the previously documented workflow were identified and investigated using a CTA [25] method.

Materials and methods

A qualitative CTA study with two phases was conducted with experienced surgical urologists. First, a written questionnaire was applied to identify challenging tasks within the workflow. This was followed by a semi-structured interview employing CTA methods to further understand the surgical challenges and the information needs that arise from them. The following sections report the specific methods applied.

Identification of challenging tasks

The written questionnaire included a list of the 46 surgical steps previously identified (see Table 1). Participants were asked to mark two to five steps, which they deemed particularly challenging and two to five steps, which they deemed particularly associated with perioperative risks.

Based on the participants' assessment, two or three steps were selected for each participant for in-depth discussion. Any steps that were marked as challenging and risky by a participant were selected for discussion with that participant. Beyond that, steps were selected such that the number of participants that a step was discussed with reflected the number of participants who marked the step as challenging or risky. This means that we aimed to discuss steps with more participants if they were rated challenging or risky by a higher number of participants. This could not be systematically ensured because many participants completed their written questionnaires after the first interviews had already been conducted. No participant rated more than three steps as challenging *and* risky. Steps 1.1 and 11 (see Table 1) were excluded in this analysis because they represent preoperative or postoperative activities.

Identification of surgical challenges and corresponding information needs. CTA [25] comprises a wide range of interview and observation methods to investigate the knowledge, cognitive processing, and decision making involved in complex tasks. This range includes the Applied Cognitive Task Analysis (ACTA) [26]. Employing the ACTA method, we could break our study's objective down into three partial objectives: First, to identify challenges that participants experience when performing LPN/RPN. Second, to understand the strategies and cues used by the participants to address these challenges. Finally, to identify potential information needs in LPN/RPN where additional software assistance may be particularly helpful. This section reports the interview techniques applied to collate the data required to fulfil the first two objectives. The information needs were extracted from these data during data analysis.

Two categories of interview prompts were used to elicit the information that was required to meet the abovementioned objectives: First, we used the ACTA method [26]. Five of the ACTA's *Basic Probes* were used (the *Job Smarts* probe was omitted). These were augmented by using the optional *Anomalies* prompt and a prompt on unmet information needs. The prompts for each discussed surgical step were applied in randomised order.

Second, a list of potential intraoperative decisions was used as interview prompts. Prior to study commencement, a brainstorming activity was conducted between two clinical experts (DS, SB) and two human factors experts (FJ, ML). This brainstorming activity aimed to identify decisions, which surgeons may have to make during any given surgical step. A total of 340 potential decisions was identified (between two and 20 decisions per surgical step). The potential decisions for the respective step under discussion were read out to participants as decision questions. Participants were asked to judge if these were relevant decisions and, if so, to describe what information helps them to make these decisions. The decision questions for each discussed surgical step were presented and discussed in randomised order.

Each prompt was followed by unstructured in-depth probing to ensure that all challenges, strategies, and cues described by the participants were sufficiently understood by the interviewer.

Study sample recruitment. We contacted, by telephone, 23 German hospitals of which we knew that they conduct LPN and/or RPN. LPN/RPN experienced surgical urologists from 14 hospitals expressed their interest in participating (one urologist from each hospital), but it was not possible to find suitable time slots with five of them. Therefore, nine interview partners participated in the study. Participants volunteered their time and were not paid or otherwise rewarded for participation.

Study execution. All interviews were conducted by one investigator (FJ). Participants could choose between a personal interview and an interview by telephone. Six interviews were conducted by telephone and three interviews were conducted in person. All interviews were conducted in German. Participants' informed consent for participation was confirmed orally at recruitment and interview commencement.

Prior to the agreed interview date, participants were sent the written questionnaire by e-mail and were asked to complete it and return it by e-mail. At the interview commencement, participants were reminded about the study's objectives, and the interviewer collected data on their relevant surgical experience. Two or three surgical steps were then discussed in detail. First, the interviewer asked the participants why they rated the step under discussion as challenging and/or risky. The steps were then further discussed using the methods described above. If time permitted, additional steps were briefly discussed. Brief discussion entailed two prompts: 1) Why did the participant rate a step as challenging and/or risky, and 2) the prompt on unmet information needs otherwise used as part of the modified ACTA method. Across the nine interviews, 21 full surgical step discussions (using all interview prompts) and 11 brief discussions (as defined above) were completed. Each interview lasted between 60 and 90 minutes.

Data recording and analysis. Questionnaire data from each participant were tallied as soon as they were received. Prior to each participant's interview, the data were used to select surgical steps for discussion as outlined above.

During the interview, the interviewer took notes of relevant participant comments, and the interviews were audio-recorded. The recordings were saved locally and only accessible to the interviewer to guarantee participant anonymity. Following the interviews, the interviewer compared the notes to the recordings to ensure that all relevant participant comments were incorporated in the subsequent analysis.

Interview notes were then analysed qualitatively by one investigator (FJ). First, the notes were filtered for specific challenges. They were then filtered for strategies and cues that participants reported to employ when facing these challenges. Explicit information needs that were expressed by participants were also assigned to the challenges from which they were understood to arise. These data were collected across participants and, where applicable, clustered across participants.

Finally, surgeon information needs were extracted from this data. We understand information needs as information, which, if provided to the surgeon, might help face the challenges identified. To extract information needs, the strategies, cues, and explicit information needs were reviewed for each challenge. We identified information needs from three types of information: First, information, which was explicitly requested by participants (hereafter referred to as *explicit needs*). Second, anatomical or pathological structures that were named as relevant for a given challenge. Third, we list information, which participants reported to have to recall from memory or judge by experience and gut feeling.

Results

This section reports the results from the pre-interview questionnaires and the interviews.

Participant background. Nine participants were interviewed. Three participants had experience with RPN only, two participants had experience with LPN only, and four participants were experienced with both procedures. Overall, LPN experience ranged from 20 to 300 procedures (median: 125) and RPN experience ranged from 10 to 300 procedures (median: 50). One participant who was experienced with only LPN did not provide this information.

Identification of challenging tasks. Fig 2 provides an overview of the number of participants who rated each surgical step as challenging or risky. The most rated steps included hilum dissection (3.3), vascular clamping (5.1), excision plane navigation (6.1), and the repair of collecting system and vascular lesions (7.1). Although the sample size and applied method do not allow for a quantitative inferential analysis, it is evident that most steps, which were rated as challenging or risky, fall into one of three surgical phases:

i. Hilar and vascular management (steps 3.3, 5.1, 5.3),

ii. Tumour excision (steps 6.1, 6.2, 6.3, 6.5),

iii. Repair of renal defects (steps 7.1, 7.2, 7.3, 8.2, 8.3, 8.4, 8.5).

Identification of surgical challenges and information needs. The interview results supported the identity of the three surgical phases we found in the questionnaire results: Participants who selected different steps from a given surgical phase tended to describe very similar challenges, strategies, cues, and information needs. Discussion with the participants often led to covering other surgical steps within the same phase.

During data analysis, 25 distinct challenging surgical decisions, activities, or circumstances (hereafter summarised as *challenges*) were identified, which had been mentioned by at least

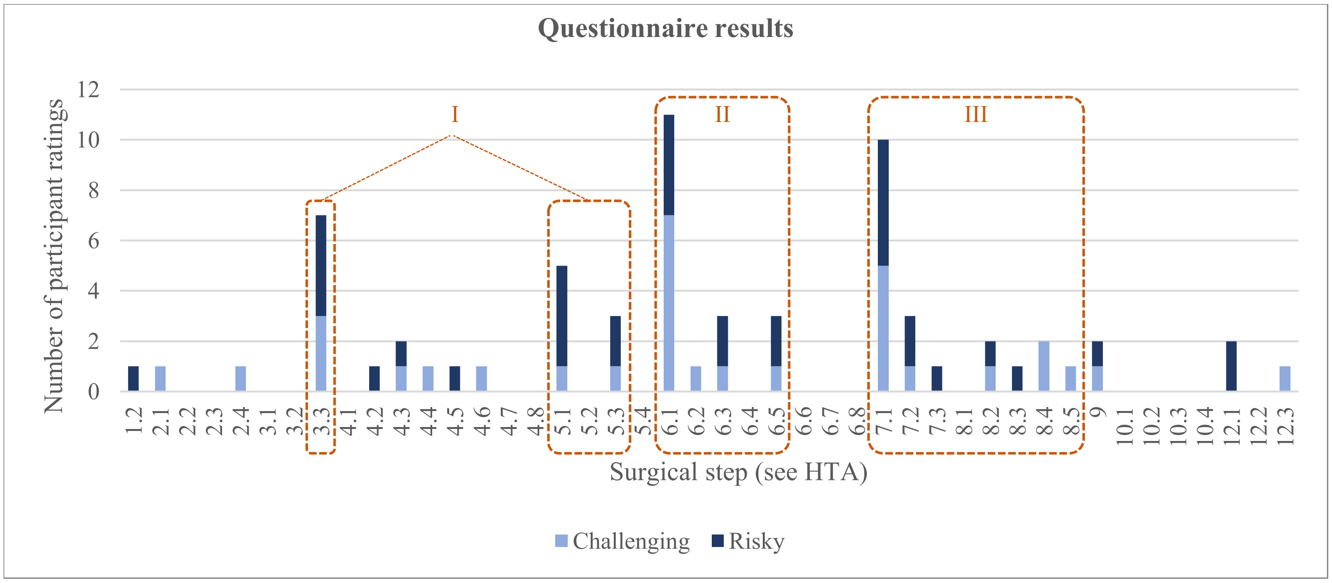

Fig 2. Assessment of surgical steps in terms of risk and challenge. Numbers greater than nine are due to participants rating steps as challenging *and* risky.

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one participant. Twenty-one (21) of these challenges could be assigned to the three surgical phases described above. For most of these challenges, participants reported a range of strategies and/or cues. Table 2 lists the reported challenges and the information needs derived from the reported strategies, cues, and explicit information needs. Most challenges reported by the participants involve spatial navigation in the surgical site, including the identification and localisation of target or risk structures (13 challenges). Other challenges include the detection of

Table 2. Challenges and information needs for most risky and challenging surgical phases.

Surgical Phase	Challenge	Information needs
I Hilar management	**I.1** Decision: Is clamping required and, if so, which vessels require clamping?	Information about tumour size, position, and tumour supplying vasculature.
	I.2 Hilar dissection in highly variable individual patient anatomy.	Information about ureter, major extrarenal vessels, renal vascular tree, and highlighting of inferior pole.
	I.3 Identify, localise, and dissect all relevant vascular branches.	Intraoperative availability of preoperative imaging data (and processed versions thereof). Highlighting of occluded vessels. Information about instrument proximity to major arteries.
	I.4 Decision: Have all relevant vascular branches been clamped?	Information about segmental perfusion. Confirmation that clamps are fully closed.
II Tumour excision	**II.1** Localise and navigate to tumour.	Intraoperative availability of preoperative imaging data (and processed versions thereof). Information about tumour position.
	II.2 Find the ideal resection plane.	Intraoperative availability of preoperative imaging data (and processed versions thereof), endophytic parts of tumour, tumour depth, spatial relationship between tools and tumour, preoperative excision plan.
	II.3 Decision: Can the tumour be enucleated?	-
	II.4 Identify current resection plane and surrounding tissue.	-
	II.5 React to unexpected anatomy or pathology.	-
	II.6 Identify, localise, and protect risk structures (vessels, collecting systems).	Information about or highlighting of parenchyma, major tumour-supplying vessels, collecting system. Intraoperative availability of preoperative imaging data. Highlighting of major occluded vessels.
	II.7 Preserve perfusion to the remaining renal tissue	Information about segmental perfusion.
	II.8 Detect and manage lesions to risk structures (vessels, collecting system).	Information about lesions of the collecting system. Information about tumour tissue in the resection plane.
	II.9 Decision: Is retroactive clamping required?	Information about segmental perfusion.
	II.10 Decision: Was the resection oncologically successful?	Information about tissue type in resection bed.
III Repair of renal defects	**III.1** Apply correct positioning, strength, and distance of sutures.	Information about arteries and tissue, which may be in the needle path.
	III.2 Identify, localise, and manage collecting system lesions.	Information about collecting system lesions.
	III.3 Identify, localise, and manage major vessel lesions.	Information about vessels crossing the resection area.
	III.4 Prevent and manage visibility issues due to profuse bleeding.	Information about major blood vessels intraoperatively. Information about source of bleeding.
	III.5 Distinguish vessels that require individual suturing from those which do not.	Information about arteries. Quantification and visualisation of strength of bleeding.
	III.6 Problem: Undetected lesions of collecting system or vasculature.	-
	III.7 Problem: In deep incision sites, the first suture can contract the resection too far to apply further sutures.	-
IV Other	**IV.1** *Step 2.1*: Trocar placement is challenging in retroperitoneal approach due to very limited space.	-
	IV.2 *Step 2.4*: Trocar placement is patient-individual and challenging due to robot arm trajectories and constraints.	Support in placement decision making to maximise surgical access and minimise interference of robot arms.
	IV.3 *Step 4.2*: Intraparenchymal tumours are difficult to detect intraoperatively, despite the use of ultrasound. No solution reported.	-
	IV.4 *Step 4.6*: The kidney may have to be fully mobilised. In laparoscopic surgery, holding the kidney in position binds one of the available tools (and arms) for the duration of the procedure.	-

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lesions or complications (5), strategic decisions (3), and intraoperative assessments of the successful completion of safety-critical surgical steps (2). Two challenges fit none of these categories.

A full overview of the strategies, cues, and explicit information needs reported by participants is documented in S1 Table. The type of data collected does not allow for quantitative analysis. However, some trends are recognisable in the data, which provide a summarising overview of the data reported in S1 Table: Key relevant anatomical structures included the hilum, tumour supplying vessels, large non-tumour related vessels, the collecting system, and the tumour(s). The interview data suggest that, unsurprisingly, visual inspection of the surgical site and preoperative computed tomography (CT) or magnetic resonance imaging (MRI) data (and processed versions thereof) are the most used information sources. Multiple participants reported using laparoscopic ultrasound (including Doppler ultrasound) and Intuitive Surgical's *Firefly*™ (Intuitive Surgical Inc., Sunnyvale, CA, USA) fluorescence imaging as intraoperative imaging modalities. Most information needs that were expressed by participants and identified during data analysis involved the intraoperative visualisation of key anatomical structures.

Discussion

The CTA interview study results identified three key surgical phases during which most reported challenges occur. Within these phases, a range of challenges was identified and participants reported a variety of strategies and cues, which they employ to meet those challenges. From these, we identified a range of information needs.

The questionnaire was successfully used to select surgical steps for an in-depth discussion with participants. The interview results confirmed the surgical phases identified in the questionnaire. This efficiency was helpful in the investigation of a procedure, which requires a high level of expertise, as this limits the population of potential interview partners. However, due to the available participant number, it is not guaranteed that all relevant challenges, strategies, and cues could be identified. This approach is, therefore, a compromise between the feasibility of a study with a highly experienced expert population and the objective to draw a full picture of a complex procedure.

Our investigation and its results may be affected by the surgical techniques applied by our interview participants and by the currently available information sources. Surgeons may not be aware of information needs, as they may have learned to compensate for missing information in their clinical routine. While CTA aims to compensate for this, there may be additional information needs that were not revealed with our method.

Generally, we believe that focusing on specific surgical steps helped to make the discussion tangible and concrete, as intended in the ACTA method. Interestingly, the overall challenging phases still manifested in the data. In future work, these phases could be used to improve the HTA of LPN/RPN further. The ACTA method enabled a good understanding of the specific expertise applied in this procedure as well as the limits of this expertise.

Review of current software assistance literature and information needs

To detect how the identified challenges and information needs in the surgical procedure at hand (i.e., LPN/RPN) are addressed in current software assistance literature, we conducted a systematic literature review. In particular, we focused on the clinical objectives pursued (i.e., the phase of the procedure which they addressed) by existing concepts and the information displayed, as these are particularly relevant for juxtaposition to the information needs we identified.

Materials and methods

This section reports the search method, publication selection process and analysis approach of the systematic literature review. A list of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses [27] is provided in S2 Table.

Search method

A PubMed and Google Scholar search was conducted with the following search terms:

((("computer"[All Fields] AND "assisted"[All Fields]) OR (("augmented"[All Fields] OR "virtual"[All Fields]) AND "reality"[All Fields]) OR ("image"[All Fields] AND ("guided"[All Fields] OR "guidance"[All Fields])) OR "navigation"[All Fields]) AND "nephrectomy"[All Fields])

The search was limited to publications in English, published from January 2008. The search was conducted in June 2019. In addition, we considered relevant publications identified in previous review work [10–12].

Literature selection process and inclusion criteria. Two reviewers (FJ, ML) independently conducted a title and abstract-based review of PubMed search results. One reviewer (FJ) conducted a title and abstract-based review of the Google Scholar search results. All publications selected by at least one reviewer underwent a subsequent full-text review by one investigator. Inclusion or exclusion was determined based on this full-text review. We included publications that fulfilled all of the following inclusion criteria:

- Publications that refer to software assistance for laparoscopic or robotic partial nephrectomy.
- Publications that present a software assistance approach for intraoperative use.
- Publications that report the information presented to the surgeon.

Publications were excluded if they presented software assistance for preoperative planning only or if they mainly focused on technical challenges (e.g., image registration or medical imaging techniques). We also excluded case studies that employed software assistance approaches also described in other publications. In cases where research teams published several iterations of the same system, we selected the most recent publication that fulfilled the inclusion criteria.

Analysis. The selected publications were reviewed for the clinical purpose pursued (i.e., the surgical phase they aim to support) and the information displayed. We also reviewed what type of data (e.g., what imaging modality) the software assistance approaches were based on previously. The identified publications were then clustered by surgical phase.

Finally, the publications were assigned to the previously identified challenges in order to review how the identified information needs are currently addressed by the existing concepts.

Results of literature review of software assistance in LPN/RPN

The PubMed search yielded 340 publications, of which 49 underwent full-text review. The Google Scholar search yielded 2,750 results. The results were sorted by relevance and the first 595 results underwent a title and abstract-based review. The last identified eligible entry was the 345th entry in the list of search results. Another 250 entries were screened without further eligible results. Thus, the screening was terminated after 595 entries. Out of these 595 search results, eight publications that had not been identified in the PubMed search or previous reviews underwent full-text review. Twenty-six (26) publications were selected for analysis from the PubMed and Google Scholar search. Eight additional publications were identified from previous reviews [10–12]. An overview of the screening and selection process is provided in S1 Fig.

Overview of literature review results. Twelve (12) software assistance solutions were aimed at the *hilar and vascular management* phase (phase I), and 20 solutions were aimed at the *tumour excision* and the intraoperative planning thereof (phase II). Two concepts were aimed at both these phases. We found no proposed solutions for the renorrhaphy phase (phase III) or any steps outside these three phases.

Fig 3 provides an overview of the raw data used in the reviewed software assistants. Most solutions employ preoperative CT or MRI imaging data (15 publications) and/or intraoperative ultrasound data (12) (one solution used both of these modalities). The remaining solutions use fluorescence imaging (4), intraoperative cone-beam CT (2), or real-time laparoscopic image processing (2) as their data basis.

The following sections detail the solutions proposed for the surgical phases of hilar and vascular management (I) and tumour excision (II). Software assistance technologies that our interview participants reported to have used before are highlighted with an asterisk (*).

Hilar and vascular management. Various approaches have been introduced to support this surgical phase and the steps it comprises.

The first group of approaches proposes to provide the surgeon with virtual 3D models of the patient's (vascular) anatomy and pathology [28–32]*. These models are made available during the operation and aim to serve as a roadmap for vessel selection in selective and superselective clamping. Two further systems take a similar approach but allow to overlay the 3D models onto the surgical scene in an AR visualisation [33,34]. These approaches support the surgeon in challenges I.1 and I.2.

The second group of systems aims to support the surgeon in identifying and localising vessels (challenge I.3). One such approach [35] uses Doppler ultrasound to detect hidden vessels*. Tobis et al. [36] use intravascular indigo cyanine green (ICG) which fluoresces under near-infrared light to detect hidden vessels. In a third approach, the laparoscopic image is analysed in real-time for tissue which subtly pulsates at approximate heart rate frequency to detect hidden arteries [37].

Various approaches have been proposed to confirm if clamping is complete (challenge I.4). One proposed method is using Doppler ultrasound to confirm if the targeted kidney segment is still perfused (in selective clamping) [35] or if the overall kidney is still perfused (in full clamping) [38]. Rao et al. [28] propose using the sonographic contrast agent *SonoVue*™ (Bracco International, Milan, Italy) to confirm segment perfusion. In a similar approach, the same contrast agent is used repeatedly to iteratively correct clamp placement [39]. Finally, two groups [40,41] propose administering ICG to visualise the segmental perfusion of the kidney*.

Tumour excision. Various research groups propose providing the surgeon with 3D models of the patient anatomy and pathology intraoperatively to support tumour excision [34,42,43]*. One of these publications [43] is the clinical experience report of applying a relevant commercial software assistant. Moreover, means of overlaying preoperatively created 3D models on the surgical scene in AR visualisations have been introduced [44–46]. A similar reported strategy involves the intraoperative generation of 3D models (using cone-beam CT imaging) and visualising them in a software assistance setting [47,48]. All of these models include the kidney, tumour, hilum, and extrarenal vessels with varying levels of detail. With this scope, they mainly support the surgeon in challenges II.1 and II.4. Some models also include information about intrarenal vasculature [34,43,45–48] or the renal pelvis / collecting

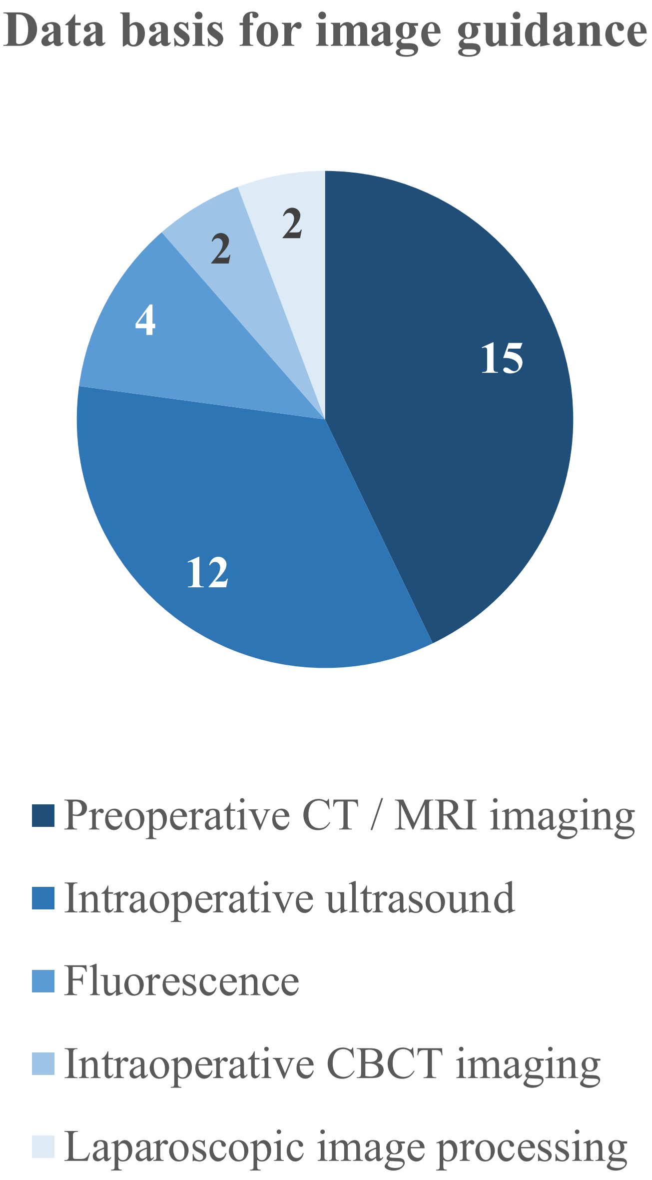

Fig 3. Data basis for software assistance approaches reported in literature. The overall number reported is 30 because one publication [28] uses both intraoperative ultrasound data and preoperative imaging data. CBCT: Cone beam CT.

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system [34,42,46,47]. These models also support the surgeon concerning challenges II.2 and II.6.

A second group describes tumour detection with intraoperative laparoscopic ultrasound [49–51]. Cheung et al. [52] and Pratt et al. [53] propose overlaying the intraoperative ultrasound images onto the laparoscopic view by tracking the ultrasound probe and laparoscope. Kawahara et al. [54] introduce an algorithm that automatically detects tumorous tissue in intraoperative ultrasound frames. To identify exophytic tumour tissue, administration of ICG fluorescence imaging [36] or an orally administered fluorescent agent that highlights tumour tissue when activated [55] have been proposed. These ultrasonographic and fluorescence-based tumour-centric approaches mainly address challenges II.1 and II.2. The ICG fluorescence imaging method [36] is also proposed to help surgeons assess the perfusion of the remaining renal segments (challenges II.7, II.9).

Several concepts aim to support the surgeon in the intraoperative resection planning by visualising the intrarenal tumour margins. One approach for this is the augmented reality display of a 3D tumour model and safety margin corridors around the tumour [44,56,57]. Another approach involves projecting the endophytic tumour contours onto the kidney surface with a laparoscopic projector probe [58]. Amir-Khalili et al. [59] also display the tumour contours as seen from the laparoscope and add a visualisation to encode the uncertainty of the segmentation algorithm. These concepts mainly address challenge II.2.

To support the surgeon in maintaining negative margins during the excision, Singla et al. [60] introduce various visualisations that convey the spatial relationship between the surgical tools and the tumour (e.g., distance, direction). Simpfendörfer et al. [48] also provide a fluoroscopy-based visualisation of the tool positions in relation to the tumour (challenge II.4).

Two approaches have been proposed to confirm the oncologic completeness of the tumour excision (challenge II.10): Hoda et al. [55] use fluorescent agents to visualise remaining tumorous tissue (which also addresses challenge II.8). Doerfler et al. [61] propose placing the resection volume in a saline-filled bag and examining it with intracorporeal ex-vivo ultrasound to confirm negative resection margins.

Results of literature and information need review

The literature review yielded publications proposing various solutions for a range of surgical challenges. The results suggest a clear trend of solutions primarily supporting the challenging surgical phases of hilar and vascular management (I) and tumour excision (II). The third challenging surgical phase of repairing the renal defects (III) is currently not addressed by software assistance solutions in the literature.

Within phases I and II, some surgical challenges were identified for which currently no software assistance concepts exist. One such challenge is the intraoperative decision if the tumour can be enucleated or needs to be resected with greater margins (II.3). There are also no current solutions that help the surgeon to react to unexpected anatomies or pathologies (II.5).

Table 3 aims to identify which surgical challenges might be met by the various software assistance solutions proposed in literature. Judging by the number of publications identified, a primary focus of research seems to lie in the identification and localisation of the tumour, as well as intraoperative resection planning.

Concerning the visualised structures, most publications focus on the tumour and vasculature (with varying degrees of detail). Only four solutions incorporating general virtual 3D models of the kidney addressed the collecting system. However, during the interviews, participants reported the collecting system as a critical structure to be considered during LPN/RPN. While a preoperative planning system has been published, which supports the surgeon in protecting the collecting system [62], the review did not find any intraoperative software assistance solutions dedicated to the collecting system.

General discussion

Current gaps in software assistance for LPN/RPN

The qualitative analysis presented in this article has revealed a range of surgeon information needs in LPN/RPN. This means information, which, if provided to the surgeon, might help to

Table 3. Surgical challenges and information needs identified in the interview study and existing software assistance solutions.

Surgical Phase	Challenge	Information needs (as per Table 2)	Proposed solutions
I Hilar and vascular management	**I.1** Decision: Is clamping required and, if so, which vessels require clamping?	Information about tumour size, position, and tumour supplying vasculature.	Preoperatively created 3D models of vascular anatomy / pathology [28–32]. AR overlay of vascular anatomy / pathology [33,34].
	I.2 Hilar dissection in highly variable individual patient anatomy.	Information about ureter, major extrarenal vessels, renal vascular tree, and highlight inferior pole.	Preoperatively created 3D models of vascular anatomy / pathology [28–32]. AR overlay of vascular anatomy / pathology [33,34].
	I.3 Identify, localise, and dissect all relevant vascular branches.	Intraoperative availability of preoperative imaging data (and processed versions thereof). Highlighting of occluded vessels. Information about instrument proximity to major arteries.	Doppler ultrasound for detection of hidden vessels [35]. ICG fluorescence for detection of hidden vessels [36]. Detection of pulsating motion in laparoscopic view to detect hidden arteries [37].
	I.4 Decision: Have all relevant vascular branches been clamped?	Information about segmental perfusion. Confirmation that clamps are fully closed.	Doppler ultrasound to check for perfusion [35,38]. Sonographic contrast agent *SonoVue*™ to check for perfusion [28,39]. ICG fluorescence to monitor segmental perfusion [40,41].
II Tumour excision	**II.1** Localise and navigate to tumour.	Intraoperative availability of preoperative imaging data (and processed versions thereof). Information about tumour position.	Display of kidney, hilum, tumour, and extrarenal vessels in preoperatively created 3D models [34,42,43], AR visualisation [44–46], or intraoperatively created 3D models [47,48]. Display of intrarenal vessels in preoperatively created 3D models [34,43], AR visualisation [45,46], or intraoperatively created 3D models [47,48]. Display of collecting system in preoperatively created 3D models [34,42], AR visualisation [46], or intraoperatively [47] created 3D models. Tumour detection with ultrasound [49–51] and AR overlay of ultrasound images [52,53] or automatic tumour segmentation in ultrasound frames [54]. Highlight of tumour tissue using fluorescent agents [36,55].
	II.2 Find the ideal resection plane.	Intraoperative availability of preoperative imaging data (and processed versions thereof), endophytic parts of tumour, tumour depth, spatial relationship between tools and tumour, preoperative excision plan.	Display of intrarenal vessels in preoperatively created 3D models [34,43], AR visualisation [45,46], or intraoperatively created 3D models [47,48]. Display of collecting system in preoperatively created 3D models [34,42], AR visualisation [46], or intraoperatively [47] created 3D models. Tumour detection with ultrasound [49–51] and AR overlay of ultrasound images [52,53] or automatic tumour segmentation in ultrasound frames [54]. Highlight of tumour tissue using fluorescent agents [36,55]. Display safety margins around tumour in AR visualisation [44,56,57]. Project tumour contours onto kidney surface [58,59].
II Tumour excision (continued)	**II.3** Decision: Can the tumour be enucleated?	-	-
	II.4 Identify current resection plane and surrounding tissue.	-	Display of kidney, hilum, tumour, and extrarenal vessels in preoperatively created 3D models [34,43], AR visualisation [44–46], or intraoperatively created 3D models [47,48]. Display of intrarenal vessels in preoperatively created 3D models [34,43], AR visualisation [45,46], or intraoperatively created 3D models [47,48]. Display of collecting system in preoperatively created 3D models [34,42], AR visualisation[46], or intraoperatively [47] created 3D models. Visualisation of spatial relationship between tools and the tumour [48,60].

(*Continued*)

Table 3. (Continued)

Surgical Phase	Challenge	Information needs (as per Table 2)	Proposed solutions
	II.5 React to unexpected anatomy or pathology.	-	-
	II.6 Identify, localise and protect risk structures (vessels, collecting systems).	Information about or highlighting of parenchyma, major tumour-supplying vessels, collecting system. Intraoperative availability of preoperative imaging data. Highlighting of major occluded vessels.	Display of intrarenal vessels in preoperatively created 3D models [34,43], AR visualisation [45,46], or intraoperatively created 3D models [47,48]. Display of collecting system in preoperatively [34,42] or intraoperatively [47] created 3D models.
	II.7 Preserve perfusion to the remaining renal tissue	Information about segmental perfusion.	ICG fluorescence for confirmation of perfusion of remaining renal segments [36].
	II.8 Detect and manage lesions to risk structures (vessels, collecting system).	Information about lesions of the collecting system. Information about tumour tissue in the resection plane.	Visualisation of tumour tissue with fluorescent agent [55].
	II.9 Decision: Is retroactive clamping required?	Information about segmental perfusion.	ICG fluorescence for confirmation of perfusion of remaining renal segments [36].
	II.10 Decision: Was the resection oncologically successful?	Information about tissue type in resection bed.	Visualisation of remaining tumour tissue with fluorescent agent [55]. Intracorporeal, ex-vivo ultrasonographic tumour examination [61].

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make LPN/RPN safer, more effective or efficient, or reduce workload for the surgeon. The surgical challenges that we identified mainly fall into three surgical phases, which include hilar and vascular management, tumour resection, and repair of the occurring renal defects. The literature on software assistance for LPN/RPN that we could identify mainly introduced systems that aim to support the surgeon throughout the first two challenging phases. A main focus of these systems seems to lie in displaying the tumour and supporting the surgeon in its resection.

Our research reveals two significant gaps in the current publication landscape, which may be fruitful fields of future research. First, our review found no software assistants that aim to support the surgeon in repairing the renal defects after the tumour has been removed. However, such systems may be valuable in addressing some of the surgical challenges our study has revealed in that phase. This may be due to limitations in the applicability and registration of preoperative imaging data.

Many solutions rely on preoperative imaging data of the kidney. One of the significant challenges in the use of preoperative imaging data lies in the registration of the preoperative imaging data and the intraoperative laparoscopic view [1]. Registration is the process of correctly aligning the virtual data that is provided for the surgeon's support with the surgical, i.e., the laparoscopic view. This registration may become more challenging because the kidney is subject to deformation due to patient positioning [63], peritoneal pressure [64], loss of turgidity (in procedures which employ arterial clamping), and tissue incisions [65]. Further research is required to investigate if and how preoperative information and the registration process can be adapted to account for these changes. E.g., it may be useful to examine how the deeper renal structures deform due to the removal of resection volumes as they occur in partial nephrectomy. If this causes the risk structures underneath the resection bed to significantly move and/or deform, this may limit the value of preoperative imaging data for supporting the surgeon in the repair of the resection bed. One potential solution to this might be the use of intraoperative imaging data. Multiple software assistants for LPN/RPN rely on intraoperative imaging modalities. However, the repair of the lower resection bed happens either under ischemia (if clamping is applied) or is associated with some level of blood loss (if clamping is not applied). Therefore, this phase of the operation is conducted under significant time pressure, which may limit the applicability of intraoperative imaging techniques. Future work could investigate if intraoperative imaging data can be acquired and processed sufficiently fast to allow for effective assistance in the repair of the resection bed.

The second gap that our review identified concerns the selection of displayed anatomical structures. Namely, a potential opportunity for further research lies in putting more focus on the collecting system. While many interview partners mentioned it as a critical anatomical risk structure throughout tumour resection and resection site repair, little focus has been put on this structure in the existing software assistance literature. Lesions of the collecting system may occur during the excision of deep tumours. When the resection instrument reaches the collecting system's proximity, the kidney has already been significantly manipulated by the surgical procedure. Hence, providing intraoperative information on the collecting system is affected by similar registration challenges as described above. Another challenge may lie in the sufficiently accurate and granular segmentation of preoperative or intraoperative imaging data. Hughes-Hallet et al. [66] show that even with structures as big as the tumour, segmentation errors can be significant. The smaller structures of the collecting system may, therefore, be subject to even more significant inaccuracies in image data segmentation. Addressing these technical challenges may help future systems to effectively support surgeons to detect and repair, or even prevent lesions of the collecting system.

Research method and its applicability to other procedures

We used an interview-based CTA method to detect surgeons' information needs during LPN/RPN. This method identified a range of information needs that have not been previously reported. It was therefore successful in the objectives it was intended to address. We believe that it is transferable to investigating other complex surgical procedures. However, our approach has limitations and some adaptations may be useful or required when applied to other procedures.

One such aspect is how the initial workflow description was developed. Ample literature is available for LPN/RPN, which was sufficient to generate the HTA reported in this article. If this is not available, other data may be necessary or more efficient to generate a valid workflow description. For example, in some procedures, observational techniques or structured interviews may be more effective or efficient methods to document the surgical workflow. It may also be sufficient to base the workflow definition on a smaller number of clinical publications if the procedure at hand has a smaller range of surgical strategies across the surgical community or if only one such strategy is of interest. Namely, the second and third inclusion criteria (i.e., coverage of laparoscopic and robotic approaches as well as coverage of different clamping strategies) are specific to LPN/RPN and may be omitted or modified for other surgical procedures. In some tasks, it may be useful to further detail and formalise the task analysis (e.g., by formalising *plans*).

Another aspect, which may affect the applicability of this approach, is the complexity of the task under investigation. Depending on the task complexity, further limitation of the interview scope may be required. This may lead to greater sample size requirements, which, at some point, may make applying the approach impractical. In those cases, the first part of our approach (i.e., applying task analysis and identifying critical steps via a questionnaire) may help to identify critical task phases, which can then be investigated in detail. On the other hand, if the approach is applied to a simpler surgical procedure or shorter parts of a procedure, this selection process may not be required at all. Another potential research focus might lie in intraoperative complications and supporting the surgeon in addressing those. This was not within the scope of this work and may require an adaptation of the technique that is used to identify workflow parts and scenarios to take into focus in the CTA interviews.

Specifically, the LPN/RPN procedure's complexity may have affected our work in two ways. First, discussion with our participants was limited to a few surgical steps per interviewee. Second, due to the limited population of surgeons who are experienced with this procedure, the number of recruited interviewees was also limited. This means that, in our study, five participants were interviewed about at least one step in surgical phase I, seven were interviewed about at least one step in phase II, and five were interviewed about at least one step in phase III. It is possible that including more surgeons in the study would have revealed additional surgical challenges and, thus, information needs. It is difficult to define a minimum number of participants for this type of study. One may argue that the duplication of interview replies may be an indicator of completeness of the results. That is, when all data points have been reported by multiple participants, this may indicate that nearly all relevant and obtainable data have been recorded. Following this criterion, additional interviewees might have broadened our results because only one participant each reported a range of the challenges and information needs reported in this article. However, in our study, the availability of experienced surgeons constituted a limiting factor.

Our research focused on LPN and RPN as the currently widely applied approaches for minimally invasive partial nephrectomy. A promising approach for minimally invasive radical nephrectomy is transvaginal natural orifice transluminal endoscopic surgery (NOTES) [67,68]. If the transvaginal NOTES approach is applied in partial nephrectomy in future clinical research, additional work will be required to determine if the workflow and information needs we identified extend to this new approach.

We conducted a literature review to answer the second research question we outlined, i.e., how current solutions cover the identified information needs. This step may be omitted if this research question is less relevant to other projects.

Finally, it should be noted that the surgical workflow, strategies and cues are not based on or reflect the opinion or recommendation of the authors. They merely reflect the data obtained with the methods reported in this article.

Conclusion

In this article, we have presented an approach to investigate surgeons' information needs during surgery to inform the future development of intraoperative software assistants. The approach involves understanding the surgical workflow at hand, identifying challenging and/or risky phases within this workflow, and understanding in depth the challenges that occur, as well as the strategies and cues that surgeons apply to address them.

For the surgical procedure under investigation (LPN/RPN), this approach yielded useful results to further develop the field of intraoperative software assistance. We identified three surgical phases during which software assistance may be particularly useful. Moreover, our results indicate what information may be useful in each surgical phase. Our literature review showed that previously published software assistance concepts primarily focus on the first two surgical phases, i.e., hilar and vascular management (phase I) and tumour resection and the planning thereof (phase II). To our knowledge, the third phase, repair of the resection site, has not been addressed in previous software assistants. Another finding was that it may be beneficial to take the renal collecting system more into focus when designing software assistants for LPN/RPN. Although there are some technical challenges to overcome, our results suggest that addressing these needs may be a worthwhile effort as it may help provide relevant information and thereby support surgeons in the safe and effective execution of LPN/RPN.

Future work is required to generate similar data for other procedures, which may lead to the detection of information needs that occur across multiple procedures. Further work may also be required to solve the technical challenges that need to be overcome to address the information needs that have been presented in this article and that have not been addressed in the relevant literature. Our work presents a crucial basis for this technical work and the development of effective future systems, as it documents the user-centred requirements against which these future systems can be developed.

Supporting information

S1 Table. Full interview results.
(DOCX)

S2 Table. PRISMA checklist. Overview of Preferred Reporting Items for Systematic Reviews and Meta-Analyses.
(DOC)

S1 Fig. PRISMA flow diagram. Overview of the literature screening and selection process.
(EPS)

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