Systematic review

A Survey of Augmented Reality Methods to guide Minimally Invasive Partial Nephrectomy

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Abstract:

Introduction. Minimally invasive partial nephrectomy (MIPN) has become the standard of care for localized kidney tumors over the past decade. The characteristics of each tumor, in particular its size and relationship with the excretory tract and vessels, allow one to judge its complexity and to attempt predicting the risk of complications. The recent development of virtual 3D model reconstruction and computer vision have opened the way to image-guided surgery and augmented reality (AR). **Objective.** Our objective was to perform a systematic review in order to list and describe the different AR techniques proposed to support PN. **Materials and Methods.** The systematic review of the literature was performed on 12/04/22, using the keywords "nephrectomy" and "augmented reality" on Embase and Medline. Articles were considered if they reported surgical outcomes when using AR with virtual image overlay on real vision, during ex vivo or in vivo MIPN. We classified them according to the registration technique they use. **Results.** We found 16 articles describing an AR technique during MIPN procedures that met the eligibility criteria. A moderate to high risk of bias was recorded for all the studies. We classified registration methods into three main families, of which the most promising one seems to be surface-based registration. **Conclusion.** Despite promising results, there do not exist studies showing an improvement in clinical outcomes using AR. The ideal AR technique is probably yet to be established, as several designs are still being actively explored. More clinical data will be required to establish the potential contribution of this technology to MIPN.

Keywords: Augmented Reality; Partial Nephrectomy; Minimally Invasive Surgery; Image-Guided Surgery.

1. Introduction

Partial nephrectomy (PN) is the standard treatment for the majority of localized kidney tumors [1]. It is nowadays performed by the laparoscopic or robotic approach in the vast majority of cases [2]. Compared to the open approach, Robot-Assisted Partial Nephrectomy (RAPN) has been shown to provide a surgical procedure with less bleeding, fewer postoperative complications, shorter hospital stays, similar preservation of renal function, and similar oncologic safety [3]. However, RAPN is still associated with some morbidity, with a risk of serious complications up to 11.9% for the most complex group of tumors [4].

The "trifecta" is commonly accepted as an indicator of successful PN. It corresponds to the absence of oncological positive margins, a duration of warm ischemia <20min, and the absence of significant postoperative complication [5]. A learning curve study showed that there was an improvement in warm ischemia time up to 150 procedures and up to 300 procedures in complication rate reduction [6]. Over the years, several surgical aids were developed and are currently used to improve surgical outcomes and decrease morbidity.

The rigorous analysis of preoperative CT imaging allows the surgeon to elaborate a virtual representation of the kidney, the tumors, the vascular elements and the urinary tree, in order to plan the operative strategy. For the most complex tumors, some teams use Image-Guided RAPN (IGRAPN) based on virtual 3D model reconstruction from imaging segmentation [7], [8], which concretizes the kidney representation. The 3D model is used to plan the surgery and to guide the precision steps of the surgical procedure, in particular vascular sparing techniques [7]. IGRAPN may improve the surgical outcomes [8].

For endophytic tumors, intraoperative ultrasound (IUS) has been shown to decrease intraoperative bleeding, reduce the duration of ischemia and improve the preservation of the renal function [9]. It represents the gold standard for the intraoperative localization of endophytic tumors in order to ensure healthy oncologic margins and to anticipate a possible vascular or excretory tract injury during resection [10]. However, the ultrasound image is only two-dimensional, the examination is operator-dependent and requires an interruption of the surgical procedure [9].

Augmented reality (AR) merges elements taken from the virtual 3D model with the surgeon's real vision on the laparoscopy screen or the 3D vision in robot-assisted laparoscopy [11]. This technology creates an impression of virtual transparency of the organ, allowing to see the subsurface structures. The implementation of AR primarily relies on a process called registration, which computes the transformation that exists between the virtual 3D model and the real operating field [11]. A further step called tracking locates the organ in the intraoperative images automatically [12]. Registration is the key step; it is highly challenging, especially for mobile and deformable organs, and owing to phenomena such as bleeding and smoke which create artefacts [13].

Over the past fifteen years, several studies have described and evaluated different AR techniques applied to Mini-Invasive Partial Nephrectomy (MIPN), which is formed of Laparoscopic Partial Nephrectomy (LPN) and RAPN, performed in preclinical and clinical settings. The main imaging technique used for virtual 3D model reconstruction is the injected CT scan [14]. We classified the registration techniques into three groups: manual registration, fiducial-based registration and surface-based registration. The growing importance of AR in the field of surgery [15] motivates our main objective, which is to achieve a systematic and exhaustive review of the different techniques of surgical assistance by AR used during MIPN procedures. Our secondary objective is to describe in depth the different approaches to registration and to bring a clear classification of the different AR techniques based on the registration approach they use.

2. Materials and Methods

2.1 Search Strategy

A systematic review of the literature was performed using the Medline and Embase databases. Search terms "nephrectomy" and "augmented reality" were used on 12-apr-22. Two reviewers (A.K. and G.M.) read the abstracts to identify those dealing with AR surgical assistance. Disagreements about eligibility were resolved by a third reviewer (J-C.B.) to reach a consensus. The flow chart summarizing the methodology is shown in Figure 1. The search strategy was completed and using linked articles from PubMed.

2.2 Eligibility Criteria

Titles and abstracts were reviewed to select full-text articles which describe the use of an AR surgical assistance system during MIPN and report surgical outcomes, either on ex vivo or in vivo procedures. The search strategy was conducted following the Patient – Intervention – Comparison – Outcome [16] criteria: patients with kidney cancer or ex vivo kidney models (P) underwent AR-guided MIPN (I) compared or not to MIPN without AR (C) to evaluate benefit on surgical outcomes (O). The articles were screened according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [17]. We excluded postprocedural articles reporting work on surgical videos, as well as articles reporting registration tests on phantom kidneys without surgical outcomes.

2.3 Bias Assessment

The risk of bias and the quality of each included in vivo study were independently assessed using the standard Cochrane Collaboration risk of bias tool for single-arm studies [16] and the Risk Of Bias In Non-randomised Studies of Interventions Tool (ROBINS-I) for comparative studies [18].

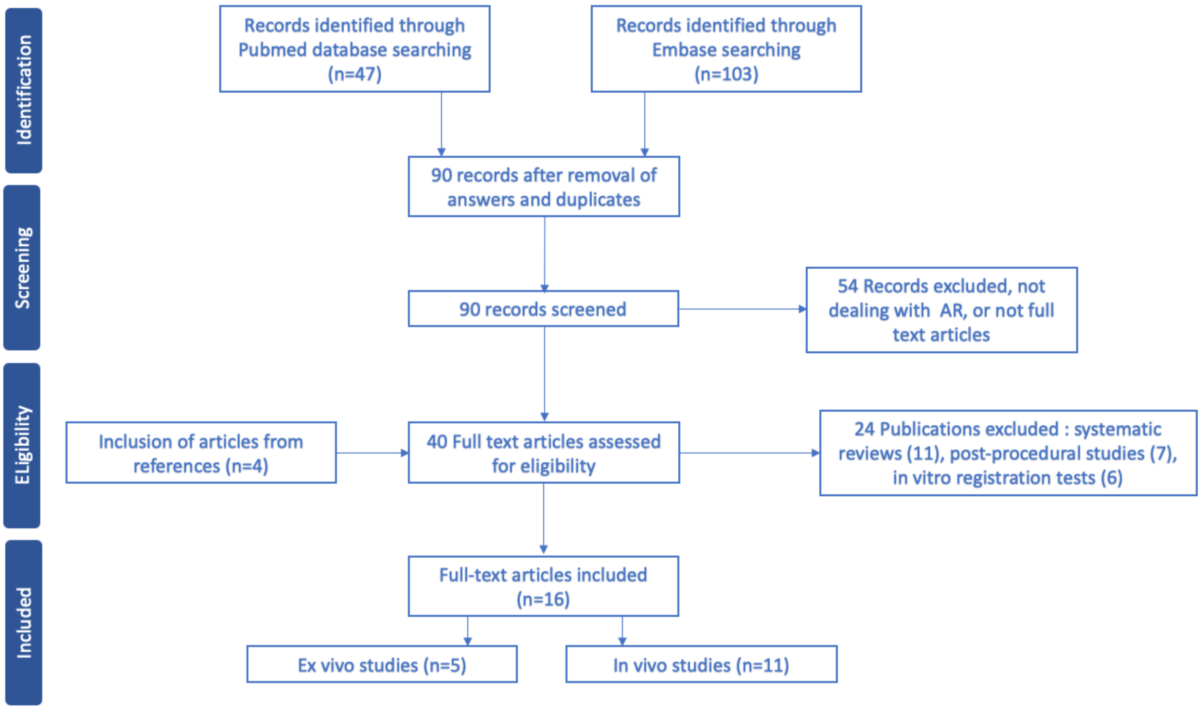

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses diagram. Literature search was performed in PubMed and Embase using “nephrectomy” and “augmented reality” keywords.

3. Evidence Synthesis

After deleting duplicates and redundant articles, the search strategy found 90 publications. The screening allowed us to select 40 full-text articles dealing with AR applied to MIPN that were reviewed. Finally, 16 articles met the eligibility criteria and were included and described in the main analysis. The characteristics and main results of the included studies are reported in Table 1.

Table 1. Results presented by the main studies that have tested AR during procedures on phantom kidneys, pig kidneys, or in clinical trials.

Year, first author	Procedure type	Registration type	Instrument tracking	n =	Main results
Case-control studies on phantom or animal kidney					
2009, Herrell [19]	Phantom RAPN	Surface-based	Yes	6 vs 7	Better resection ratio and shorter procedure
2010, Cheung [20]	Phantom LPN	IUS-based	No	6 vs 6 vs 6	Feasibility and improvement in resection planning times

2017, Chauvet [21]	Pig kidney LPN	Surface-based	No	29 vs 33	More accuracy in tumor resection
2017, Singla [22]	Phantom RAPN	IUS-based	Yes	9 vs 9	Reduced healthy tissue excised
2018, Edgcumbe [23]	Phantom RAPN	IUS-based	Yes	16 vs 16	Reduced healthy tissue excised and trend to less positive surgical margins
			In vivo single-arm studies		
2008, Ukimura [24]	LPN	Manual	Yes	1	Demonstration of feasibility
2009, Teber [25]	LPN	Manual	No	10	No complications, no positive margins and good feedback from operative surgeon
2010, Nakamura [26]	LPN	Manual	No	2	Demonstration of feasibility
2014, Chen [27]	LPN	Manual	No	15	Good surgical outcomes, successful setting in all cases adding 6 min (5-7)
2016, Simpfendorfer [28]	LPN	Fiducial-based with Mobile C-arm CBCT	Yes	10	Good surgical outcomes, 15.5 min of prolongation of intervention
2020, Schiavina [29]	RAPN	Manual	No	15	More adoption of selective or superselective clamping
2022, Amparore [30]	RAPN	Indocyanine green surface-based	No	10	Succesful automatic tracking, negative margins and no complications
2022, Amparore [31]	RAPN (imperative indication)	Manual	No	3	No complications, negative margins and good renal function preservation
2022, Piramide [32]	RAPN	Manual	No	65	High rate of enucleation and selective clamping, low rate of positive margins (2,5%) and significant complications (1,5%)
			In vivo case-control study		
2018, Porpiglia [7]	RAPN (High-complexity tumors)	Manual	No	21 vs 31	Lower global ischemia rate and higher planned pedicle management
2020, Porpiglia [33]	RAPN (High-complexity tumors)	Manual	No	48 vs 43	Lower global ischemia rate, higher enucleation rate, lower rate of collecting system violation

4. Risk of bias assessment

A moderate to high risk of bias was recorded in all in vivo studies according to Cochrane Collaboration risk-of-bias tool for single-arm studies and the ROBINS-I tool for case control studies (supplementary Figures 2 and 3).

5. AR Based on a Preoperative CT-Scan

The first step of surgical guidance by AR is the reconstruction of the virtual 3D model, which is performed by imagery segmentation software applied to the preoperative CT-scan [34]. The second step is the registration, which computes the transformation between the virtual 3D model and the intraoperative images [35]. This step requires one to collect images of the surgical field and possibly additional information depending on the method. We review the principles of registration and existing methods.

5.1. Registration Principles

Registration of the virtual 3D model on the real images during surgery is a crucial step. Here, registration means that the virtual 3D model is virtually moved and possibly deformed in the 3D space, to fit the organ shape as observed in the real intraoperative images. Registration is critical because its accuracy will condition the reliability of further AR guidance of the surgeon gesture. The implementation and accuracy of registration are variable across the different AR techniques [35].

There are at least three main surgical stages at which AR is relevant. First, to facilitate the localization and dissection of the main anatomical structures, especially vascular [7]. Second, for the precise localization of the deep tumor limits to ensure a complete resection with negative oncologic margins [36]. Third, for the reconstruction of the tumor bed, to preserve the opening of the urinary tract that may be responsible for postoperative urinoma [37]. It is during the localization of tumor limits that the accuracy of the registration is the most important in order to allow a complete resection of the tumor as well as an optimal preservation of the healthy parenchyma [36]. We classified registration approaches found in the literature in three groups as shown in Figure 2.

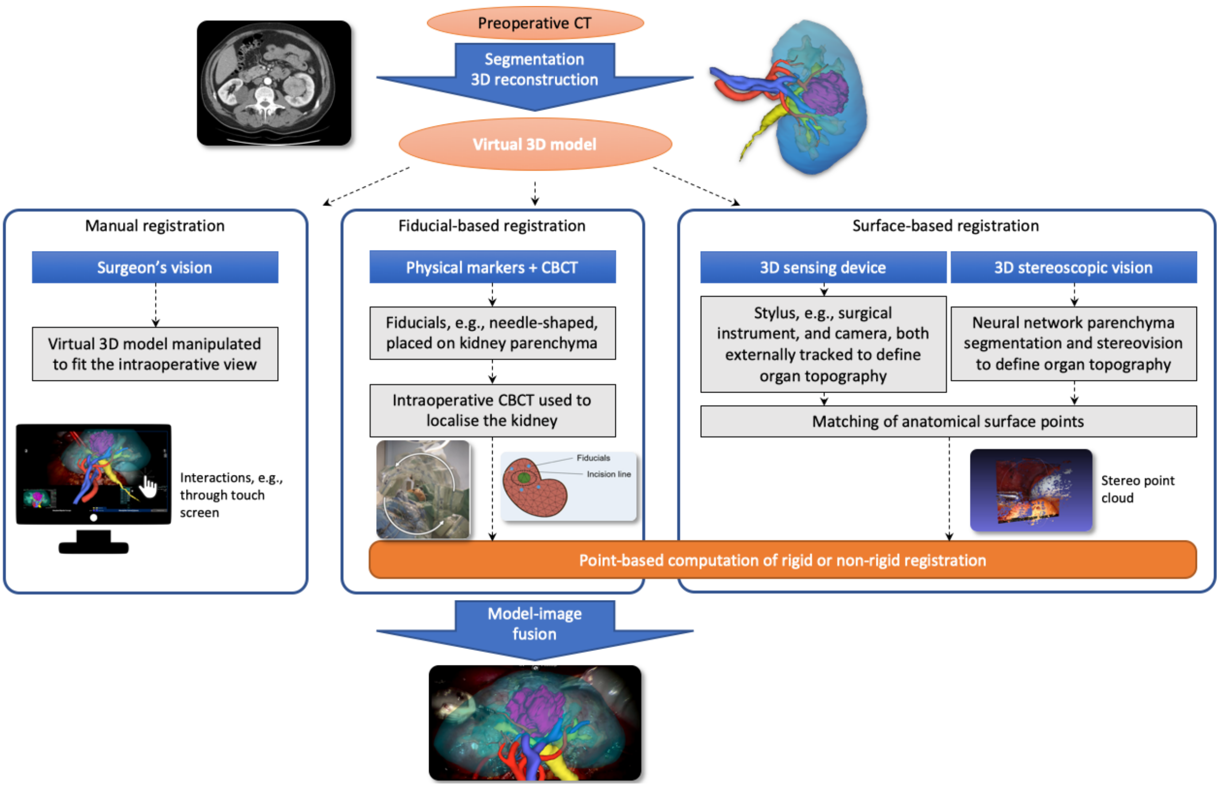

Figure 2. Flowchart of the main registration techniques allowing surgical assistance by AR during MIPN (3D: 3 dimensions, AR: augmented reality, MIPN: mini invasive partial nephrectomy).

5.2. Manual Registration

The simplest type of registration is manual registration by the surgeon, using their own experience, knowledge of anatomy, and the human brain's ability to align two objects in space. This technique facilitates intraoperative guidance by providing an "anatomical map" superimposed on the surgical field that can be mobilized by the surgeon during the different stages of surgery but has important limitations. The surgeon must indeed mobilize the virtual 3D model at each camera movement and the mobility and deformation of the organ and adjacent anatomical structures make the registration imprecise and may even be a source of larger errors.

Once the technical feasibility was shown [24]–[26], several studies reported large series with interesting surgical outcomes [27], [29], [31]. They showed an increasing adoption of selective clamping and enucleation, which may allow one to better preserve the renal function [38], [39]. The largest series, including 65 patients, revealed a high rate of selective clamping (58.4%) and pure enucleation (63.1%) and a low rate of positive margins (2.5%) and significant complications (1.5%) [32].

Porpiglia et al. [7], [33] published two case-control studies of AR-guided RAPN, using manual registration and including patients with high-complexity renal tumors. The latest study compared 48 patients in the AR group and 43 patients in an IUS group [33]. They showed a significant reduction in the total arterial clamping rate, a reduction in the urinary tract opening rate, and a similar complication rate. Assessment of renal function showed less eGFR degradation at 3 months in the AR group, but not significantly (-14.26% vs. -19.46%, p = 0.11).

These results are encouraging for the use of AR to guide RAPN, simply by manually superimposing the virtual 3D model on the surgeon's real vision. The obvious disadvantages of manual registration suggest that the use of more sophisticated registration techniques could further increase accuracy and improve usability, thus assisting the surgeon more finely and with fewer procedure disruptions.

5.3. Fiducial-based Registration

The use of fiducials to track the renal parenchyma is a solution that appears to be accurate. Nevertheless, it requires intraoperative imaging CBCT (cone-beam computed tomography) to allow registration, which is thus not performed in real-time.

Fiducial-based registration with CBCT was described first during 10 LPN on ex vivo porcine kidneys [25], [40] requiring the implantation of 5 fiducials. This first in vivo series concerned 10 AR-guided nephrectomies combining fiducial-based registration and inside-out tracking, reporting satisfactory surgical outcomes and a median procedure time extension of 15.5 min [28].

5.4. Surface-based Registration

AR by surface-based registration appears to be the most convenient technique to guide surgery because it may be implemented with limited surgeon interactions required during setup and does not require the use of artificial fiducial markers. This implies the use of computer vision algorithms capable of reconstructing the intraoperative 3D organ, from which the registration is then solved. There exist two main approaches for intraoperative 3D reconstruction : instrument-based probing and stereovision.

5.4.1. Use of Instrument Tracking

The use of optical tracking to track robotic instruments has been described in many ex vivo phantom studies [19], [41], [42], allowing the use of an instrument as a stylus to map the renal surface and define its topography. The surgeon must probe the organ surface with the instrument in dozens of points, whose 3D positions are then computed by the system. The instrument thus acts as a sensing stylus, which provides precise 3D measurements [19], [41], [42]. The surface anatomy is eventually registered with the surface of the virtual 3D model. The main weakness of this registration technique is the requirement for the procedure-disrupting organ-probing step.

5.4.2. Surface Recognition and Reconstruction by Stereovision

The use of stereovision to map the intraoperative organ shape works in two steps. First, it localizes the intraoperative renal surface in the images. Second, it triangulates its position in 3D with stereovision. The first step may be performed by a deep neural network [43]. This stems from the recent development of deep learning, which has dramatically improved the performance of image segmentation methods [44]. The second step of 3D triangulation is performed by stereovision. The use of stereovision in this context was first described in a study on collected 3D surgical videos [45]. This technique uses the disparity between the two eyes of the 3D camera to triangulate the location of each point of the organ surface in the surgical field [46], [47]. It however present several obstacles in MIPN, pertaining to the variability of the inter-patient renal shape, the presence of peri-renal fat, bleeding and smoke.

A first in vivo study described a combined manual and stereoscopic vision-based registration technique during RAPN [48]. A single point on the renal surface was taken as a fiducial by the camera and allowed the registration of the 3D model. This point was used as the center of rotation around which the 3D model can be moved manually to fully conform to the surgeon's vision. Nevertheless, as ideal as it sounds in terms of usability, this system, for it relies on automatic computations, may fail owing to the variability of the surgical scenarios. These failures are progressively overcome thanks to the dramatic improvements in the theory and implementations of deep learning over the last decade [49].

5.4.3. Improvement of Surface Recognition Algorithms

A recent AR technique applied to surgery is based on automatic recognition and tracking of the organ surface [50]. This was first developed for uterine surgery, which is less difficult than renal surgery because the uterine surface is smooth and not covered by fatty tissue. This is made possible by the progressive constitution of a database of segmented surgical images, allowing the deep neural network being involved to reach an admissible performance [43]. This technique goes schematically through three steps: first, the preoperative imaging is used for the reconstruction of a virtual 3D model. During surgery, the automatic segmentation of the endoscopic image is based on the recognition of the image areas where the organ surface is visible [50]. Using multiple images, the organ surface is then reconstructed in 3D, similarly to the stereovision technique [47]. The deep neural network also detects the organ contours, which are used to improve registration accuracy. Finally, the organ is tracked in realtime, to realize full frame-rate AR, allowing the surgeon to see, for example, the tumor limits in depth [21]. This technique represents an improvement of the stereoscopic 3D technique, which uses deep learning to allow the recognition of the organ surface and its contours. This improves the usability of intraoperative registration and its accuracy [51].

The results during resections on experimental uterus models were more than 20 times more accurate in the AR group [52]. A similar experimental study in a kidney tumor model reported less failed resections in the AR group (13.8% vs 30.3%) [21]. The augmentation of endoscopic intraoperative views seems to be efficient in improving the accuracy of resection of endophytic tumors and preliminary trials on surgical videos have shown promising results [12], [53].

Zhang et al. worked on adapting the coherent point drift (CPD) algorithm to surface-based registration [46], [54]. It is an algorithm for the accurate prediction of volume deformation using a non-rigid point set on the surface of the volume, which has been optimized to allow the accurate registration of the virtual 3D model to the renal surface. They showed convincing results in experiments on phantom kidneys and when applied to LPN videos. A real-time motion tracking technique based on deep learning was also described with encouraging results [44].

An innovative AR technique based on renal surface tracking after intravenous injection of indocyanine green allowed automatically anchoring the virtual 3D model with the endoscopic view of the real organ. Registration was successful with a mean anchorage time of 7s. Satisfying surgical outcomes were reported on ten RAPN [30].

The recent development of computer vision technology and artificial intelligence has paved the way to these innovative techniques with recent encouraging results. However, there is a lack of in vivo data in the literature to date.

6. AR Based on Intraoperative Ultrasound

Some publications described AR surgical assistance systems using 3D reconstruction from IUS [20], [22], [23]. This AR technique uses 2D IUS to locate the tumor and reconstructs it in 3D, allowing its projection in the endoscopic image to guide the procedure. Edgcumbe et al. tested on phantom kidneys an AR surgical assistance system combining IUS, instrument tracking and the use of a projector to project tumor limits. The use of the system showed a significant reduction in the amount of healthy tissue excised, by 30% [23].

However, these techniques are used only for the localization of tumor limits and the reconstructed image includes less information than the virtual 3D model reconstructed from the preoperative CT-scan, especially on the vascular aspect.

7. Discussion

Although there is a rich body of literature regarding the design of AR approaches to guide RAPN, the number of clinical studies is still very low. After several single-arm publications describing the feasibility of AR with manual registration [27], [29], two articles have reported surgical outcomes using this technique in retrospective comparative studies [7], [33]. Lower global ischemia rate and higher enucleation were reported without showing any objective clinical improvement. The other comparative studies concerned ex vivo procedures on silicone kidneys or pig kidneys, and concerned IUS-based and surface-based registration ([19], [21]–[23]. Given the increasing amount of data, it seems important to summarize the published concrete results, which we have achieved in this systematic review. In addition, we have tried to provide a clear classification of the different AR techniques described in the literature according to the registration approach.

AR by manual registration is an improvement of image-guided surgery also using a virtual 3D model, allowing one to integrate this model into the operating field and to guide more precisely the surgical gesture [7]. This is the least advanced technique but the only one evaluated in vivo in case-control studies [7], [33]. Fiducial-based AR makes it necessary to implant trustees in renal parenchyma and to use intraoperative CBCT. One single-arm in vivo study on LPN procedures was in 2016 but the technique has not been explored further [28]. In addition, the use of CBCT with the Da Vinci surgical robot seems difficult to envisage.

Surface-based registration is made possible by the use of a stereoscopic camera, and more recently the progress of computer vision and deep-learning [43]. It aims to recognize and localize the renal surface and attempts to reconstruct an intraoperative 3D model that can be registered with the preoperative 3D model to augment the intraoperative view. It should allow the best possible registration because of taking into account the spatial position of the renal surface and parenchyma deformation [54]. However, it is currently imperfect despite the different techniques used to overcome the various challenges and will require further combined technical and clinical research. Published studies report good ex vivo comparative results with a better accuracy in tumor resection with expected better parenchymal preservation [21]. Also, the most recent studies testing this technique on recorded surgical videos showed a good consideration of renal parenchyma deformation [44], [54]. Future in vivo studies may confirm this trend.

The main limitations of this review is the important bias of the different studies evaluated and the fact that most of them are pilot-studies. The absence of RCTs and the small number of case-control trials on the subject reflect a limited level of evidence. Although case-control studies have shown an improvement in the rate of enucleation, the rate of selective clamping, and the rate of opening of the urinary tree, these results are not necessarily related to a reduction in the rate of postoperative complications or preservation of renal function, which are objective criteria of surgical procedure improvement. Even if it is difficult to doubt the helpful contribution of AR to surgery, showing the improvement of surgical outcomes will require well conducted RCTs.

8. Conclusion

Considering the promising results of comparative in vivo studies performed with simple manual registration, it is conceivable that a tested and developed automatic registration could guide the surgeon during LPN or RAPN and improve clinical outcomes. The AR technique with automatic registration that seems the most advanced and promising is the one involving surface recognition and intraoperative 3D reconstruction, taking into account the deformation of organs and tissues. Much progress remains to be made, and more studies on in vivo procedures are awaited with more convincing results. However, given the recent tremendous progress of computer vision techniques, AR surgical assistance should logically represent the future of image-guided minimally invasive PN.

Author Contributions:

A Khaddad: Project development, Methodology, Data collection, Data analysis, Manuscript writing

JC Bernhard: Project development, Methodology, Manuscript editing, Supervision

G Margue : Methodology, Data collection, Data analysis.

C Michiels: Project development

S Ricard: Project development

K Chandelon: Project development, Data analysis

F Bladou : Manuscript editing

N Bourdel: Project development, Methodology, Supervision

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All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: No acknowledgements.

Conflicts of Interest: Nicolas Bourdel is the CEO of the SurgAR company.

Kilian Chandelon is an R&D engineer at the SurgAR company.

Adrien Bartoli is the CSO of the SurgAR company.

Informed Consent Statement: Not applicable.

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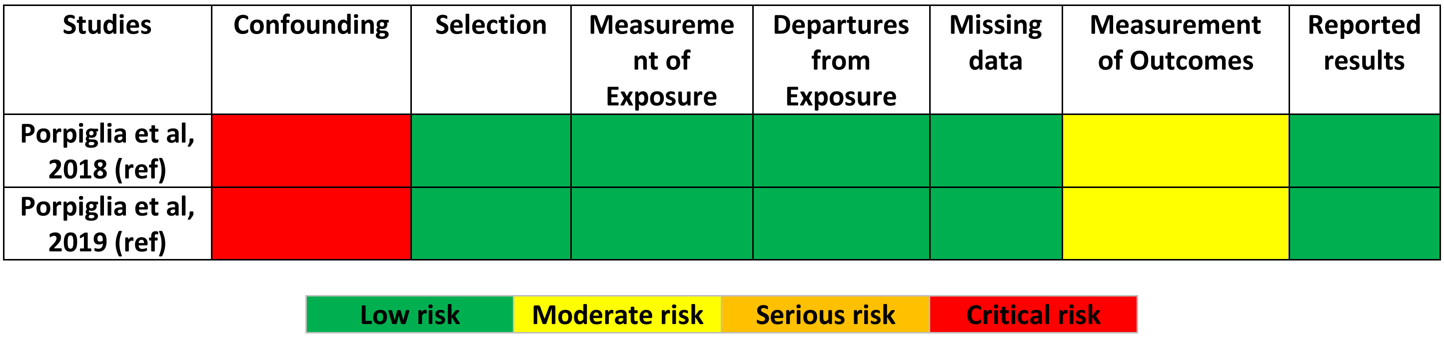

Supplementary figure 1. Risk of bias assessment of in vivo case-control studies according to Risk of Bias in Non-Randomized Studies – of Interventions tool for comparative studies.

Supplementary figure 2. Risk of bias assessment according to the Cochrane Collaboration risk-of-bias tool for in vivo single-arm studies.