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Real-time Augmented Reality 3D-guided Robotic Radical Prostatectomy: preliminary experience and evaluation of the impact on surgical planning

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ABSTRACT

Background: Augmented Reality (AR) is a novel technology adopted in prostatic surgery.

Objective: to evaluate the impact on surgical planning of 3D model with AR (AR-3D model) to guide nerve sparing (NS) during robot-assisted radical prostatectomy (RARP)

Design, Setting, and Participants: Twenty-six consecutive patients with diagnosis of prostate cancer (PCa) and multiparametric resonance imaging (mpMRI) available were scheduled for AR-3D NS RARP.

Intervention: Segmentation of mpMRI and creation of 3D virtual models were achieved. To develop the AR guidance, the surgical DaVinci video stream was sent to an AR-dedicated personal computer and the 3D virtual model was superimposed and manipulated in real-time on the robotic console.

Outcome Measurements and Statistical Analysis: The concordance of localization of the index lesion between the 3D model and the pathologic specimen was evaluated using a prostate map of 32 specific areas. A preliminary surgical plan to determinate the extent of NS approach was recorded basing on mpMRI. The final surgical plan was re-assessed during surgery by implementation of the AR-3D model guidance.

Results and limitations: PSMs rate were 15.4% in the overall patients' population; 3 patients (11.5%) had PSMs at level of the index lesion. AR-3D technology changed the NS surgical plan in 38.5% of men on patient-based and in 34.6% of sides on side-based analysis, resulting an overall appropriateness of 94.4%. The 3D model revealed 70%, 100% and 92% of sensitivity, specificity and accuracy at 32-areas map analysis.

Conclusion: AR-3D guided surgery is useful to improve the real-time identification of the index lesion and allows to change the NS approach in approximately one out three cases, with overall appropriateness of 94.4%.

Patient Summary: AR-3D guided RARP allows to identify the index PCa during surgery, to tailor the surgical dissection to the index lesion and to change the extent of NS dissection.

Introduction

Major technological innovations applied to robotic surgery have set the "precision medicine" as a novel standard tailored to each patient for the surgical treatment of prostate cancer (PCa)[1]. The ideal nerve sparing (NS) approach during robotic radical prostatectomy (RARP) should obtain the optimal compromise between the preservation of neurovascular bundles (NVBs) and the higher risk of positive surgical margins (PSMs)[2]. As consequence, different surgical techniques were introduced to reduce PSMs[3] and several methods have been proposed for "real-time" evaluation of surgical margins[4].

Moreover, multi-parametric Magnetic Resonance Imaging (mpMRI) may modify the NVB dissection in one out of three individuals[5,6,7] with overall appropriateness of 75%[2]. Recently, some authors reported that 3D models elaborated from 2D conventional imaging can be used as additional tools to guide surgery[8,9,10,11,12]. Similarly, Augmented Reality (AR) technology is increasingly adopted in the surgical field[13] and it has been introduced also in prostatic surgery[9,14]. Of note, AR technology could increase the understanding of surgical anatomy and facilitate intraoperative navigation during RARP.

Thus, we aimed to evaluate the impact on surgical planning of AR-3D model to guide surgical dissection during NS RARP for real-time assessment of surgical anatomy and to test the concordance of the reconstructed anatomical 3D models with the final pathologic evaluations.

Materials and methods

Study design and participants

We prospectively enrolled 26 consecutive patients with diagnosis of PCa basing on positive MRI-targeted Fusion biopsy at the index lesion[15] with systematic prostate biopsy and preoperative preserved erectile function (International Index of Erectile Function-5 [IIEF-5] questionnaire >21[16]) scheduled for RARP at our institution between April 2019 and September 2019. Participants signed a written informed consent document. The study was conducted after Institutional Ethics Committee (IRB approval 4325/2017). Exclusion criteria were contraindications for RARP, undetectable index lesion at preoperative mpMRI or mpMRI not available. Prior to intervention, patients were addressed to undergo 3D virtual model reconstruction based on preoperative mpMRI images. Finally, the surgeon performed RARP with the help of the 3D model projected in AR inside the robotic console (AR-3D guided RARP).

Preoperative imaging

All the mpMRI examinations were performed with a 1.5-T whole body scanner (Signa HDxt; GE Healthcare, Milwaukee, WI, USA) and a standard 8-channel pelvic phased-array surface coil combined with a disposable endorectal coil (MedRad, Indianola, Pa) as previously described[2]. All lesions were scored using the PI-RADS-v2 score[17].

3D Model reconstruction

All 3D virtual model reconstructions based on preoperative mpMRI, were carried out by the Laboratory of Bioengineering of the University of Bologna (S. Orsola-Malpighi Hospital) and the development of AR technology was performed by bioengineers of the University of

Bologna, Department of Electrical, Electronic and Information Engineering “Guglielmo Marconi”.

Segmentation, i.e. the labelling of each structure of interest in each mpMRI slice was achieved using D2P^{TM} software (‘DICOM to PRINT’; 3D Systems Inc., Rock Hill, SC; Figure 1). Semi-automatic tools (*multi-slice interpolation* and *threshold segmentation)* of D2P^{TM} software were adopted to segment the healthy prostatic gland, the index lesion, the urinary sphincter and the NVBs. D2P^{TM} was also used to obtain the 3D virtual models which are navigable, by converting the segmented structures to 3D triangulated surface mesh file (STL), using mesh creation methods of D2P^{TM} (*contour* or *gridbase*; Figure 2).

To replicate the prostate map used by the pathologist in the whole mount prostate to localize PCa, the 3D model was stratified in the 3 dimensional space, using Meshmixer software (Autodesk Inc, San Rafael, CA, US), from base to apex, from right to left and from anterior to posterior, leading to 32 specific areas including 3-4 macro-sections in which the seminal vesicles, the base and the apex were analysed separately (Supplementary Figure 1).

Augmented Reality technology

The augmented reality was delivered through a dedicated hardware and software set-up (Figure 3). The surgical video stream has been acquired from DaVinci video cart via a frame grabber (USB3HD, Startech, London, Ontario, Canada) and sent to an AR-dedicated PC (equipped with an Intel i7 CPU, 8 GB RAM and NVIDIA GeForce 840M video card). A 3D view of the virtual model obtained using Meshmixer software (Autodesk Inc, San Rafael, CA, US), was superimposed on the operatory field with vMIX (StudioCoast Pty Ltd, Robina, Queensland, Australia). During the intervention, the DaVinci TilePro has been activated in the console and real-time manual alignment has been carried out by a biomedical engineer using a 6 degrees of freedom (3D) mouse (SpaceMouse, 3D Connexion, Munich, Germany).

The resulting augmented video stream was also sent to a second external monitor for quality control by the surgeon.

Surgical technique

All patients underwent RARP using four-arm DaVinci Xi Surgical System (Intuitive Surgical, Sunnyvale, California, USA), as previous described[18,19,20]. The NS approaches were classified on patient-based level (considering 26 patients) as bilateral NS, unilateral NS, or non–NS. Indeed, the extent of neurovascular bundles (NVBs) preservation was recorded on side-based level (considering 52 sides) as Grade 1, Grade 2, Grade 3-4 according to incremental NS classification as described by Tewari et al[21]. The main surgeon, when needed, switched to the TilePro visualization, using the AR technology in which the phantom of the 3D model was overlaid to the surgical field (Supplementary Video).

Surgical planning

The surgical plan to evaluate the extent of NS approach, was planned by surgeons basing on mpMRI findings together with clinical data. Moreover, the effective intraoperative surgical plan regarding the level of NVBs preservation[2], both on patient-based and side-based level was assessed through a combination of clinical parameters, mpMRI results and the implemented AR-3D model in the robotic views. At the end of the procedure, the effective intraoperative surgical approach was compared with the preoperative intended planning in order to evaluate the potential success of AR-3D guided technology in the management of surgical dissection.

Histopathological examination

Pathologic examinations were performed by a single dedicated uro-pathologist, following a prostate map in which the gland was divided into 32 specific areas (stratified in the 3-dimensional space from base to apex, from right to left and from anterior to posterior; Supplementary Figure 2). The whole mount histological examinations from the RARP specimens were used as the reference standard, as previously described[22].

Statistical analyses

The McNemar-Bowker test was used to compare the surgical plan regarding NS surgery, before and after its revision following the AR-3D guidance during surgery. The proportion of surgical plan change was recorded both on patient-based and side-based level. The appropriateness of surgical plan change was assessed on side-based level and was based on the presence of ECE or PSMs in the NVBs area at final pathological examination[2]: a less oncologically radical approach, leading to a grade 1 NS, was considered appropriate in case of pT2 with negative surgical margins; a less oncologically radical or a more radical approach, leading to a grade 2 NVBs preservation, was considered appropriate in case of pT2 or pT3a with negative surgical margins; a more oncologically radical approach leading to a grade 3-4 NVB preservation was considered appropriate in case of pT3a/pT3b regardless surgical margins status. Finally, to evaluate the accuracy to localize the index lesion within the 3D model, the presence of suspected index PCa in each of the 32 prostatic areas obtained from model stratification was assessed by visual inspection, and it was compared with the presence of PCa in the corresponding 32 prostatic areas evaluated separately at pathologic examination, following the prostate map analysis (Supplementary Figure 3). A p value of <0.05 was considered statistically significant. All statistical tests were performed using SPSS 22.0.

Results

Demographic and clinical characteristics are summarized in Table 1. Preoperative mpMRI reported organ confined index lesion in 23 patients and suspected ECE in 3 individuals; index lesions were classified as PIRADS 3, 4 and 5 in 9 (34.6%), 9 (34.6%) and 8 (30.8%) men, respectively. Overall, PSMs rate was 15.4%: 1 (5.3%) PSM in pT2, 2 (33.3%) PSMs in pT3a and 1 (100%) PSMs in pT3b. Only 3 patients (11.5%) had PSMs at level of the index lesion detected with 3D-AR model (Table 2). Overall, 2 men experienced postoperative complication (Clavien<3). The continence recovery rate (0/1 safety PAD) was 57.7%, 73.1%, 88.5% and 92.3% at catheter removal, 1, 3 and 6 months, respectively. The erectile function recovery rate (IIEF-5>21 with or without Phosphodiesterase 5 inhibitor) was 23.1% at 1 months, 53.8% at 3 months and 65% at 6 months. No patient had biochemical recurrence at median follow up of 8 months (Supplementary Table 1). On side-based level, Grade 1, 2 and 3-4 NS would have been performed in 23 (44.2%), 6 (11.5%) and 23 (44.2%) sides without 3D-AR model; however, Grade 1, 2 and 3-4 NS was finally performed in 19 (36.5%),17 (32.7%) and 16 (30.8%) sides with the use of 3D-AR technology, respectively ($p=0.02$; Supplementary Table 2). The initial surgical plan of NS techniques was changed by the use of AR-3D model in 38.5% of men. In 3 (30%) cases, surgery was changed to more radical approaches, while in 7 (70%) cases the NS approach was attempted (less radical approach; Table 3a).

The use of AR-3D technology induced the surgeon to change the NS surgical plan in 18 (34.6%) sides with overall appropriateness of 94.4% (Table 3b). In 50% of cases surgery was changed towards a more radical approaches (appropriateness of 77.8%); in the other half of cases, surgical plan was changed into a less radical approach, (appropriateness of 88.9%). Finally, Supplementary Figure 3 depicts the concordance between the 3D model and the whole mount specimen according to the 32 prostatic areas to localize the index lesion: the 3D model revealed 70%, 100% and 92% of sensitivity, specificity and accuracy in the prostate map analysis (Supplementary Table 3).

Discussion

In the era of precision-medicine, the evolution of real-time imaging-guided technology is an increasing need to improve the surgical dissection for a tailored surgery of PCa[14]. Of note, continuous efforts and technique's modifications aiming to reduce PSMs and to preserve both the periprostatic NVBs[21,23] and the periapical tissue[3] are proposed to obtain better surgical outcomes[24,25,26]. Despite the use of mpMRI represents nowadays a routine practice to guide NS surgery[2], it is not a "real-time" method to evaluate the surgical anatomy during RARP. Thus, "in vivo" assessment of prostatic gland and periprostatic tissue has gained special interest in PCa surgery[4]. High fidelity 3D models represent one of the most appealing method for better understanding of surgical anatomy and guiding surgical planning in different fields[10,11,14,27]. As consequence, the use of 3D models in urology, showed a significant impact on surgical planning and decision-making process that may influence patients' outcomes[28]. Porpiglia and coworkers[14,29] have reported their preliminary experience with the use of AR technology. Thus, the AR-3D guided surgery is proposed to facilitate the intraoperative "real-time" navigation and dissection in crucial steps.

Several findings are noteworthy in our study. First, the 3D virtual model overlapped to the DaVinci console through TilePro connection proved to be feasible to define the anatomy of the prostatic glands and the index lesion, as demonstrated by the good concordance with the whole-mount pathological analysis. Previously, Porpiglia et al. showed that AR-3D models were able to identify the index lesion in 100% of patients[14,30], with a mismatch between the 3D reconstruction and the scanned prostate recorded from 1 to 5 mm[14]. In our cohort we used a simple method (a prostate map stratified into 32 specific areas) to validate the 3D model in terms of index lesion's localization, considering the whole-mount pathologic specimens as reference: overall, the 3D model revealed 92% of accuracy to localize the index lesion. The proposed prostate map analysis has two main advantages: firstly, the 32-areas prostate map on the 3D model is easy to obtain using a free software (Meshmixer);

secondly, the proposed prostate map analysis to compare the 32 areas on the 3D model and the pathologic specimen is able to assess the concordance/non-concordance to localize the index lesion in the same areas or the presence of PCa in areas nearby the index lesion. Second, for the first time ever, we evaluated the impact of AR-3D guided surgery to modify the real-time intraoperative approach to NS both on patient-based and side-based analyses. The surgical plan was changed through real-time AR-3D visualization, in 38.5% patients and in 34.6% sides with safe results in terms of PSMs (15.4% overall). Third, the NS plan changed due to AR-3D was appropriate in the vast majority of cases: overall, in 50% of sides the AR-3D lead a more radical NS (appropriateness of 77.8%); while in the remaining half of cases, the AR-3D lead a less radical NS (appropriateness of 88.9%). Fourth, the AR-3D guided approach to NVBs allows to modulate the NS approach tailored to the index lesion, by resecting more tissue nearby the lesion and preserving more tissue outside the lesion, aiming to maximize both oncologic and functional outcomes. Thus, PSMs at level of index lesion were 11.5% and the erectile function recovery was 65% at 6 months in patients referred to NS RARP. These findings suggest that the accuracy offered by AR-3D technology could allow for "real-time" robotic procedure tailored to the patient-specific anatomy and to the specific cancer location. Future applications of intraoperative frozen section targeted to the index lesion and guided by AR-3D models could allow further improvement of surgical outcomes.

Despite several strengths, our study is not devoid of limitations. First, in spite of the prospective nature of the study, the number of patients included is limited. Second, we used rigid 3D prostate models, that do not represent the tissue deformation during surgical dissection and the biological realism necessary to create more functional and dynamic overlapping. Third, the lack of a control group of patients submitted to RARP without the use of AR-3D model, did not allow to assess the real impact of this technology to modify the surgical approach. Furthermore, the adoption of different definitions of appropriateness of surgical plan would affect the final results. Moreover, the superimposed screen with the 3D model can create some problems during the dissection, since the surgeons need to switch from conventional to the TilePro view that consist in a double and smaller screen. Fourth, we included also the first patients treated with this novel technology, with possible effect to prolong the surgical time due to the learning curve process. Indeed, we found that 2 to 5 cases are needed both for the surgeon and the bioengineer to improve the overlap of the 3D model in the surgical field. Finally, the major limitations of AR-assisted surgery consist of possible registration inaccuracy, translating into a poor navigation precision and the need of manual external adjustments of the 3D model overlapping on the surgical field[9]. Thus, automatic registration of the 3D model to the surgical view, based on artificial intelligence, could be the further implementation to obtain an automated overlapping of the 3D virtual model inside the DaVinci console liable with the organ movements during surgery.

Conclusions

The use of AR-3D guided surgery can be a feasible tool to improve the real-time identification of the index lesion and it could be useful to modulate the NS approach during RARP. The surgical plan change after the intraoperative adoption of AR-3D guidance technology was recorded in approximately one out of three cases, with overall appropriateness of 94.4%.

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Conflict of interest

The project was supported by a Technology Research Grant by Intuitive Surgical for the development of augmented reality technology in robotic surgery.

Figure legend

Figure 1. Example of process to obtain the 3D virtual anatomical model starting from patient mpMRI (a), by the segmentation (b) of the anatomical regions of interest (prostatic gland, index lesion, urinary sphincter and neurovascular bundles) to the final 3D model (c).

Figure 2. Example of the definitive 3D virtual model that can be explored by the surgeon for surgical planning: the model could be rotated and zoomed and is navigable, i.e. the surgeon can interact with it changing the transparency of each structure in the 3D rendering, as well as creating a detailed view of the interaction among the different anatomical structures.

Figure 3. A schematic diagram of the hardware and software required to implement the intra-operative use of AR to guide robotic surgery.

Supplementary Figures

Supplementary Figure 1. Three-dimensional stratification of the prostate 3D model (from base to apex, from right to left and from anterior to posterior) leading to 32 specific areas including 3-4 macro-sections used to evaluate the concordance of the reconstructed 3D model with the prostate map stratified in the same 32 areas by pathologist on the whole mount specimen.

Supplementary Figure 2. Prostate map used to divide the gland into 32 specific areas (stratified in the 3-dimensional space from base to apex, from right to left and from anterior to posterior) on the whole mount specimen.

Supplementary Figure 3. Prostate map analysis: concordance (green) and discordance (red) to localize the index lesion between the 3D model and the pathologic whole mount specimen by visual assessment in each patient (n=26) after stratification of the whole gland (both on 3D model and on pathologic specimen) according to the 32 prostatic areas.

Supplementary Video

Example of AR-3D guided surgical dissection for real-time assessment of the index lesion during the RARP through the TilePro visualization: the 3D model is overlapped inside the surgical view during nerve sparing approach and helps the surgeon to modulate the surgical dissection of the neurovascular bundle.

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