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VALIDATION OF AN INTRAOPERATIVE AUGMENTED REALITY (3D-AR) SYSTEM FOR SUTURELESS ROBOT-ASSISTED TUMOR ENUCLEATION OF LOCALIZED RENAL MASSES: A PROSPECTIVE SINGLE-CENTER STUDY ON 20 PATIENTS

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Abstract

Robot-assisted tumor enucleation (RATE) is a nephron-sparing approach for localized renal tumors. However, cortical renorrhaphy and diffuse "blanket" cauterization of the resection bed can compress or thermally injure healthy parenchyma, potentially affecting postoperative renal function. We prospectively evaluated an intraoperative three-dimensional augmented reality (3D-AR) system developed by the DIMES Bioengineering Laboratory (University of Bologna) to guide a sutureless RATE workflow. Twenty consecutive patients underwent AR-guided enucleation with targeted, point-by-point coagulation of the main vessel facing the resection bed, avoiding routine renorrhaphy. Primary endpoints were feasibility of AR guidance and intraoperative need for renorrhaphy; secondary endpoints included operative time, clamping/ischemia, complications, and renal function changes. AR guidance facilitated accurate identification of the anatomical plane and main bleeding vessel, enabling selective hemostasis while preserving healthy parenchyma. No major complications or acute kidney injury were observed; renal function was preserved at short-term follow-up.

Introduction

Robot-assisted partial nephrectomy (RAPN) represents the gold-standard minimally invasive approach for the management of clinical T1 renal tumors, offering an optimal balance between oncologic control and maximal preservation of functioning renal parenchyma [1]. Following tumor excision, the reconstructive phase remains a critical determinant of postoperative function. Conventional techniques rely on cortical renorrhaphy and widespread coagulation of the resection bed to achieve hemostasis [2]. Although effective in preventing bleeding, these maneuvers may compress intraparenchymal microvasculature, propagate thermal injury, and compromise peri-lesional perfusion. As a consequence, a potentially significant portion of viable parenchyma may be functionally lost, despite being anatomically preserved.

The sutureless concept was proposed to mitigate this form of secondary ischemic damage by omitting or limiting renorrhaphy when feasible, provided that meticulous and selective hemostasis can be ensured [1,2]. This philosophy aims to preserve the delicate microvascular architecture surrounding the resection plane, allowing spontaneous closure of minor collecting system breaches

and physiologic tamponade by surrounding tissue rather than mechanical compression or excessive thermal spread.

Three-dimensional augmented reality (3D-AR) models, reconstructed from preoperative CT images, provide a real-time, patient-specific representation of intrarenal anatomy—including segmental arteries, veins, and the collecting system—superimposed directly onto the operative field [3,4]. This technology enables the surgeon to visualize not only the external tumor boundaries but also the subsurface vascular structures that are typically invisible to the naked eye. When integrated into RAPN, AR guidance enhances spatial orientation, facilitates pure enucleation, reduces the need for global ischemia, and minimizes collecting system violations, particularly in anatomically complex tumors [3,4].

Building on these premises, the present study validates a 3D-AR–guided sutureless enucleation strategy, specifically designed to achieve targeted hemostasis by selectively coagulating the main arterial and venous feeders exposed at the tumor bed—identified in real time through augmented visualization—while avoiding cortical sutures that would compress functional parenchyma or diffuse cauterization that would propagate thermal injury. This approach aims to transform the reconstructive phase from a mechanically compressive and thermally aggressive step into a precisely guided, physiology-respecting process, maximizing nephron preservation without compromising hemostatic security.

Materials and Methods

We conducted a prospective, single-center cohort study between April 2024 and June 2025 at a tertiary academic referral center. Twenty consecutive patients with localized renal masses underwent 3D-augmented reality–guided robot-assisted tumor enucleation (RATE) performed by a single expert robotic surgeon using a multiport da Vinci Xi system (Intuitive Surgical, Sunnyvale, CA, USA). The study protocol was approved by the institutional ethics committee (approval no. 59/CE/2024, April 17 2024; DDG no. 345, May 3 2024), and written informed consent was obtained from all participants.

Patient-specific three-dimensional reconstructions were created from high-resolution, contrast-enhanced multiphase CT scans. Segmentation included the renal tumor, arterial and venous trees, and the collecting system. During surgery, the virtual 3D model was registered with the intraoperative endoscopic view, enabling dynamic visualization of the vascular branches lying beneath the intended cleavage plane. Tumor enucleation was performed with minimal traction and selective application of monopolar Swift energy (effect 8; Swift Coag 45–55 W).

In the reconstructive phase, augmented-reality guidance allowed real-time identification of the principal vessel facing the resection bed. Hemostasis was achieved by targeted, point-by-point coagulation of visible bleeding sources under AR guidance, avoiding both diffuse parenchymal cauterization and cortical renorrhaphy. A thin layer of human-derived thrombin sealant was applied to the resection bed at the end of the procedure. Sutures were reserved exclusively when selective coagulation was insufficient to ensure hemostatic control.

Baseline demographic data, tumor characteristics according to the PADUA classification [5], and renal function parameters were prospectively collected. Intraoperative variables included total operative time, ischemia/clamping status, and any conversion to conventional renorrhaphy or standard reconstruction. Postoperative complications were classified according to the Clavien–Dindo system [6]. Renal function (serum creatinine, urea, and estimated glomerular filtration rate [eGFR]) was assessed preoperatively, at discharge, and at three months postoperatively. Acute kidney injury (AKI)was defined as a >25% reduction in eGFR from baseline to discharge, consistent with previous robotic partial nephrectomy studies [7].

3dModeling, AR technique, Surgical technique

To minimize bias due to inaccurate 2D preoperative imaging, all patients underwent high-quality contrast-enhanced chest and abdominal computed tomography (CT) at our institution prior to surgery. Scans were acquired using an angiographic protocol with a slice thickness of 1.25–2.5 mm and a step interval of 0.8–2.0 mm. Intravenous non-ionic contrast medium (Iomeprol 350 mg/mL, Iomeron; Bracco Imaging Srl, Milan, Italy) was administered at a flow rate of 3 mL/s. The acquisition timing was determined according to the standard phases: renal arterial (25–30 s), parenchymal (80–100 s), and delayed (5–10 min).

All 3D virtual model reconstructions based on the preoperative high-quality CT scans were performed by the Laboratory of Bioengineering, DIMES Department, University of Bologna. Multiple imaging series with different contrast levels were employed to selectively identify each anatomical structure of interest (healthy parenchyma, tumour lesion, arterial tree, renal veins, and collecting system) during image segmentation [8].

Segmentation—i.e., labelling each structure of interest in every CT slice—was performed using D2P software ("DICOM to PRINT"; 3D Systems Inc, Rock Hill, SC), a modular CE-certified software package designed for converting patient DICOM medical images into 3D digital models for preoperative surgical planning. Manual refinement of the semi-automatic segmentation output required approximately 2–4 h. The segmented anatomical structures from the various imaging series were subsequently merged into a single file by aligning common regions, such as the healthy renal parenchyma, which was consistently segmented across all series [8].

D2P was also used to generate the 3D virtual models by converting the segmented structures into triangulated surface mesh files through the software's contour- or grid-based mesh creation methods. For each case, the surgeon reviewed the 3D virtual model preoperatively on a dedicated personal computer (PC) in the operating room.

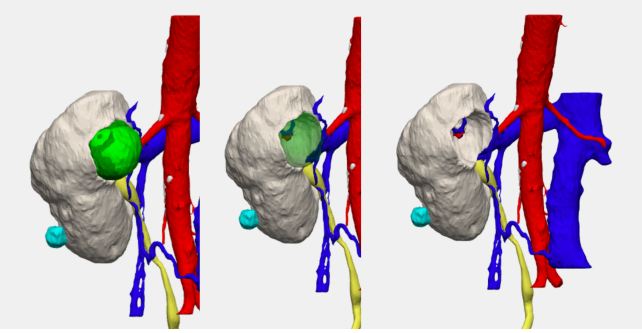
An ad hoc hardware and software setup was implemented to develop an augmented reality (AR) system to guide robotic surgery. The Da Vinci video stream was captured using a frame grabber (USB3HD, Startech, London, Ontario, Canada) connected to an AR-dedicated PC (Intel i7 CPU, 8 GB RAM, NVIDIA GeForce 840M graphics card), as previously described for prostatic surgery [4]. The Da Vinci video stream and the 3D virtual model (MeshMixer, Autodesk Inc, San Rafael, CA) were overlapped in real time using vMIX (StudioCoast Pty Ltd, Robina, Queensland, Australia). [4,8].

To achieve optimal alignment between the Da Vinci video stream and the 3D virtual model, a biomedical engineer manipulated the model using a six-degrees-of-freedom (3D) mouse (SpaceMouse, 3D Connexion, Munich, Germany), in agreement with the operating surgeon. The resulting AR-3D video stream—comprising the 3D virtual model superimposed on the actual

intraoperative anatomy—was displayed in real time on a secondary monitor for quality control and simultaneously imported into the surgeon's console via TilePro.

However, current AR technology is not elastic, meaning that it does not compensate for soft-tissue deformation during surgery; as a result, misalignment between the virtual and real anatomy may occur, particularly after renal mobilization or during resection [3]. In light of this limitation, we focused our use of AR primarily on the reconstructive phase rather than tumour resection. Once the lesion was excised and the resection bed exposed—often variably bleeding—the real intraoperative image did not allow selective coagulation of the vessel primarily supplying the tumour area. For oncological safety in case of positive margins and for hemostasis, the entire bed is often coagulated, though this causes non-selective thermal injury to surrounding healthy parenchyma. [10-13]. (Figure 1).

Figure 1. Reconstructive phase: targeted, point-by-point coagulation of the main vessel facing the resection bed under AR guidance.



The aim of AR guidance in our workflow was therefore to indicate the main feeding vessel to the lesion via the 3D overlay, allowing focused coagulation at that point while sparing adjacent parenchyma where the bleeding risk is low, and minimizing postoperative haemorrhagic risk. By limiting the AR overlay to the resection bed only, we theoretically reduced alignment variability and enhanced the precision and effectiveness of its intraoperative use.

Robot-assisted partial nephrectomy (RAPN) was performed using the Da Vinci Xi Surgical System (Intuitive Surgical Inc, Sunnyvale, CA) in a four-arm configuration, with the integrated Firefly fluorescence imaging mode, as previously described [9]. During the procedure, tumour

localization and renal hilum dissection were guided by the AR-3D video stream, with the 3D model manually adjusted in real time by the assistant engineer. After tumour excision, early unclamping was systematically performed between inner and outer renorrhaphy using the sliding-clip technique [1, 2].

Statistical Analysis

Continuous variables were expressed as mean and standard deviation or as median and range, as appropriate. Categorical variables were summarized as absolute and relative frequencies. Pre- and postoperative laboratory parameters (hemoglobin, creatinine, urea, and eGFR) were compared using the Wilcoxon signed-rank test for paired samples. A p-value < 0.05 was considered statistically significant. All analyses were performed using STATA.

Results

Twenty patients (16 males, 4 females) were included. Mean age was 61 years (range 56–70), mean BMI 27.4 kg/m², mean tumor size 25 mm (range 20–50), and mean PADUA score 7. Histopathology revealed 14 clear-cell RCC, one papillary RCC, two oncocytomas, and three complex cysts. No positive surgical margins were recorded.

Median operative time was 115 minutes (range 75–130). Main artery clamping and parenchymal suturing were required in one case only (ischemia time 15 minutes) to control bleeding. Median length of stay was three days. No major intraoperative or postoperative complications occurred; one patient developed postoperative fever (Clavien I), resolved with oral antibiotics. No early recurrences were detected at three months.

Hematologic and renal function changes were modest. Variations in hemoglobin, creatinine, and urea from baseline to discharge and follow-up were not statistically significant. Median eGFR decreased by 8% at discharge and 16% at three months, not meeting the predefined threshold for AKI. (Figure 2, 3,4)

Figure 2. Trend in estimated hemoglobina rate

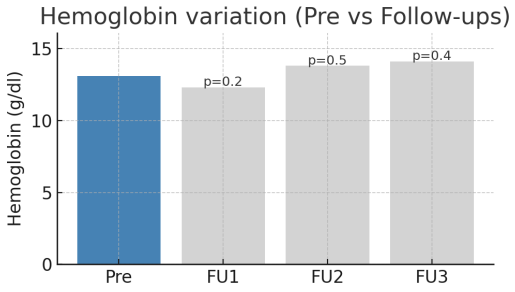


Figure 3. Trend in estimated glomerular filtration rate (eGFR)

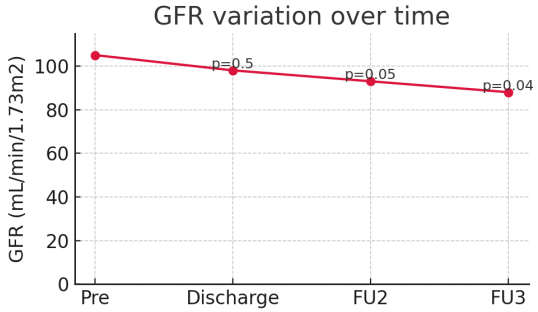


Figure 4. Trend in estimated creatinine

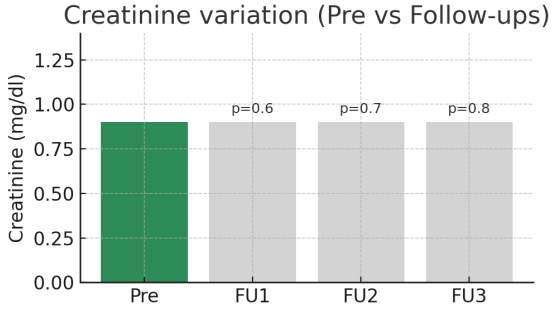
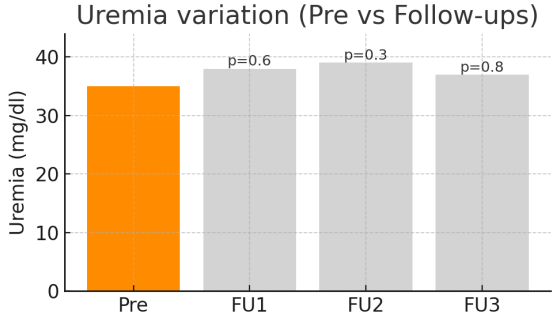


Figure 4. Trend in estimated uremia



Discussion

This single-center experience demonstrates that intraoperative three-dimensional augmented reality (3D-AR) can safely and effectively guide the reconstructive phase of robot-assisted tumor enucleation. Beyond facilitating tumor excision, 3D-AR provides a unique intraoperative capability: it reveals the intrarenal vascular anatomy lying beneath intact parenchyma and normally invisible to the surgeon's eye. In particular, AR allows real-time identification of the main vessel facing the resection bed after tumor removal. This vessel often represents the principal source of bleeding but cannot be visually recognized without AR support, as it is hidden under healthy tissue [14,15].

In conventional practice, hemostasis after tumor resection is achieved either by suturing the entire parenchymal defect or by applying diffuse cauterization across the resection bed. Although effective, both strategies are physiologically detrimental. Cortical renorrhaphy exerts mechanical compression on microvascular structures and may compromise perfusion of the preserved parenchyma, while blanket coagulation propagates thermal injury into adjacent viable tissue [16,17]. Together, these maneuvers increase the risk of both acute and chronic renal function loss.

The AR-guided workflow fundamentally changes this paradigm. By projecting the segmented vascular network onto the operative field, the surgeon can accurately localize and selectively coagulate the principal vessel responsible for bleeding. This targeted, point-by-point coagulation achieves rapid hemostasis while sparing surrounding nephron-rich tissue. It eliminates the need for parenchymal suturing and avoids indiscriminate cauterization of the entire resection bed. As a result, the technique minimizes collateral thermal and mechanical injury, preserves peri-lesional microcirculation, and provides a truly anatomy-based reconstructive strategy [18].

In our series, this selective coagulation strategy achieved excellent hemostasis without increasing intraoperative blood loss or postoperative complications and was not associated with any case of acute kidney injury (AKI). Early renal function trajectories (−8% eGFR at discharge and −16% at three months) remained well above the AKI threshold, supporting the physiological rationale of focusing energy delivery precisely where it is needed [19].

Postoperative AKI after partial nephrectomy is a clinically relevant event because it correlates with inferior functional recovery and chronic kidney disease (CKD) progression. Large multicenter analyses have shown that patients developing AKI after partial nephrectomy have significantly lower odds of recovering baseline renal function and higher rates of CKD upstaging at one year [20]. Preventing AKI is therefore not a cosmetic or perioperative endpoint, but a determinant of long-term nephron preservation and patient outcomes.

Importantly, AKI after partial nephrectomy is not purely ischemia-driven. Although warm ischemia time plays a role, systematic reviews have demonstrated that microvascular and thermal injury from diffuse cauterization, and mechanical compression from renorrhaphy, are major contributors to parenchymal insult. These non-ischemic mechanisms of injury are modifiable through surgical technique. A family of strategies has therefore emerged to mitigate such damage—off-clamp approaches, selective clamping, and sutureless reconstructions—all aimed at minimizing parenchymal trauma and preserving renal function [21,22].

Our 3D-AR–guided workflow operationalizes this renoprotective principle within the reconstructive phase itself, which is often under-addressed in the literature. After tumor removal, the principal bleeding vessel facing the resection bed is typically hidden beneath healthy parenchyma and cannot be identified by direct vision alone. By overlaying a patient-specific vascular map, 3D-AR reveals this culprit vessel in real time, enabling selective, vessel-oriented coagulation. This approach replaces diffuse cauterization and obviates routine cortical renorrhaphy—two maneuvers directly implicated in microvascular and thermal injury. The result is a substantial reduction in the cumulative “dose” of trauma delivered to the parenchyma [15,18].

Functionally, this refined reconstructive strategy that limits indiscriminate energy delivery and avoids cortical compression is expected to lower the incidence of AKI and support early eGFR

recovery. These results align with high-quality evidence showing that sutureless and off-clamp techniques preserve function without increasing complications. In our cohort, targeted coagulation under AR guidance achieved hemostasis without excess bleeding, complications, or AKI signal—consistent with the mechanistic rationale and with previously reported renoprotective effects of minimizing parenchymal injury [19,22].

Reducing AKI has broad implications. Beyond renal preservation, it may decrease the risk of CKD progression, lower transfusion requirements, reduce ICU and monitoring needs, shorten hospital stay, and limit readmissions. From a population-health perspective, decreasing AKI events can translate into lower healthcare costs and better long-term quality of life for patients undergoing nephron-sparing surgery [20,21].

Our findings are also consistent with prior AR-assisted RAPN studies. Porpiglia et al. first demonstrated that 3D-AR enhances visualization of intrarenal structures and facilitates pure enucleation with less ischemia; Schiavina et al. confirmed its role in guiding selective clamping and tumor dissection. Amparore et al. advanced the field with automatic model overlapping using indocyanine green and computer vision, while Piana et al. validated AI-driven automatic AR alignment, paving the way for real-time augmented surgical navigation. However, while the majority of these studies focused on the excisional phase, the current work extends the benefit of AR into the reconstructive step, emphasizing its capacity to reduce postoperative renal damage and enhance nephron preservation [14,23].

Even when clamping strategy alone yields neutral differences in AKI incidence, the additive benefit of AR-guided, vessel-focused hemostasis is conceptually distinct: it specifically targets the bleeding source while protecting functional parenchyma. As AR platforms evolve toward fully automated, deformation-aware overlays and AI-assisted navigation, their ability to maintain stable registration during respiration and tissue manipulation will further improve selective hemostasis. This evolution may ultimately enable truly nephron-sparing, low-energy, sutureless partial nephrectomythat minimizes both ischemic and non-ischemic renal injury [23].

Conclusions

Intraoperative three-dimensional augmented reality (3D-AR) proved to be a feasible and safe adjunct to sutureless robot-assisted tumor enucleation. Beyond facilitating tumor excision, AR provided an additional reconstructive advantage by enabling real-time identification and selective coagulation of the principal bleeding vessel beneath the resection bed. This anatomy-based, vessel-focused approach minimized diffuse parenchymal cauterization and eliminated the need for routine cortical renorrhaphy, thereby reducing both mechanical and thermal injury to the preserved parenchyma. In our cohort, perioperative outcomes were excellent, with no complications or acute kidney injury, and postoperative renal function remained well preserved.

To our knowledge, no previous studies have directly linked the **sutureless reconstructive concept** with **targeted, vessel-oriented coagulation under 3D-AR guidance**. This represents a novel, physiology-driven application of AR, extending its utility beyond tumor excision into the reconstructive phase of nephron-sparing surgery. The proposed workflow transforms this step from an empiric maneuver into a data-guided process based on patient-specific vascular anatomy, enhancing both precision and safety.

These results support the rationale for incorporating AR into the reconstructive phase, where selective hemostasis can directly translate into superior parenchymal preservation. Future developments in deformation-aware and AI-assisted AR systems are expected to further improve overlay stability and anatomical registration, paving the way toward **truly nephron-sparing, low-energy, sutureless partial nephrectomy**. Multicenter, prospective trials with long-term follow-up are warranted to validate these early findings and quantify their impact on renal function recovery and oncologic safety.

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