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Research Article

Impact of Three-Dimensional Reconstruction on Surgical Planning in Moderate- and High-Complexity Kidney Cancer: A Pre- and Post-Intervention Study

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Abstract

Background: Nephron-sparing surgery poses challenges in surgical planning, especially for larger or more complex tumors.

Objectives: To evaluate the impact of Three-Dimensional (3D) reconstructions on 1) surgical planning (primary outcome) and 2) understanding of renal anatomy (secondary outcome) in moderate- and high-complexity kidney tumors.

Methods and Participants: This pré- and post-intervention study included patients who underwent partial or radical nephrectomy between 2018 and 2023. Three-dimensional images achieved from contrast-enhanced Computed Tomography (CT) scans were interpreted by a radiologist and randomly reviewed by 18 blinded urologists specialized in nephron-sparing surgery (Reference and Case group, based on case volume). Outcomes were assessed through questionnaires before the intervention (2D images) and 4-5 weeks later, with the 3D reconstruction.

Results: Fourteen patients (57% female and 43% male) with moderate- and high-complexity lesions (R.E.N.A.L. score > 7) were included. Case and Reference groups presented similar experiences and frequency of opinion change. Urologists altered their opinions more frequently following 3D reconstruction, mainly in high-complexity cases. 3D reconstruction enhanced urologists' understanding of renal anatomy, increasing selective clamping use and decreasing reliance on intraoperative Ultrasound (USG) and hemostatic agents ($p < 0.05$) in surgical planning.

Conclusions: Our findings suggest that incorporating 3D reconstruction into clinical practice can enhance the understanding of renal anatomy, optimize surgical planning, and promote a nephron-sparing approach.

Keywords: Nephrectomy; Renal cell carcinoma; Robotic surgical procedures; Three-dimensional imaging

Abbreviations: 2D: Bi-Dimensional; 3D: Three-Dimensional; AR: Augmented Reality; CEP: Ethics And Research Committee; CT: Computer Tomography; ICMJE: International Committee of Medical Journal Editors; NSS: Nephron-Sparing Surgery; UFSC: Federal University of Santa Catarina; USG: Ultrasound

Introduction

Nephron-Sparing Surgery (NSS) has emerged as a safe and feasible approach for managing kidney tumors, particularly for small renal masses (cT1) [1]. Partial nephrectomy has demonstrated superior preservation of overall renal function compared to radical nephrectomy while achieving comparable oncological outcomes [2,3]. Previous studies suggest the application of NSS to larger tumors, including cT2 masses-with no significant differences in perioperative complications compared to radical nephrectomy-underscoring its expanding role in urological practice [4]. Consequently, the adoption of minimally invasive techniques has increased in recent decades, expanding to more complex and challenging cases [5,6]. NSS presents a highly variable complexity and depends on several factors, including patient demographics -such as age, weight, comorbidities, and previous surgeries-and tumor characteristics-such as size, location, and proximity to critical renal structures as the collecting system and the vessels of the renal hilum [3]. Thus, a complete and accurate understanding of renal anatomy and tumor complexity is crucial for ensuring the successful outcomes of NSS [7].

Nephrometry systems have been commonly used to assess renal tumor complexity and predict complications during partial nephrectomy [8]. Nephrometry systems provide comprehensive information regarding tumor location, size, and its relationship to the collecting system [9,10]. However, they fail to provide a complete understanding of the morphological and anatomical features of the renal mass, which is crucial for optimal partial nephrectomy planning [7]. Recent advances in imaging technology have significantly enhanced the understanding of surgical anatomy, enabling the adoption of less invasive interventions and contributing to better patient outcomes [11]. 3D virtual reconstruction of 2D cross-sectional imaging provides volumetric and morphological parameters that predict surgical complexity of renal mass and surgical outcomes after robot-assisted partial nephrectomy [7]. Several studies indicate that 3D models can improve preoperative planning for kidney tumors, facilitating nephron-sparing surgeries [12,13]. However, the use of 3D reconstruction in the surgical management of kidney tumors is still scarce. In this study, we investigate the impact of 3D reconstructions on surgical planning and surgeons' perceptions of renal anatomy and lesions in patients with moderate and high complexity kidney tumors (R.E.N.A.L. score ≥ 7).

Materials and Methods

Study Design and Participants

This pre- and post-test intervention study assesses the impact of 3D reconstructions on surgical planning and anatomy perceptions for renal tumors. All patients who underwent partial or radical nephrectomy by a single surgeon between 2018 and 2023 at Hospital Baía Sul/IHC, Florianópolis – Brazil, were screened. Inclusion criteria included adults over 18 years old; legally competent, with renal lesions of moderate to high complexity, as indicated by a R.E.N.A.L. score of 7 to 12 on their CT scans; and had contrast-enhanced CT scans at Clínica Imagem in Florianópolis, Brazil. Patients with a R.E.N.A.L. score of 4 to 6 (low complexity), those with tumors staged > T2a (> 10 cm), patients who did not undergo CT scans at Clínica Imagem, and those who did not have contrast-enhanced CT scans (three-phase uro-CT) before surgery were excluded from the study.

The CT scans were evaluated by a single radiologist from Hospital Baía Sul in Florianópolis, who was also a participant in the study. The nephrometry was calculated by this same physician according to the criteria of the R.E.N.A.L. score [14]. The 3D images were reconstructed from the CT scans by the Brazilian company InfiniBrains™, responsible for the DocDo application. Urologists were initially presented with CT-based imaging data to determine their surgical approach (through the application of S1 Questionnaire 1). After 4-5 weeks, the same cases were randomized and re-evaluated by the same urologists, this time with the addition of 3D reconstructions (Questionnaires 1 and 2 were applied, see Supplementary Material S1 and S2). All questionnaires were applied online through the Google Forms platform. According to volume surgeons, the urologists were divided into two groups based on their surgical experience: the Reference (n = 3) and the Case group (n = 15). Each urologist evaluated all cases twice, allowing for a comparison of decision-making before and after exposure to 3D reconstructions. The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics and Research Committee (CEP) of the Federal University of Santa Catarina (No. 6.281.044). Informed Consent Forms were obtained from all patient participants, urologist specialists, and radiologists who reported the examinations. Additionally, Commitment Terms for Data Use were secured from InfiniBrains™, which manages the DocDo application. The manuscript preparation process follows the recommendations of the International Committee of Medical Journal Editors (ICMJE).

Three-Phase Uro-Computed Tomography (CT) Scans

A triphasic computed urogram was performed using a Siemens/ Somatom Definition AS 128-channel CT scanner. First, a non-contrast sequence was obtained. Then, sequences were acquired following intravenous injection of the contrast medium, using 1 mL/kg of contrast. The corticomedullary phase (30 seconds post-

intravenous contrast), nephrographic phase (90 seconds), and excretory phase (8 minutes) were performed. The slices were acquired with a thickness of 2 mm [15].

Statistical Analysis

The variables were expressed as frequencies and percentages. Pearson and Fisher's statistical tests were applied to assess the significance of results in proportions, while the t-test was used to compare means. The number and proportions of times the urologists changed their choices were calculated by comparing their responses before and after the 3D reconstruction (Z statistic). To assess the effect of 3D reconstruction on changes in surgical approach, the number of opinion changes in medical conduct after viewing the reconstructed images was compared to a hypothetical value of zero (indicating no change). Spearman's rank correlation was applied to assess the relationship between the frequency of opinion changes by urologists and the percentage of physicians who believed that 3D reconstruction altered their perception of renal anatomy. Analyses were conducted using R software version 4.2.3, with a statistical significance level set at 5%.

Results

A total of 92 patients underwent partial and radical nephrectomy between 2018 and 2023 at Hospital Baía Sul/IHC, Florianópolis – Brazil. Among these, 62 patients had CT scans and were assessed for eligibility for the study. Fourteen participants with a R.E.N.A.L. score > 7 met the eligibility criteria and consented to participate (Figure 1). Three-dimensional reconstructions were performed from contrast-enhanced CT scans, as demonstrated in Figure 2. Data from 14 patients were analyzed, of which 8 (57%) were female and 6 (42%) males, as per self-reported sex. The mean age across the group was approximately 59 years. Regarding nephrometry, 64% of the patients were classified as having moderate-complexity lesions (R.E.N.A.L. scores of 7 to 9), with an average tumor size of 5 cm. The remaining patients presented with high-complexity lesions, characterized by a mean tumor size of 6.60 cm and R.E.N.A.L. scores ranging from 10 to 12 (Table 1).

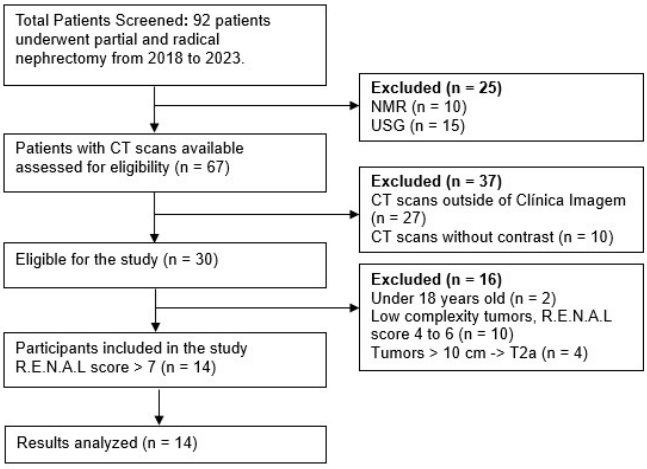

Figure 1: Flow diagram of participants selected for the study according to the established criteria. CT: Computed Tomography; NMR: Nuclear Magnetic Resonance; USG: Ultrasonography.

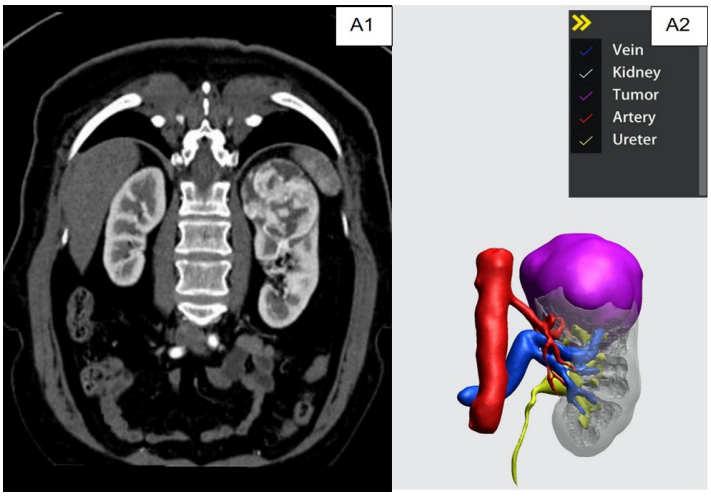

Figure 2: Computed tomography image with 3D reconstruction of a kidney lesion. Female patient, 58 years old, with a tumor lesion in the left kidney suggestive of neoplasia. A1: coronal computed tomography section. A2: 3D image reconstruction. Nephrometry shows an R.E.N.A.L. score of 11 points (highly complex lesion). Source: personal file.

Variable	Mean ± SD	n = 14 (%)
Sex*		
Male		6 (42.86)
Female		8 (57.14)
Age (years)		
Male	59.83 ± 14.74	
Female	59.00 ± 15.40	
Nephrometry (score)		
High Complexity (10 to 12)		5 (35.71)
Moderate Complexity (7 to 9)		9 (64.29)
Lesion size (cm)		
High Complexity	6.60 ± 2.30	
Moderate Complexity	5.06 ± 2.42	

* Self-reported. SD: Standard Deviation.

Table 1: Demographic and clinical characteristics of patients included in the study.

The urologists participating in this study had an average of 17 years of experience. No significant differences were found in the average years of experience between the Case and Reference groups ($p = 0.25$), nor in the total number of times the physicians changed their opinions ($p = 0.36$). Given that no significant differences were observed between the Case and Reference groups, the results in subsequent tables are presented for the group as a whole (Table 2). Urologists altered their surgical plans more frequently after 3D reconstruction when the lesion complexity was higher. For patients with high nephrometry scores, surgical plans were adjusted 2.7 ± 0.8 times, compared to 1.8 ± 0.9 adjustments for those with moderate-complexity lesions ($p < 0.05$) (Table 2). Table 3 presents the proportion of procedures adopted according to the urologists' opinions before and after viewing the 3D reconstruction. The results indicate that the proportion of urologists who used selective clamping (segmental) increased significantly, from 0.000 to 0.020 ($p < 0.05$). Additionally, there was an increase in the proportion of urologists who did not use intraoperative USG, from 0.332 to 0.440 ($p < 0.05$). The proportion of urologists who did not apply hemostatic agents significantly rose after the exposure to 3D reconstruction, from 0.375 to 0.478 ($p < 0.05$). No significant differences were observed in the proportions of other procedures performed.

Characteristics	n	Mean	SD	p-value
Experience of study physicians (years)	18	17	8.1	
Experience of physicians according to study group (years)				0.25
Case	15	16.6	8.1	
Reference	3	22.7	7.6	
Total number of changes				0.36
Case	15	31	8.7	
Reference	3	26	8.1	
Total number of changes according to lesion complexity				0.008*
High	18	2.7	0.8	
Moderate	18	1.8	0.9	

SD: Standard Deviation. * $p < 0.05$ when comparing the total number of changes after 3D reconstruction according to the complexity of the cases (Student's t-test).

Table 2: Characteristics of the study groups, total number of times they changed their opinion, and number of changes according to the complexity of the cases.

		3D reconstruction		
Procedure		**Before**	**After**	**p-value[1]**
Surgical approach	Partial Nephrectomy	0.694	0.738	0.213
	Radical Nephrectomy	0.306	0.262	0.273
Preoperative biopsy of the lesion	No	0.933	0.964	0.115
	Yes	0.067	0.036	0.115
Access route	Extraperitoneal	0.016	0.028	0.358
	Intraperitoneal	0.679	0.710	0.449
	Not Applicable	0.306	0.262	0.273
Type of resection	Enucleation	0.524	0.548	0.589
	Polar Nephrectomy	0.048	0.044	0.830
	Segmental Resection	0.123	0.147	0.430
	Not Applicable	0.306	0.262	0.273
Clamping type	Total Clamping (arterial + venous)	0.139	0.167	0.718
	Total Clamping (arterial only)	0.552	0.536	0.382
	No Clamping	0.004	0.016	0.175
	Selective Clamping (segmental)	0.000	0.020	0.024*
	Not Applicable	0.306	0.262	0.273
Renorrhaphy method	Two layers	0.563	0.575	0.786
	One layer	0.131	0.163	0.31
	Not Applicable	0.306	0.262	0.273
Intraoperative ultrasound (USG)	No	0.332	0.440	0.012*
	Yes	0.368	0.304	0.128
	Not Applicable	0.308	0.256	0.194
Hemostatic agent	No	0.375	0.478	0.019*
	Yes	0.323	0.263	0.138
	Not Applicable	0.307	0.259	0.231

[1] Z-statistic for the difference in proportions. * $p < 0.05$ when compared the difference in proportions.

Table 3: Proportion of procedures adopted according to the urologists' opinion before and after viewing the 3D reconstruction.

Most urologists reported that 3D image reconstruction altered their perception of renal anatomy and the tumor, altering their surgical approach in 57% of cases (cases 01, 03, 05, 08, 09, 12, 13, and 14). After reviewing the CT scans with 3D reconstruction, urologists changed their surgical approach planning in all cases ($p < 0.05$) except for case 7 ($p = 0.16$). These findings suggest that exposure to 3D reconstructions can significantly influence the decision-making process regarding surgical procedures adopted (Supplementary material S3).

The Spearman correlation coefficient (ρ) was applied to assess the relationship between the number of times urologists changed their surgical planning decisions and the percentage of urologists who believed the 3D reconstruction altered their anatomical perception. The results yielded a ρ value of 0.659, indicating a moderate positive correlation between the analyzed variables ($p < 0.05$, two-tailed). Our results demonstrate that as the percentage of urologists who believe that 3D reconstruction alters their perception of renal anatomy increases, the average number of times they change their opinion on surgical planning also rises.

Discussion

In this study, we evaluate the effect of 3D reconstruction on surgical planning and the anatomical perceptions of kidney tumors. Our findings indicate that exposure to 3D reconstruction significantly alters urologists' perception of renal anatomy with the tumor, leading to changes in their surgical approach planning. After 3D exposure, urologists increased the choice of selective clamping and reduced the use of intraoperative USG and hemostatic agents in surgical planning. Our results suggest that 3D reconstruction may enhance understanding of renal anatomy, improving surgical planning and promoting adopting nephron-sparing approaches. Our study includes CT scans from 14 patients with moderate to high complexity lesions (R.E.N.A.L. score > 7). In this study, 18 urologists with experience in nephron-sparing surgeries evaluated 2D and 3D CT scans from pre-selected cases, resulting in 252 assessments. For each clinical case, the urologists were asked to consider the main surgical actions that could influence the outcome and the preservation of renal function during nephron-sparing surgery, before and after exposure to the 3D image reconstructions.

Our study revealed that after viewing 3D reconstructions, urologists changed their opinions more frequently when R.E.N.A.L. scores increased, reflecting the greater complexity of renal lesions. These findings suggest that in patients with high anatomical complexity, preoperative 3D reconstruction models may play a crucial role in planning surgeries for complex renal masses [12]. However, for extreme cases-either high or low complexity-3D reconstruction appears to have a limited impact on the decision to proceed with partial nephrectomy [16]. Urologists changed their opinions regarding surgical planning after viewing CT scans with 3D reconstruction in 13 out of the 14 cases evaluated. When analyzing the proportion of procedures adopted according to the urologists' opinions before and after viewing the 3D reconstruction, significant changes were observed in certain surgical practices. These included an increased preference for selective clamping, reduced use of intraoperative USG, and decreased use of hemostatic agents during surgery planning. A more selective clamping plays an essential role in vascular control of the renal hilum, which, along with kidney exposure, identification and isolation of the renal mass, tumor excision, and reconstruction of the parenchymal and collecting system defects caused by tumor removal, are among the most critical steps in partial nephrectomy [17].

Previous studies demonstrated that 3D visualization of the tumor and kidney during NSS increases the preference for selective versus total clamping, an increased incidence of tumor enucleation compared to resection, and a reduced likelihood of opening the collecting system [13]. In addition, 3D visualization reduces surgical duration and clamping time and decreases ischemia time and shorter hospital stays [18]. Reducing ischemia time in complex renal masses following 3D reconstruction can mitigate renal damage caused by prolonged ischemia [19,20]. Thus, surgical planning following the visualization of 3D images may result in clinical advantages, improve surgical outcomes, and facilitate the adoption of a nephron-sparing approach due to the reduced renal ischemia time. Furthermore, the use of 3D reconstruction can enhance the understanding of renal anatomy, particularly renal vasculature, thereby improving surgical planning [21], and reducing the reliance on intraoperative USG. Although 3D reconstruction influenced opinions on surgical planning, it did not lead to significant changes in the outcome regarding partial versus radical nephrectomy. A previous study demonstrated that after viewing 3D reconstructions of high-complexity tumors eligible for surgery, physicians changed their recommendations, increasing the indication for partial nephrectomy to 74.5 %. The opinions shifted independently of surgical experience [21]. In our case, the lack of change may have been influenced by the characteristics of the cases and/or the sample size.

After viewing the 3D imaging, the urologist participants in the study responded to a questionnaire regarding their perception of changes in surgical planning: "Do you believe that the 3D image reconstruction changed your perception of the renal anatomy with the renal lesion to the extent that it altered your surgical approach?" A correlation was established between this perception and the actual change in opinion regarding surgical conduct, revealing a moderate positive correlation between these variables. These data indicate that when physicians believe that 3D reconstruction enhances their understanding of renal anatomy in the context of a renal lesion, there is also an increase in their willingness to modify their surgical planning.

Currently, 3D reconstructed images are invaluable tools for surgeons enhancing their understanding of renal anatomy and lesions. These images are being utilized in robot-assisted surgeries through Augmented Reality (AR), aiding various applications in surgical planning, execution, and education [22]. The integration of 3D guidance with AR enables precise identification of lesions and intraparenchymal structures, offering a more accurate perception of their location and nature compared to standard 2D ultrasound orientation [23]. Despite recent technological advancements, 3D reconstruction techniques are still developing. Several technical issues need to be addressed in future studies, as the process of reconstructing 3D models lacks standardization [24]. Our analysis has some limitations. Firstly, clinical cases exhibit heterogeneity. Although we selected examinations from patients with high and medium complexity lesions, the nephrometries varied, and the cases differed regarding tumor size and lesion location. Another factor to consider is the sample size. While some similar studies had even smaller samples, including 14 participants may still be insufficient to demonstrate statistically significant results. Additionally, the images were re-evaluated within a 4 to 5-week period, which may lead surgeons to recall previously viewed cases and potentially influence their decision-making in a similar manner as before. Lastly, changes in surgical planning based on

the evaluation of 3D images do not necessarily translate into the best option for the patient. A controlled study comparing surgical outcomes after viewing CT scans versus outcomes following CT scans with 3D reconstruction would be needed to establish this relationship.

Conclusion

Our results indicate that preoperative 3D reconstruction significantly influences surgeons' opinions regarding surgical planning by enhancing their perceptions of both renal anatomy and the renal lesion. 3D reconstruction may impact surgical outcomes by enabling the development of better operative strategies and promoting a nephron-sparing approach, which is particularly beneficial for complex cases. Furthermore, 3D reconstructions can be a supplementary tool for nephrometric systems, providing additional information to assess tumor complexity and supporting clinical decision-making.

Author Contributions: Conceptualization and Methodology: VCN; JLBM; FM. Acquisition of data: VCN; FM; GW. Analysis and interpretation of data: VCN; FM; GW. Drafting of manuscript and critical revision: VCN; JLBM; FM; GW. Technical and material support: JLBM; ADM; GRL.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics and Research Committee (CEP) of the Federal University of Santa Catarina (UFSC), protocol code No. 6.281.044.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Conflicts of Interest: ADM is a co-founder of InfiniBrains™, the company responsible for developing and owning the Docdo software. All other authors declare no financial interests or potential conflicts of interest.

Data available on request from the authors: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supplementary Material

S1: Questionnaire 1

1. Would you perform a biopsy of the lesion before surgery?

a. ( ) Yes

b. ( ) No

2. Considering the surgical methods available at your institution (Open surgery, Videolaparoscopic, and Robotic), which surgery would you perform?

a. ( ) Radical nephrectomy

b. ( ) Partial nephrectomy

The following questions apply if you answered "b" in the 2nd question of Questionnaire 1.

3. Which access route would you use?

a. ( ) Intraperitoneal

b. ( ) Extraperitoneal

4. What type of resection would you perform?

a. ( ) Enucleation

b. ( ) Segmental resection

c. ( ) Polar nephrectomy

5. What type of clamping would you use?

a. ( ) No clamping

b. ( ) Total clamping (arterial only)

c. ( ) Total clamping (arterial + venous)

d. ( ) Selective clamping

6. Which closure method (renorrhaphy) would you use?

a. ( ) One plane

b. ( ) Two planes

7. Is it necessary to use intraoperative USG?

a. ( ) Yes

b. ( ) No

8. Is it necessary to use a hemostatic agent?

a. ( ) Yes

b. ( ) No

S2: Questionnaire 2

Questionnaire used only after presentation of 3D reconstruction.

1. Did you think that the 3D image reconstruction changed your perception of the renal anatomy with the renal lesion to the point of altering your surgical conduct?

a. ( ) Yes

b. ( ) No

S3: Supplementary Table

ESM_3: Effect of 3D reconstruction on changes in surgical planning and perception of renal anatomy and lesion according to urologists.

Variables	Change in perception of renal anatomy after 3D imaging. N = 18 (%)	Number of changes in surgical planning after 3D imaging (mean ± SD)	p-value
Case 01 – High Complexity		5.1 ± 2.9	0.0001*
No	7 (39%)		
Yes	**11 (61%)**		
Case 02 - Medium Complexity		1.7 ± 2.1	0.004*
No	10 (56%)		
Yes	8 (44%)		
Case 03 – Medium Complexity		2 ± 2.3	0.002*
No	7 (39%)		
Yes	**11 (61%)**		
Case 04 – High Complexity		2.2 ± 2.4	0.001*
No	9 (50%)		
Yes	9 (50%)		
Case 05 - Medium Complexity		1.8 ± 2	0.001*
No	4 (22%)		
Yes	**14 (78%)**		
Case 06 - Medium Complexity		2 ± 3.1	0.017*
No	9 (50%)		
Yes	9 (50%)		
Case 07 - High Complexity		0.7 ± 2.2	0.16
No	12 (67%)		
Yes	6 (33%)		
Case 08 - Medium Complexity		2.9 ± 2.9	0.001*
No	6 (33%)		
Yes	**12 (67%)**		
Case 09 - High Complexity		2.7 ± 3.3	0.004*
No	7 (39%)		
Yes	**11 (61%)**		
Case 10 - Medium Complexity		1.2 ± 2.1	0.03*
No	10 (56%)		
Yes	8 (44%)		
Case 11 - Medium Complexity		0.9 ± 1.3	0.007*
No	9 (50%)		
Yes	9 (50%)		
Case 12 - Medium Complexity		1.1 ± 1.1	0.0001*
No	8 (44%)		
Yes	**10 (56%)**		
Case 13 - Medium Complexity		2.6 ± 2.8	0.001*
No	8 (44%)		

Yes	**10 (56%)**		
Case 14 - High Complexity		3.1 ± 3.2	0.001*
No	5 (28%)		
Yes	**13 (72%)**		

*p < 0.05 when comparing the number of times physicians changed their surgical approach with the theoretical value of zero (indicating no change after the presentation of the 3D image); Student's t-test.