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Accuracy Assessment of a Three-dimensional Printed Model for Surgical Planning of Living Kidney Donors

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ABSTRACT

Introduction: Three-dimensional (3D) printing has emerged as a promising tool for surgical planning in living donor kidney transplantation, particularly for vascular anatomical assessment of the donor kidney. **Objective:** To develop a three-dimensional printed model for preoperative evaluation of the kidney donor and to assess its anatomical accuracy based on renal vessel length measurements. **Methods:** Observational, prospective, multicenter study including 15 kidney donors undergoing laparoscopic nephrectomy with polymer clips. Only left kidney cases with a single vascular trunk were included. 3D models were generated from computed tomography images through digital segmentation and printed in translucent resin. Vessel measurements obtained from the 3D model and from the surgical specimens were compared using an analog caliper. Linear association between measurements was assessed by Pearson's correlation coefficient, and agreement between methods by Bland-Altman analysis. **Results:** A very strong correlation was observed between renal artery measurements on the 3D model and the surgical specimen (R = 0.91), and a strong correlation for the renal vein (R = 0.85). Paired comparisons showed no statistically significant differences (artery: p = 0.614; vein: p = 0.268). Bland-Altman analysis, considered the reference method for comparing measurement instruments, demonstrated low mean bias with overall acceptable agreement, although with considerably wider limits of agreement for the renal vein (-9.79 to +7.21 mm) compared with the renal artery (-7.53 to +6.57 mm), reflecting greater variability in venous measurements. No severe complications (Clavien-Dindo ≥ 3) occurred among donors. **Conclusion:** In a sample of donors with single left-sided vessels, the results suggest that the 3D model exhibits strong linear association with actual measurements (Pearson correlation) and acceptable agreement with the surgical specimen (Bland-Altman analysis). These findings are preliminary and should not be generalized without confirmation in larger samples and more complex anatomies.

Descriptors: Kidney Transplantation; Living Donors; Preoperative Care; Printing, Three-Dimensional; Models, Anatomic; Renal Circulation.

Avaliação da Acurácia de Modelo Tridimensional Impresso para Planejamento Cirúrgico de Doadores Renais Vivos

RESUMO

Introdução: A impressão 3D tem se consolidado como ferramenta promissora no planejamento cirúrgico de transplantes renais intervivos, especialmente na avaliação anatômica vascular do rim doador. **Objetivo:** Desenvolver um modelo tridimensional impresso em 3D para avaliação pré-operatória do doador renal e verificar sua acurácia anatômica com base na mensuração do comprimento dos vasos renais. **Métodos:** Estudo observacional, prospectivo e multicêntrico, com 15 doadores renais submetidos à nefrectomia laparoscópica com clipes poliméricos. Foram incluídos apenas casos de rim esquerdo com tronco vascular único. Os modelos 3D foram confeccionados a partir de tomografia computadorizada com segmentação digital e impressão em resina translúcida. As aferições dos vasos foram comparadas entre o modelo 3D e as peças cirúrgicas, utilizando paquímetro analógico. A associação linear entre as medidas foi avaliada pelo coeficiente de correlação de Pearson, e a concordância entre os métodos por meio do método de Bland-Altman. **Resultados:** Observou-se correlação muito forte entre as medidas da artéria renal no modelo 3D e na peça cirúrgica

(R = 0,91), e forte correlação para a veia renal (R = 0,85). Quanto às medições pareadas, não demonstraram evidência de diferença estatisticamente significativa (artéria: $p = 0{,}614$; veia: $p = 0{,}268$). A análise de Bland-Altman, considerada o método de referência para comparação entre instrumentos de medição, demonstrou viés médio reduzido, com concordância global aceitável entre os métodos, embora com limites de concordância consideravelmente mais amplos para a veia renal (-9,79 mm a +7,21 mm) em comparação à artéria renal (-7,53 mm a +6,57 mm), refletindo maior variabilidade nas medidas venosas. Não houve complicações graves (Clavien-Dindo ≥ 3) entre os doadores. **Conclusão:** Em uma amostra de doadores com vasos únicos à esquerda, os resultados sugerem que o modelo 3D apresenta forte associação linear com as medidas reais (correlação de Pearson) e concordância aceitável com a peça cirúrgica (análise de Bland-Altman). Esses achados são preliminares e não devem ser generalizados sem confirmação em amostras maiores e anatomias mais complexas.

Descritores: Transplante de Rim; Doadores Vivos; Cuidados Pré-Operatórios; Impressão Tridimensional; Modelos Anatômicos; Circulação Renal.

INTRODUCTION

Living donor kidney transplants represent one of the most relevant therapeutic strategies for the management of end-stage renal failure, being directly influenced by the quality of surgical planning. Therefore, the preoperative period plays an extremely important role in the outcome of the case[1]. The selection of the donor kidney and a detailed assessment of the vascular and excretory anatomy are crucial steps for surgical success. In this context, these aspects are essential to guarantee anatomical and physiological integrity after the procedure[1].

Traditionally, Computed Tomography (CT) has been the gold standard for this analysis, providing accurate images of renal structures and their vessels[2,3]. Accurate determination of renal vessel length is a critical challenge in planning living-donor kidney transplants, with direct implications for the procedure's success, as anatomical variations can significantly increase the risk of perioperative complications. Currently, traditional imaging techniques provide two-dimensional information that, while detailed, can sometimes be limited in realistically demonstrating the situation[2,3]. In this context, three-dimensional printing (3D printing) emerges[4,5].

In recent years, 3D printing has become a promising complementary tool, capable of transforming 2D images into physical models that faithfully reproduce each patient's anatomical characteristics. This technology offers not only benefits in surgical planning, such as the simulation of procedures and the anticipation of technical challenges, but also educational and interdisciplinary communication advantages[6,7].

Despite growing interest in the application of three-dimensional printing in kidney transplantation, most available studies focus primarily on education, surgical simulation, or on improving surgeons' anatomical understanding. However, there is still a scarcity of work that quantitatively evaluates the anatomical accuracy of three-dimensional printed models based on real vascular structures encountered during surgery. In particular, the ability of these models to accurately reproduce the effective usable length of renal vessels after the vascular control stage, while accounting for technical factors such as clip placement or the actual level of vascular section, remains poorly explored in the literature.

In this context, the present study seeks to fill this gap by systematically comparing vascular measurements obtained from 3D-printed models—planned with pre-specified polymer clip placement—against direct measurements from surgical specimens. Thus, our work proposes not only to evaluate the anatomical accuracy of the 3D model but also to explore its practical applicability in the preoperative planning of living-donor kidney transplants, while acknowledging the limitations inherent in a small, selected sample.

METHODS

The present study is an observational, prospective, multicenter, method-comparison study, with pairwise analysis of agreement between measurements obtained from the 3D model and the surgical specimen, planned and executed according to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines, following the checklist stipulated for cohort studies.

As a multicenter study, the project was approved by two local ethics committees, registered under numbers 6,949,617 (University Tuiuti of Paraná) and 6,815,360 (Pontifical Catholic University of Paraná).

Inclusion criteria were: left-sided living kidney donors with a single vascular trunk who underwent laparoscopic nephrectomy using polymer clips, performed by a single surgeon across three hospitals in Paraná, Brazil.

To mitigate selection bias, we excluded right kidney donors, multivessel donors, open nephrectomies, and nephrectomies performed by surgeons other than the primary surgeon.

Sample size was calculated based on a two-tailed paired *t*-test (α=0.05; power = 80%; β=0.20), assuming a standard deviation of differences of 5 mm and a minimum clinically important difference of 3.5 mm. This yielded a minimum requirement of 15 donors (calculated n = 15.28).

Preoperative assessment and creation of the 3D model

Following a multidisciplinary assessment, the donor's eligibility and the laterality of the kidney to be transplanted are determined. If the left kidney was selected, the kidney donor was invited to participate in the study by signing a consent form.

Vascular and excretory anatomy were assessed using computed tomography (Siemens SOMATOM Sensation 64; slice thickness 1.0 mm; effective mAs 105). The contrast administration protocol used a 10–15-second delay and a flow rate of 3.0–3.5 mL/s. Following CT image acquisition, structures were segmented in DICOM format using Slicer 5.7 software (https://www.slicer.org). The kidney, renal artery, renal vein, an adrenal vein stump, and small segments of the aorta and inferior vena cava were selected for 3D modeling.

The modeling process was performed using Blender 4.0 software (https://www.blender.org), which enabled the necessary adaptations for model fabrication and the positioning of structures mimicking 2-mm-thick polymer clips at locations pre-specified by the surgeon. In the renal artery, clips were positioned 2 mm from its origin with 2 mm spacing between them, in accordance with the manufacturer's recommendations (Weck® Polymer Locking Ligation System, Wayne, USA). In the renal vein, the clips were positioned immediately distal to the insertion of the ipsilateral adrenal vein, also featuring two clips spaced 2 mm apart.

Three-dimensional printing of the models was performed using a translucent photopolymer resin (Anycubic®, Shenzhen, China). Each model was printed as a single piece (monoblock) with all segmented structures (kidney, renal artery, renal vein, aorta, inferior vena cava, adrenal vein stump, and polymer clip mimics) integrated.

Image segmentation, three-dimensional modeling, and the fabrication of printed models were carried out by a company specialized in three-dimensional medical printing, under the technical supervision of a radiologist expert in anatomical reconstruction and modeling for surgical purposes. The unit cost of the 3D models was US$ 83.30.

Measurement of renal vascular length in the 3D model

After the three-dimensional model was created, renal vessel length was measured directly on the printed specimen. Vascular length was defined as the distance between two previously standardized anatomical landmarks: point A, corresponding to the anterior lip of the parenchyma at the renal hilum; and point B, defined as the lateral face of the polymeric clip previously positioned on the model during the digital planning stage.

Measurements were obtained using an analog caliper [Rhosse®, ANVISA Registration: 80310620016], as illustrated in Fig. 1. All assessments were photographically recorded for documentation and subsequent verification.

The surgery

All procedures were performed by a single surgeon with extensive experience in laparoscopic donor nephrectomies.

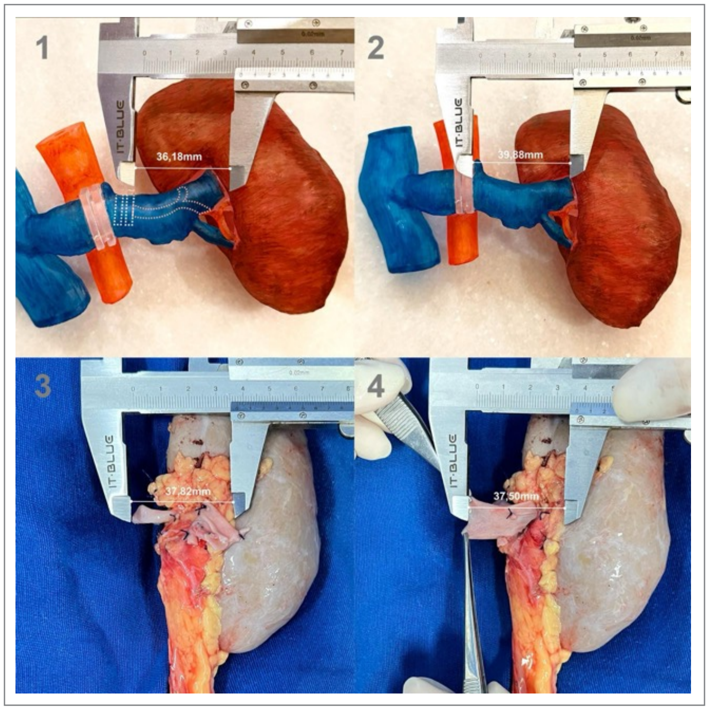
The technique used was pure transperitoneal laparoscopy, with vascular control using two polymeric clips (Weck® Polymer Locking Ligation System, Wayne, USA), placed approximately 2 mm apart. Patients were positioned in the right lateral decubitus position and underwent pneumoperitoneum using the Hasson technique. Three trocars were initially placed: (1) a 10-mm left pararectal trocar at the level of the umbilicus for the laparoscope; (2) a 5-mm left pararectal trocar 2 cm below the costal margin for the surgeon's left hand; and (3) a 10-mm trocar at the anterior axillary line at the level of the umbilicus for the surgeon's right hand. A fourth 5-mm trocar was placed at the posterior axillary line, 5 cm above the level of the umbilicus, whenever colonic mobilization was required.

Renal vascular control was performed using polymer clips according to the prior surgical plan established with the 3D model, followed by a transection 1–2 mm distal to the clips.

Measurement of renal vascular length

The length of the renal artery was determined as the distance between two previously standardized anatomical points: point A, corresponding to the anterior lip of the parenchyma at the renal hilum; and point B, defined as the most distal end of the renal artery at rest. For the renal vein, length was defined as the distance between Point A, corresponding to the anterior lip of the parenchyma at the renal hilum, and Point B, represented by the most distal end of the renal vein under light manual traction. This traction was sustained by two anatomical forceps and applied sufficiently to remove visible vessel redundancy without evidence of excessive stretching (Fig. 1).

During the measurements, the analysis was blinded: the surgeon responsible for the caliper measurements was unaware of the values previously obtained by another author before surgery. All measurements were re-verified and photographically recorded for documentation purposes.



Source: Elaborated by the authors.

Figure 1. Metric measurements were taken on the renal artery and vein, as well as on the 3D model and surgical specimen.

Variables analyzed

Other data analyzed were: age, gender, weight, height, Body Mass Index (BMI), surgery time, Cold Ischemia Time (CIT), Warm Ischemia Time (WIT), blood loss, need for bench surgery, length of hospital stay, Clavien-Dindo Classification, pre- and post-transplant creatinine (at hospital discharge).

Statistical analysis

The data compilation was performed using Microsoft Excel® software, version 16.85, and the statistical analysis was conducted using SPSS Statistics® software, version 29.0.1.1 (IBM Corp, Armonk, New York).

Continuous variables were expressed as mean ± standard deviation, and categorical variables as numbers and percentages. The Shapiro-Wilk test was performed on all variables to assess data normality. The correlation between the measurements of the 3D model and the surgical specimen was performed using Pearson's test. Mean paired differences were assessed using a paired *t*-test, and agreement between metric variables was examined by Bland–Altman analysis, with estimation of mean bias and limits of agreement. The Bland-Altman test was also applied to assess the agreement of the metric variables. For the Bland-Altman analyses, the differences were calculated as 3D model minus surgical specimen (3D model - specimen). Correlation was considered very strong when the R-coefficient was ≥ 0.90, strong between 0.70 and 0.90, moderate between 0.50 and 0.70, and weak when less than 0.50. Statistical significance was set at $p < 0.05$.

RESULTS

Fifteen living-donor kidney transplant cases, performed between April and August 2024, were included in the study and underwent preoperative evaluation using a 3D model. Twelve (80%) patients were female, the mean age was 39.7 ± 9.09 years, and the mean BMI was 26.2 ± 4.02 kg/m². The mean operative time was 87.1 ± 11.9 minutes; the mean cold ischemia time was 86.7 ± 24.2 minutes; and the warm ischemia time was 188.6 ± 89.1 seconds. The mean estimated blood loss was 76 ± 82.2 mL.

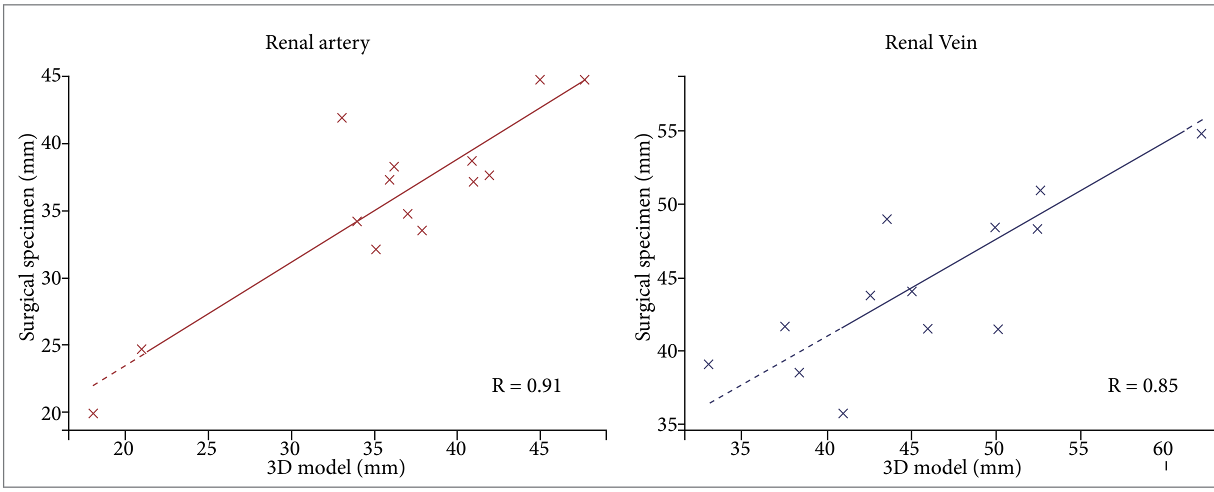
Two patients were classified as Clavien-Dindo Grade 2, one presenting with adynamic ileus and the other with a more prominent increase in creatinine levels (1.82 mg/dL). The mean creatinine increase was 0.42 ± 0.30 mg/dL. No patients experienced major surgical complications (Clavien-Dindo Grades 3, 4, or 5).

The results regarding the metric measurements of the renal vessels on the bench and 3D model are shown in Table 1. A very strong correlation (R = 0.91) was observed, with no statistically significant difference between paired measurements in the renal artery (p = 0.614). Regarding venous measurements, a strong correlation was noted (R = 0.85), also without evidence of a statistically significant difference between the measurements (p = 0.268) (Fig. 2).

Table 1. Results of bench and 3D-based metric assessments

	Bench (mm)	3D model (mm)	R Pearson*	*p*-value**
Renal artery	36.8 ± 8.4	36.3 ± 7.1	0.91	0.614
Renal vein	46.7 ± 8.21	45.4 ± 6.4	0.85	0.268

*Pearson's Test. **Paired *t*-test. Source: Elaborated by the authors.



Source: Elaborated by the authors.

Figure 2. Scatter plots demonstrating a very strong correlation in the renal artery and a strong correlation in the renal vein.

Based on the Bland-Altman analysis of renal vessel measurements, a mean systematic bias of -0.48 mm (SD 3.6 mm) was observed for the renal artery, with limits of agreement of -7.53 mm to +6.57 mm. For the renal vein, the mean systematic bias was -1.29 mm (SD 4.34 mm), with limits of agreement between -9.79 mm and +7.21 mm (Table 2).

Table 2. Bland-Altman analysis.

	Average bias (3D model - surgical specimen) (mm)	Standard deviation (mm)	Minimum (mm)	Maximum (mm)
Renal artery	-0.48	3.6	-7.53	6.57
Renal vein	-1.29	4.34	-9.79	7.21

Source: Elaborated by the authors.

DISCUSSION

Three-dimensional printing has emerged as a promising tool in surgical practice, especially in urology, enabling the creation of precise anatomical models that aid preoperative planning and understanding of complex anatomy. These three-dimensional models facilitate the spatial visualization of anatomical structures when compared to traditional two-dimensional images, contributing to more individualized surgical strategies[8-10].

In urologic oncology, 3D models have been used to improve understanding of relationships between tumors and adjacent structures. In prostate cancer, for example, customized models can help identify tumor location in relation to neurovascular bundles, favoring nerve-sparing prostatectomies and potentially better functional outcomes[9,11]. In kidney surgery, three-dimensional models also allow for better evaluation of the relationships between the tumor, vessels, and collecting system, contributing to greater precision in partial nephrectomy and preservation of the renal parenchyma[12-14].

In kidney transplantation, 3D printing is being applied to both surgical planning and operative simulation, allowing a better understanding of vascular anatomy and preoperative training. Recent studies demonstrate that patient-specific three-dimensional models can improve surgeons' anatomical understanding and aid in technical preparation for complex kidney transplants[5,15-18].

In living-donor kidney transplantation, graft vascular length is a critical factor for anastomotic success and the prevention of technical complications such as thrombosis or vascular stenosis. Therefore, a detailed preoperative assessment of vascular anatomy is fundamental, particularly in cases of anatomical variations or multivessel anatomy[4,5]. Furthermore, bench vascular reconstruction has been previously described as an independent risk factor for transplant renal artery stenosis, underscoring the importance of precise surgical planning[19].

In this context, three-dimensional models offer a more intuitive visualization of the donor's vascular anatomy, enabling anticipation of relevant technical details, such as the optimal level of vascular dissection and the positioning of clamping devices. This approach can aid in preserving vascular length and in defining the most appropriate surgical strategy[20,21].

Historically, digital subtraction angiography was considered the gold standard for renal vascular assessment. However, less invasive methods, such as multidetector computed tomography (MDCT) and three-dimensional magnetic resonance angiography (3D-MRA), demonstrate high accuracy in evaluating renal vascular anatomy and are currently widely used in the preoperative assessment of living donors[22-27].

Another relevant aspect is the cost of the technology. Systematic reviews demonstrate a wide variation in the costs associated with three-dimensional printing in urological practice, ranging from approximately US$ 3.90 to US$ 1,000 per model[8,10]. In the present study, the average cost was US$ 83.30, a value consistent with the literature and potentially viable for clinical application.

Among the limitations of this study, the exclusion of donors with complex vascular anatomy or right kidneys stands out, situations in which three-dimensional planning could have an even greater impact. Furthermore, a control group using traditional measurement methods, such as evaluation based exclusively on tomography, was not included. Additionally, no formal analysis of intra- and interobserver variability was performed, which represents a methodological limitation.

The strengths of this study include the standardized workflow for segmentation, modeling, and printing, conducted under specialized technical supervision, as well as the uniformity of the surgical technique, performed by a single surgeon. These factors contributed to the model fabrication process and ensured the technical reproducibility of the modeling stage.

The results demonstrated a good linear association between the measurements obtained in the 3D model and those measured in the surgical specimen. For both the renal artery ($R = 0.91$) and the renal vein ($R = 0.85$), the correlations were strong, and there was no statistically significant difference between the paired measurements ($p > 0.05$). However, as widely reported in the literature, Pearson's correlation does not imply agreement between measurement methods; the Bland-Altman analysis is the statistical reference tool for this evaluation. Therefore, the results of the Pearson correlation should be interpreted as complementary, while the Bland-Altman analysis constitutes the main interpretative pillar of this study. Bland-Altman analysis demonstrated acceptable overall agreement between the 3D model and the surgical specimen.

Regarding sample size, the calculation was based on a two-tailed paired *t*-test ($\alpha = 0.05$; power = 80%; $\beta = 0.20$), with an estimated standard deviation of differences of 5 mm and a minimum clinically relevant difference of 3.5 mm, resulting in a minimum sample size of 15 donors (calculated n = 15.28). Although the *a priori* sample size calculation supported the statistical viability of the proposed analysis, the limited number of cases still warrants caution in interpretation and restricts the generalizability of the findings.

Although we adopted 5 mm as a clinically acceptable margin for planning and interpreting differences between methods, this value should be understood as an operational premise of the present study rather than a universally validated threshold. In living-donor kidney transplantation practice, small variations in vascular length can be technically relevant. Studies on donor kidney laterality and on renal vascular control methods reinforce the clinical relevance of differences measured in millimeters[20,21]. However, there is no consensus establishing 5 mm as a universal cutoff point; therefore, this value was used in this study as a pragmatic reference for comparative analysis between the 3D model and the surgical specimen.

Based on the Bland-Altman analysis of renal vessel measurements, a low mean systematic bias was observed between the 3D model and the surgical specimen. For the renal artery, the mean difference was -0.48 mm (SD 3.60 mm), with limits of agreement ranging from -7.53 mm to +6.57 mm, indicating a near-zero mean difference and no clinically relevant systematic bias from the 3D model. For the renal vein, the mean difference was -1.29 mm (SD 4.34 mm), with limits of agreement ranging from -9.79 mm to +7.21 mm, suggesting a slight tendency toward underestimation and, notably, greater variability between measurements.

The limits of agreement for the renal vein were considerably wider than those observed for the renal artery, reaching nearly 10 mm at the lower end. This amplitude reflects greater imprecision in the 3D model's estimation of venous length, which has direct clinical relevance: in living-donor kidney transplantation, variations of this magnitude in renal vein length can influence the vascular anastomosis strategy, potentially necessitating bench venous extension and its inherent risks. Although the average bias was small for both vessels, the observed individual dispersion, particularly in the renal vein, deserves highlighting in the interpretation of the results and certainly limits their clinical extrapolation.

Furthermore, the renal vein was found to have a greater mean length in the surgical specimen compared to the 3D model. This finding may be related to the slight traction applied during the measurement of the surgical specimen to remove the vessel's natural redundancy. Since the 3D model represents the vascular anatomy at rest, this difference may reflect the variation introduced by manipulation during intraoperative measurement.

From a clinical perspective, these results suggest that three-dimensional models can provide potentially useful estimates of effective vascular length during surgical planning for renal donors, particularly the renal artery, aiding in predicting surgically usable vascular length and in planning pedicle dissection and vascular clip placement.

CONCLUSION

In selected renal donors with a left kidney and a single vascular trunk, the fabricated 3D models showed a strong linear association and acceptable overall agreement with measurements obtained from the surgical specimen, as assessed by Bland-Altman analysis. However, it should be noted that the limits of agreement were wider for the renal vein, which should be considered in the clinical interpretation of the results. These findings should be interpreted as preliminary, derived from a small, selected sample. Still, they suggest that the printed three-dimensional model may be a useful tool for preoperative planning in this specific subgroup. Studies with larger samples and more complex anatomies are needed to confirm the applicability and generalizability of these results.

CONFLICT OF INTEREST

The authors declare no direct financial conflict of interest. The company specializing in 3D printing performed the technical steps of digital segmentation, modeling, and printing of the models according to a protocol previously standardized by the research team, without participating in the study design, statistical analysis, data interpretation, or manuscript writing.

AUTHOR’S CONTRIBUTION

Substantive scientific and intellectual contributions to the study: Pimpão BF; **Conception and design:** Pimpão BF; **Data analysis and interpretation:** Pimpão BF; **Article writing:** Pimpão BF, Rocco ASCM, Lessa LV, Costa IR; **Critical revision:** Pimpão BF, Fraga R; **Final approval:** Pimpão BF, Rocco ASCM, Lessa LV, Costa IR, Fraga R.

DATA AVAILABILITY STATEMENT

Data will be available upon request.

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DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE TOOLS

The authors declare the use of artificial intelligence-based tools to aid in linguistic refinement and editorial structuring during manuscript preparation.

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