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ORIGINAL ARTICLE

Computed-tomography image segmentation and 3D-reconstruction of the female pelvis for the preoperative planning of sacrocolpopexy: preliminary data

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Abstract

Background Minimally-invasive sacrocolpopexy is the gold standard procedure for advanced apical prolapse. Nonetheless, sacrocolpopexy has potential serious complications leading many surgeons to avoid this excellent surgical procedure. To overcome these limitations, preoperative planning with 3D models of the female pelvis is proposed. The aim of the study is to evaluate the feasibility of pelvic anatomy reconstruction with the ITK-SNAP software and highlight its potential benefits in this intervention.

Methods Thirty patient-specific 3D models of the female pelvis were created using ITK-SNAP and the EndoCAS Segmentation Pipeline extension for image segmentation: contrast-enhanced computed tomography (CE-CT) data sets of women who underwent examinations for reasons other than prolapse were used. The distances of pelvic structures from the sacral promontory were standardised and measured, and correlations among these distances were evaluated with Spearman's correlation coefficient.

Results Pelvic anatomy reconstruction was feasible for all CE-CT data sets. A statistically significant correlation was found between the distances of the cava bifurcation and common iliac vessels from the sacral promontory. An area for proximal mesh attachment was defined: it is free from the passage of iliac vessels in 97.5% of cases. A significant statistical correlation was found between the distances of the midpoint of the bispinous diameter and the uterine cervix from the sacral promontory; a process of linear regression showed that the latter measure can be estimated by multiplying the first one by 0.86.

Conclusions Pre-surgical 3D reconstructions of the female pelvis using ITK-SNAP could help achieve widespread use of sacrocolpopexy: further comparative studies are needed to evaluate the outcomes with and without their use.

Keywords Image segmentation · Patient-specific 3D models · Pelvic reconstruction · Sacrocolpopexy · Surgical planning · Urogynaecology

Introduction

Minimally invasive sacrocolpopexy is the gold standard procedure for stage III–IV apical prolapse treatment [1–3], and it is performed with traditional laparoscopy [4] or, more frequently, robot-assisted surgery [5]. Many operators tend to avoid this excellent procedure for the treatment of pelvic organ prolapse (POP) as the isolation of the presacral ligament requires working close to delicate anatomical structures such as the vena cava bifurcation and iliac vessels. Moreover, performing the dissection of the presacral space carries a risk of haemorrhage, which can be difficult to manage [2, 6, 7]. These factors can interfere with the outcome of the surgery. Moreover, tailoring the surgical procedure in POP surgery is relevant for surgical outcomes [8]. Therefore, the perfect tensioning of the mesh represents another critical surgical step of sacrocolpopexy: an excessive laxity of the prosthetic device can undermine the surgery's utility, while excessive tension of the mesh can cause chronic pain and discomfort [2].

In this context, surgical planning of sacrocolpopexy with a patient-specific 3D reconstruction of the pelvic anatomy could be helpful to perform a safer, patient-tailored surgery. This

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would make sacrocolpopexy practical even for surgeons who are less experienced with this technique. The benefits of the application of 3D models in surgery have already been outlined in several studies [9, 10]. Currently, segmentation tools are often integrated with radiological software, even though 3D models are not widely used in everyday surgical practice. This is probably because of the time required to learn how to use these tools and the necessity of specialised personnel [11].

This research project arises from a collaboration with the engineers of the Center for Computer Assisted Surgery of the University of Pisa, EndoCAS (www.endocas.org). Working on the open-source ITK-SNAP software, the EndoCAS Center perfected an extension called the EndoCAS Segmentation Pipeline. Using this software and its extension, we segmented 30 contrast-enhanced computed tomography (CE-CT) image data sets, obtaining 30 patient-specific 3D models of the pelvis. Series of standardised parameters were measured on the 3D models obtained to find numerical relations that enable the characterisation of the anatomical relationships among the pelvic structures.

This article first evaluates the feasibility of CE-CT image segmentation with ITK-SNAP and the EndoCAS Segmentation Pipeline for the creation of patient-specific 3D models of the pelvis. Second, another objective is to assess the potential numeric relations among the distances of the main anatomical structures of the presacral area from the theoretical point for mesh attachment during sacrocolpopexy to describe a "safe area" in the sacral promontory to fix the mesh. The last objective is to preoperatively define a mathematical relation to estimate the length of the mesh required for a patient undergoing sacrocolpopexy.

Materials and methods

ITK-SNAP is a software for 3D model creation expressly produced by Cognitica Corp. to make semiautomatic segmentation accessible to a wider range of users [12]. The segmentation is the process needed to obtain 3D models starting from 2D images: it consists of the characterisation of each voxel by its nature, not only by its intensity [11]. In other words, the segmentation of a structure consists of colouring its voxels with a specific label. The EndoCAS Segmentation Pipeline is a semiautomatic segmentation tool based on the region-growing algorithm: it requires the user's interaction to set parameters that can be modified in the function of the segmentation result. Together, ITK-SNAP and the EndoCAS Segmentation Pipeline have been shown to permit the generation of patient-specific 3D models of several anatomical regions from a CE-CT image [11]. The major advantage of ITK-SNAP with the EndoCAS Segmentation Pipeline compared with other segmentation tools is a simple and user-friendly interface that allows the operator to obtain a 3D model in less time [12]. The segmentation process with ITK-SNAP is simple and intuitive and can be performed by any doctor after engineering training in the use of the computer programme: two or three assisted reconstructions are generally sufficient to learn all the software commands. No technical support is needed on a continuing basis, but the obtained 3D reconstructions have to be validated by an expert radiologist if being used for surgical planning.

We selected 30 CE-CT examinations of female patients who underwent the imaging examination for reasons other than prolapse from our hospital's radiological database. The mean age of our sample was 59 ± 15 years. The BMIs of these patients were not reported on radiological records. The slice thickness of the CE-CT examinations varied between 3 and 0.625 mm. With adequate anonymity, patients' data sets were organised in directories by phase identifiers. Every patient had a basal, arterial, venous and delayed phase in their data set. As is well known, contrast enhancement is necessary for the segmentation process to allow better distinction between anatomical structures.

CE-CT image segmentation was performed with ITK-SNAP implemented by the EndoCAS Segmentation Pipeline extension. The creation of 3D models involves a series of segmentation processes: each one foresees the labelling of the voxels belonging to the same anatomical structure. The user has to set two parameters: the grey levels to include in the segmentation and the starting point of the algorithm. After this step, the software automatically starts labelling the neighbouring voxels included in the selected grey levels. A 3D preview of the segmentation result is then displayed, and, if necessary, it can be immediately corrected by modifying the above-mentioned parameters (Fig. 1). Once the result is acceptable, the segmentation continues with the next anatomical structures, and the process is repeated. The software automatically integrates the segmented structures in a single 3D image.

The segmentation process involved the following anatomical elements: the pelvic bones (hip, sacrum, coccyx and last lumbar vertebrae), caudal parts of the abdominal aorta and inferior vena cava, common iliac vessels with their branches, ureters and uterine cervix (Fig. 2). To create the 30 3D models, the segmentation sequence of the anatomical structures of interest was standardised. The bone voxels were first labelled from the delayed phase of the CE-CT examination. Second, the arterial vessels were segmented from the arterial phase. Therefore, the venous vessels were reconstructed from the venous phase. Finally, the ureters and uterine cervix were segmented from the delayed phase (Fig. 2). This approach allows reconstructing the structures whose voxels could possibly interfere with the labelling process of other anatomical structures in advance. In fact, the algorithm automatically excludes voxels that have already been labelled. Three-dimensional models were then examined and validated by the radiologist.

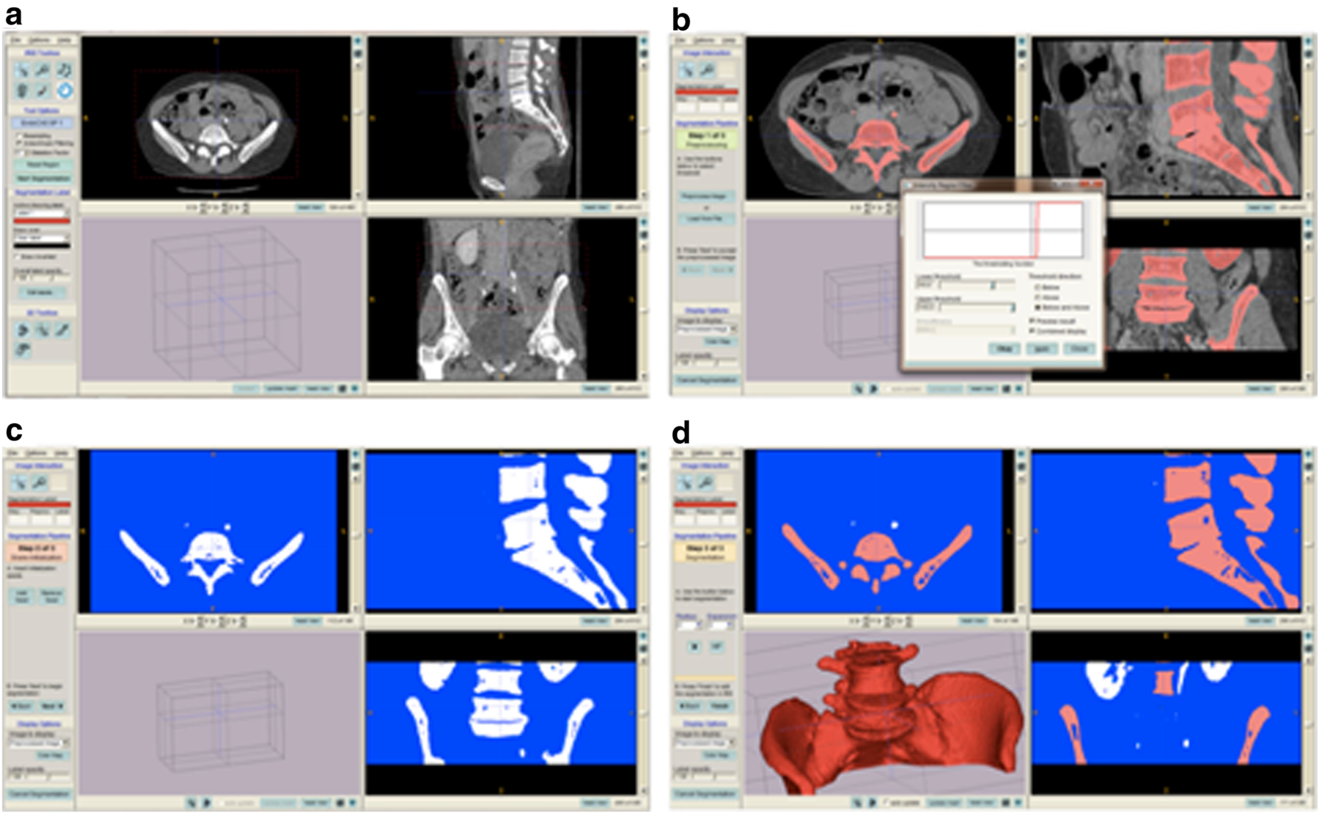

Fig. 1 Segmentation process with ITK-SNAP **a** Identification of the segmentation volume and selection of the label to use (colours can be modified later). **b** Selection of the grey level thresholds to include in the segmentation: results are shown in 2D windows in real time. **c** Binarisation of the image and placement of the seeds (starting points of the segmentation algorithm). **d** After running the algorithm, the result is shown in the 3D window

Based on the literature data [6, 13, 14], the theoretical attachment point of the mesh was standardised as follows: the point on the upper margin of the S1 corpus resulted from the anterior projection of the midpoint between the centre of the S1 upper endplate and its right border. We referred to this point as the “C-point”. Its exact location was defined for each 3D reconstruction. The measurements taken on 3D models were standardised to obtain reproducible results among patients. All of the considered measurements are computed based on their distance from the previously defined C-point and calculated point to point in the 3D space. We measured the distance of the vena cava bifurcation (C-VCB), considering the lowest labelled voxel before the branching in the common iliac veins. The distance of the right common iliac vein (C-RCIV) was measured on the same horizontal plane of the C-point. Two distances were measured for the left common iliac vein: the first (C-LCIV 1) was taken on the same horizontal plane as the C-point; the second (C-LCIV 2) was taken considering the nearest point of the vein to the C-point in 3D space. The distance of the right ureter (C-RU) was measured on the same horizontal plane of the C-point. The distance of the midpoint lying on the bispinous diameter (C-MBS) and the distance of the uterine cervix (C-UC) considering the external orifice of the cervical canal were measured.

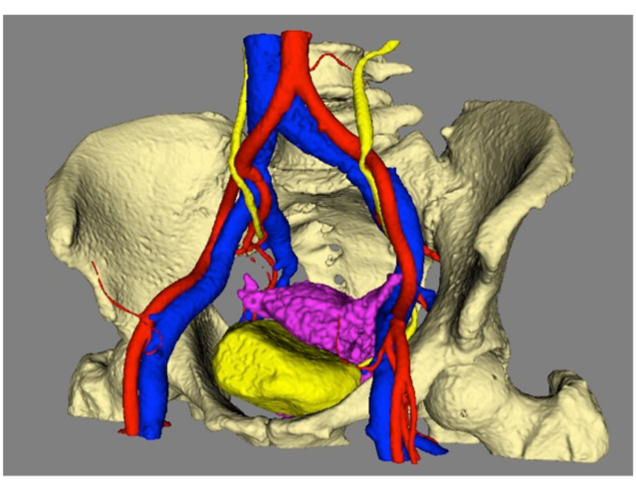

Fig. 2 Example of the final result of the CE-CT image segmentation process: the patient’s 3D model of the pelvis can be zoomed, rotated and seen from different perspectives

The obtained measures were expressed in millimetres. For each anatomical element we computed the mean value of its distance from the C-point and its standard deviation. The presence of statistical correlations among the above-mentioned measures was evaluated with Spearman’s correlation coefficient (ρ_s). The relationship between the hypothetical length of the mesh assessed by measuring the distance C-UC (dependent variable) and the distance C-MBS (independent variable) was modelled using linear regression. This study was approved by the Institutional Review Board of the University of Pisa (protocol number 808–2015).

Results

The segmentation with ITK-SNAP and the EndoCAS Segmentation Pipeline and the reconstruction of the pelvic anatomy were finalised in all of 30 patients. The pelvic bones, arterial vessels and venous vessels were segmented for all CE-CT examinations independently from the slice thickness of the examination. The cervix was not visualised in 6 of 30 patients. The right ureter was not visualised at the level of the C-point in 10 of 30 patients. Small presacral vessels, such as the middle sacral artery and presacral veins, were not visualised by our algorithm in any of our patients.

The arithmetic means of our measurements as well as their standard deviations and the results of the mean value minus two standard deviations were calculated (Table 1).

A significant statistical correlation was found between the distances C-VCB and C-RCIV ($\rho_s = 0.65$ with a significance level < 0.01), between the distances C-VCB and C-LCIV 1 ($\rho_s = 0.42$ with a significance level < 0.05) and between the distances C-VCB and C-LCIV 2 ($\rho_s = 0.78$ with a significance level < 0.01). Other statistical correlations were found among other measurements, but they lacked clinical relevance for the evaluation of the presacral area (Table 2). The C-RU distance showed no significant statistical correlation with other considered measures.

A significant statistical correlation was also found between the distances C-UC and C-MBD ($\rho_s = 0.579$ with a significance level < 0.01). The linear regression of the data obtained from these two measures resulted in a regression equation with an angular coefficient of 0.86 and an associated R^2 statistic of 0.29 (Fig. 3). The standard error of the estimate calculated from the regression equation is 12.6 mm.

Discussion

The main result of this study is that patient-specific reconstruction of the pelvis with ITK-SNAP and the EndoCAS Segmentation Pipeline was feasible in all the women in the study. In 10 of 30 patients it was not possible to visualise the right ureter at the pelvic brim: this was likely due to ureteral peristalsis that “squeezed away” the iodinated contrast medium. The cervix was not correctly visualised in six of our patients, perhaps because of a limitation of the technique, but it could also have been caused by a previous hysterectomy, considering that the clinical history of the study patients was not known.

The surgical approach to the presacral area during sacrocolpopexy may be challenging for many surgeons of the pelvic floor and potentially associated with serious intraoperative complications. Awareness of these potential complications during the identification of the presacral ligament discourages the recourse to sacrocolpopexy, therefore limiting the access of women with advanced apical prolapse to the best treatment option. The obtained 3D models are potentially valuable for surgical planning for sacrocolpopexy. It is reasonable to think that the accurate reconstruction of the promontory anatomy may offer the surgeon the possibility to better evaluate the presacral area available to fix the mesh preoperatively. For instance, low vena cava bifurcations and tortuous paths of the iliac arteries are conditions that complicate the presacral dissection, thus limiting the space available for the cranial mesh fixation. At present, these anatomical conditions are discovered by the surgeon during the procedure. The preoperative evaluation of such patient-specific variations can lead the surgeon to have a friendlier approach to this complex anatomical area or to change the surgical indication.

Another possible advantage of patient-specific reconstruction of the pelvis is the possibility to tailor the surgery to the patient; therefore, the 3D reconstruction may help in evaluating the optimal length and placement of the mesh required for a correct suspension and traction of the apical compartment for each patient, thus reducing the failure rate of this procedure, which is reported to be 6.4% in the literature [15].

Table 1 Mean values (MV) and standard deviations (SD) of anatomical structures’ distances from the theoretical point for proximal attachment of the mesh (C-point)

Distance	Sample size	Mean value (MV) [mm]	Standard deviation (SD) [mm]	MV – 2 SD [mm]
C-VCB	30	39	11	17
C-RCIV	30	14	5	4
C-LCIV 1	30	35	8	19
C-LCIV 2	30	30	6	18
C-RU	20	23	6	11
C-MBS	30	101	11	79
C-UC	24	85	14	57

In the last column, the values of “MV – 2 SD” indicate the “safe margin” starting from the C-point relative to each anatomical structure

Table 2 Correlations between the considered pelvic measurements: **ρ_s** Spearman's correlation coefficient; **α** significance level of the correlation. **N** Sample size, *significance level < 0.05, **significance level < 0.01

		C-VCB	C-RCIV	C-LCIV 1	C-LCIV 2	C-RU	C-MBD	C-UC
C-VCB	ρ_s		0.654**	0.418*	0.784**	−0.084	−0.612**	−.0457*
	α		0.000	0.022	0.000	0.724	0.000	0.025
	N		30	30	30	20	30	24
C-RCIV	ρ_s			0.413*	0.512**	0.077	−0.459*	−0.320
	α			0.023	0.004	0.745	0.011	0.128
	N			30	30	20	30	24
C-LCIV 1	ρ_s				0.705**	−0.095	−0.336	−0.273
	α				0.000	0.691	0.070	0.197
	N				30	20	30	24
C-LCIV 2	ρ_s					0.173	−0.644**	−0.423*
	α					0.466	0.000	0.040
	N					20	30	24
C-RU	ρ_s						−0.209	−0.026
	α						0.376	0.922
	N						20	16
C-MBD	ρ_s							0.579**
	α							0.003
	N							24
C-UC	ρ_s							
	α							
	N							

From the data obtained by our 3D models, a method can be established to preoperatively estimate the length of the mesh required for each patient undergoing sacrocolpopexy. Considering the cervix's position as the optimal point to suspend the apical compartment, the length of the mesh required for a patient corresponds to the distance C-UC. To estimate this parameter, it is possible to consider the correlation found between the distances C-UC and C-MBD. In fact, our data demonstrate the presence of a statistically significant relation between these two measures with a direct proportional relation. Consequently, for our sample group, the hypothetical distance between the cranial and caudal points of attachment of the mesh required for a correct tensioning corresponds to the distance C-MBD multiplied by 0.86.

The analysis of our data (Table 1) shows the possibility to detect an area in the sacral promontory adequately far from the

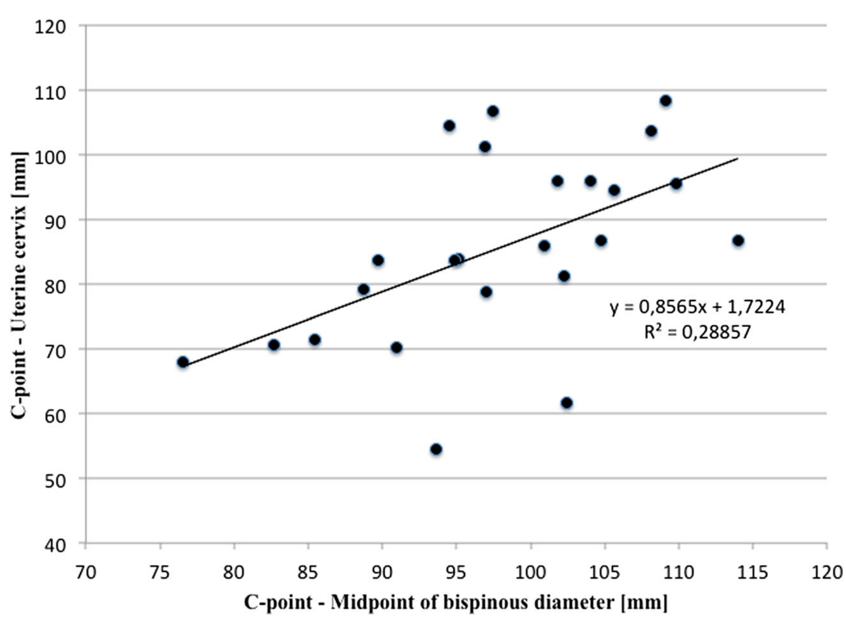

Fig. 3 The graph shows the relation between the distance C-UC (y-axis, dependent variable) and the distance C-MBD (x-axis, independent variable). The obtained correlation equation can be used to estimate the length of the mesh required for a correct tensioning of the apical compartment

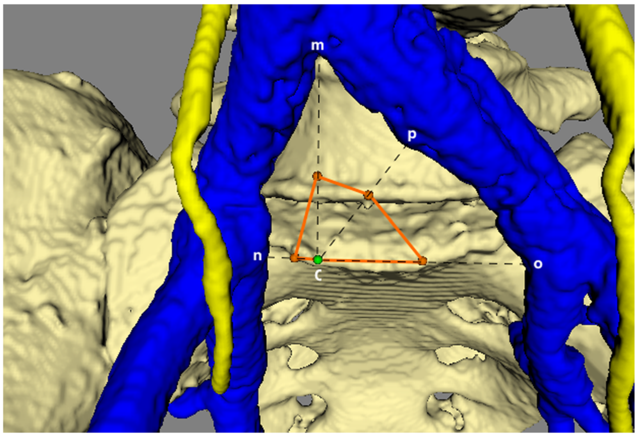

Fig. 4 The safe area identified for the mesh fixation is bordered in orange. *C* C-point. *m* Distance of the vena cava bifurcation (C-VCB). *n* Distance of the right common iliac vein (C-RCIV). *o* Distance of the left common iliac vein on the horizontal plane (C-LCIV 1). *p* Minimum distance of the left common iliac vein in 3D space (C-LCIV 2)

closest and most critical anatomical structures: this area is theoretically safe for fixing the mesh during sacrocolpopexy. To define the limits of this area, for each anatomical structure we considered the mean value of its distance from the C-point minus the value of two standard deviations. From a statistical standpoint, it was demonstrated that the computed value represents the safe margin starting from the C-point where the anatomical structure of interest is not found in 97.5% of cases. Applying this concept to all the analysed anatomical elements, it is possible to obtain a safe area with the shape of a polygon whose radii's lengths are the mean value minus the value of two standard deviations (Fig. 4). This result would be more valuable if these conclusions could be extended to the general population.

Clinically, an interesting element emerges from the interpretation of the observed correlation between the C-VCB and the distances from the C-point of the other venous elements. This implies that in those patients where the two common iliac veins originate at a cranial level, the venous axes are located further from the C-point: this implies a wider and safer space in the sacral promontory for the cranial attachment of the mesh. The opposite applies to those patients where the common iliac veins originate caudally, closer to the C-point. In summary, according to our results, the distance C-VCB can predict the space available for the proximal attachment of the mesh and potentially indicate greater difficulty in the surgical approach to the promontory, or even the necessity to perform another surgical procedure.

The limitations of our preclinical study are mainly related to the small number of women enrolled and to the fact that they were not selected from a group of women affected by POP, but from a radiological database. From a technical point of view, the greatest limitation to promontory segmentation was the impossibility to visualise and reconstruct small vessels running in the presacral region, such as the presacral veins. This was primarily due to the CT scan resolution, which did not allow the identification of these vessels, which could be the cause of intraoperative bleeding.

Another limitation is that there is currently no indication for performing a CE-CT scan before undergoing sacrocolpopexy, since apical prolapse is benign and not a life-threatening condition.

In conclusion, the main result of the study is that the patient-specific segmentation and reconstruction of the female pelvis with ITK-SNAP and the EndoCAS Segmentation Pipeline was feasible in all 30 cases. The analysis of the detected measurements demonstrated the presence of a polygonal-shaped area in the presacral region that is free from the main anatomical structures in 97.5% of the cases; here the surgeon can theoretically perform a safer presacral dissection and fixation of the mesh. Moreover, the identification of a mathematical relation that allows estimating the length of the mesh may lead the surgeon to perform a tailored approach to the apex suspension.

It is plausible to speculate that pre-surgical 3D patient-specific reconstruction of the female pelvis using ITK-SNAP and the EndoCAS Segmentation Pipeline can help achieve widespread use of an excellent technique such as sacrocolpopexy as well as optimal anatomic pelvic reconstruction. Moreover, planning sacrocolpopexy by using segmented images of the pelvis may be useful for teaching and simulating programmes.

Further and wider studies are needed to confirm the current results. The comparison of surgical outcomes after sacrocolpopexy performed with and without preoperative planning with 3D models is mandatory to assess the real benefit derived from this technology.

Compliance with ethical standards

Conflicts of interest Gianluca Albanesi, Andrea Giannini, Marina Carbone, Paolo Mannella, Eleonora Russo, Vincenzo Ferrari and Tommaso Simoncini have no conflicts of interest or financial ties to disclose.

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