Three-dimensional magnetic resonance based morphometric evaluation of the pyelocalyceal system after pyeloplasty

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Abstract

Purpose: The purpose of this paper is to evaluate the morphological changes after pyeloplasty using 3D modeling of the renal pyelocalyceal system and introducing the pyelocalyceal volume-surface ratio as a marker for assessment of the pyelocalyceal distension. Mesh generation tool for pyelocalyceal system analysis is proposed.

Materials & Methods: Eight patients with diagnosed ureteropelvic junction (UPJ) obstruction underwent open pyeloplasty. Three MRI (Magnetic Resonance Imaging) exams were performed in each patient: the first one, before pyeloplasty intervention, the second one, 2 to 4 weeks after the pyeloplasty intervention and the third one, 3 to 12 months after pyeloplasty intervention. Each MRI investigation consisted of a stack of 20 axial images (TR = 600 msec, TE = 19 msec, slice thickness = 7 mm). Images were processed with 3DSlicer, a specialized software for segmentation, 3D models generation and tissue meshing.

Results: Compared to pre-pyeloplasty values, the pyelocalyceal K indices were significantly changed on late exams (p = 0.017). Pyelocalyceal meshes were obtained.

Conclusion: Using the volume-surface index, the pyeloplasty intervention success is best assessed on late exams. Volume-surface index is proposed as an important parameter in evaluating treatment success after pyeloplasty surgery. Pyelocalyceal system meshes were obtained and proposed for an eventual finite element analysis.

Key words: mesh, MRI imaging, pyeloplasty, 3D modeling

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Introduction

Pyeloplasty represent the surgical technique of ureteropelvic junction (UPJ) reconstruction, in order to reduce intrarenal pressure and pyelocalyceal distension, ultimately improving renal function.

It is general knowledge that post-surgical renal function is related to post-surgical morphological renal changes [1-3]. Therefore morphometric studies during the course of pyeloplasty treatment and recovery are an area of intense research interest. One of the factors that define the success of the pyeloplasty intervention is the decrease in the pyelocalyceal volume [2; 3]. Many studies use linear ultrasound measurements of the renal pelvis, calyx and parenchyma [1; 3-5]. This type of measurements may suffer from several error sources since both the level of the slice chosen for the measurement and the position of the relative organ in relation to the imaging plan can differ from one 2D (two-dimensional) ultrasound exam to another.

3D (three-dimensional) modeling and volume rendering methods has become the established imaging tool in many areas of medicine including obstetrics and gynecology, cardiovascular disease, oncology, neurology and neurosurgery as well as in interventional radiology [6]. 3D modeling and volume rendering methods offer marked improvements in organ volume assessment with superior standardization and lower inter and intra-observer variability [7]. However, at present, only a few reports have been published about the use of 3D volume assessment in the kidney. One of these reports demonstrated that 3D ultrasound is an accurate method for assessing the renal parenchyma volume and relative renal size in patients with hydronephrosis [8].

Another advantage of using volumetric instead of linear measurements is that they are more sensitive to morphometric changes. For example, for a spherical shaped object, a linear variation for a diameter of 20% means a volumetric variation of about 52%. Therefore, subtle morphological changes can be detected easier performing 3D modeling and volumetric measurements [6].

The surgical technique used for all patients in our study was the Hynes-Anderson technique for UPJ reconstruction. With this technique, the affected segment is excised, resulting in a reduction of the pelvis size [9] (Fig. (1)).

Due to the reconstruction of the pelvis, its capacity is changed after surgery. For recovery assessment, monitoring the renal pelvis volume after Hynes-Anderson pyeloplasty is less meaningful, as the residual reduced renal pelvis size reflects surgical technique [3]. Consequently, we used the ratio between renal pelvis volume and its surface ($K$, $K = \text{Volume/Surface}$, as a normalized morphologic index. The $K$ index can be used to compare pyelocalyceal systems of different shapes, in the same patient, at different time points during follow-up.

To our knowledge, there are no previous studies dealing with pyelocalyceal system 3D morphometry in pyeloplasty follow-up. Therefore the aim of the present study is to propose the $K$ index as a tool for assessing the renal collecting system after pyeloplasty.

The three-dimensional perspective on the pyelocalyceal system suggests the possibility to use mesh generation and, eventually, finite element analysis. Consequently, we show that meshes can be generated for this specific renal component and a further use of this tool might be of interest.

Materials & Methods

Eight adult patients (age range 19-52 years, mean age 31.5 years; one man, seven women) with UPJ obstruction (diagnosed by intravenous pyelography (IVP) and ultrasound exam) underwent open pyeloplasty intervention (Hynes-Anderson technique). MRI (Magnetic Resonance Imaging) exams were performed before pyeloplasty, two to four weeks after the pyeloplasty (early exam) and three months to one year after pyeloplasty (late exam). The MRI system is a low field 0.28 Tesla (T) machine, Bruker, Germany. A phased array body coil was used for abdominal imaging. The patients were imaged following three hours of fasting. The main purpose of the clinical MRI exam was to quantitatively assess the volume and area of the kidney collecting system and the volume of the renal parenchyma, before and after pyeloplasty intervention. At each MRI exam, a stack of 20 axial images (T1 weighted, TR = 600 msec, TE = 19 msec, slice thickness...
varied from 6 to 7.5 mm, FOV = 36 cm) was acquired. The images were processed with specialized software. 3DSlicer software (http://www.slicer.org/) was used to perform segmentation as well as quantitative analyses and generate 3D surface models of the pyelocalyceal system. The pyelocalyceal volume was assessed manually tracing the dilated collecting system contour through the series data sets. The sum of the above areas multiplied by the section thickness (automatically interpolated between traced slices) provided the total 3D model volume and area for the pyelocalyceal system.

IA-FE Mesh (http://www.ccad.uiowa.edu/mimx/IA-FEMesh/), a freely available software toolkit was used for pyelocalyceal hexahedral mesh generation for each patient, before and post pyeloplasty intervention.

A two-tailed paired t-test with a type I error probability of 5% was conducted to compare the early exam to the pre-surgical pyelocalyceal $K$ index values and the late exam to the pre-surgical pyelocalyceal $K$ index.

Results

Pielocalyceal system 3D models were obtained before, early post and late post pieloplasty intervention, for each individual. Corresponding hexahedral meshes were generated for each patient. Three-dimensional models generated for one patient are shown, as examples, in Fig. (2 a,b,c). Figure 3 shows one of the meshes generated in the late exam, post pyeloplasty, in the same patient.

The pyelocalyceal $K$ values on the early exam after pyeloplasty do not differ significantly from values before the pyeloplasty intervention ($p = 0.245$). The pyelocalyceal $K$ values on late exams showed a significant reduction ($p = 0.017$) compared to the pre-pyeloplasty intervention values. The $K$ values decreased gradually after the pyeloplasty intervention (Table 1).

Table 1: Pyelocalyceal volumes and $K$ index values as assessed before pyeloplasty, on early exam and on late exam after pyeloplasty.

<table>
<thead>
<tr>
<th>Patient nr.</th>
<th>Volume (ml)</th>
<th>$K$ index</th>
<th>Volume (ml)</th>
<th>$K$ index</th>
<th>Volume (ml)</th>
<th>$K$ index</th>
<th>Early vs. pre-values</th>
<th>Late vs. pre-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>128.84</td>
<td>0.00565</td>
<td>63.23</td>
<td>0.00416</td>
<td>13.14</td>
<td>0.00276</td>
<td>0.245</td>
<td>0.017</td>
</tr>
<tr>
<td>2</td>
<td>37</td>
<td>0.0033</td>
<td>68.6</td>
<td>0.00485</td>
<td>19.44</td>
<td>0.00257</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>55.08</td>
<td>0.00464</td>
<td>15.84</td>
<td>0.002473</td>
<td>5.923</td>
<td>0.001285</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>11.77</td>
<td>0.003186</td>
<td>28.2</td>
<td>0.003246</td>
<td>23.45</td>
<td>0.002597</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>16.9</td>
<td>0.002998</td>
<td>29.9</td>
<td>0.003854</td>
<td>10.65</td>
<td>0.002431</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>22.76</td>
<td>0.003444</td>
<td>17.7</td>
<td>0.003314</td>
<td>5.022</td>
<td>0.001908</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>43.4</td>
<td>0.003055</td>
<td>50.8</td>
<td>0.003529</td>
<td>46.14</td>
<td>0.004235</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>104.1</td>
<td>0.005721</td>
<td>50.9</td>
<td>0.003741</td>
<td>17.43</td>
<td>0.003944</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average ±SD</td>
<td>52.48 ±42.47</td>
<td>0.00367 ±0.001</td>
<td>40.64 ±20.39</td>
<td>0.00365 ±0.0008</td>
<td>17.64 ±13.74</td>
<td>0.002259 ±0.0005</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Discussion

A reduction of the pyelocalyceal system’s distension is an important index of patient recovery and surgical outcome after pyeloplasty. Our results demonstrated a statistically significant reduction in pyelocalyceal $K$ index later than 3 months after pyeloplasty intervention. The lower $K$ indexes indicate a lower degree of hydronephrosis in our patients at late exam. The $K$ values assessed on early exams are not significantly smaller than values before pyeloplasty, however, a gradual decrease for $K$ index in the pyeloplasty outcome can be noticed. This suggests that the success of the surgical intervention should be assessed on long-term follow-up.

Our results correspond to other findings in the literature dealing with kidney recovery after pyeloplasty intervention. Kis group observations are that improvements in pelvic dilatation are quite slow in the first postoperative year [4]. Significant changes should not be expected in the first few months. Another group noticed that renal function (assessed by serum creatinine level and glomerular filtration rate) improved gradually during the follow-up period [10]. Sheu group assessed, by isotope renal scans, the pyeloplasty outcome and noticed that 61.5% of the kidneys had a gradual improvement of renal function on follow-up [11].
Renal ultrasound three months after pyeloplasty demonstrated a significant hydronephrosis decrease and 12 months diuretic renography reveals a normal UPJ drainage. The authors suggest that these changes should not be expected in the short-term but on the long-term follow-up [12]. Other study results show that improvement on renal ultrasound after pyeloplasty appears to be gradual [1].

Most recent studies proved limitations to the 2D ultrasound technique (2DUS). It is operator dependent and can be inaccurate in irregularly shaped organs [8]. The 2DUS may also obscure subtle changes in slowly evolving renal morphological changes. Another study [9] focused on the advantages and disadvantages of using 3D ultrasound technique (3DUS) to assess overall kidney volume. Riccabona et al [6; 8] discuss the method’s potential for optimizing imaging comparisons standardization; they also showed that volume measurements were more accurate using a 3D imaging technique. The authors point out some of the drawbacks of the technique which include like limited spatial and grey-scale resolution as well as a reduced field-of-view [8].

Magnetic resonance imaging can overcome the imaging technique problems addressed above. To date, MRI 3D has only been scarcely used in assessing pyelocalyceal system distension and, to the best of our knowledge, it has not been previously used in the pyeloplasty follow-up. In our study, MRI was used in conjunction with 3D rendering methods. This combination may become a powerful tool in the follow-up of pyeloplasty.

Although the pyelocalyceal volume measurements provide us with information on the pyelocalyceal distension, there are reasons to consider the K index as a better indicator of kidney recovery after pyeloplasty intervention. One reason is that the pelvis is trimmed during pyeloplasty so that pelvis capacity is reduced by the intervention itself. Therefore comparing only the pyelocalyceal volumes may not be accurate enough. To eliminate surgical reduction of kidney size as a variable in kidney recovery, a normalization is necessary. The volume-surface ratio (K index) eliminates this variable. The volume-surface relationship has been largely used in biomedical studies to precisely characterize changes in tissue morphometry. Numerous reports have been using the K index to study the cellular growth, alveolar dispensability in lung inflation/deflation etc [13; 14], left ventricular anatomy and function [4; 15-17].

It is well known that the maximum volume for a specific area is comprised into a spherical shape. A sphere is the three-dimensional shape that has the greatest compactness, i.e. the largest volume-surface ratio. The hydronephrosis degree is related to the shape of the calyx/pelvis, a higher degree of hydronephrosis meaning a higher compactness for the pyelocalyceal system, actually, a maximum K index.

This generation of hexahedral meshes of the pyelocalyceal systems [Fig. (3)] intends to show that these tools, although they have been developed initially in the context of skeletal structures, can be applied to a virtually endless number of modeling. These meshes could eventually undergo a finite element analysis to assess the local forces acting on the pyelocalyceal system wall. Already, mesh generation and finite element analysis have been used in heart, vascular and musculoskeletal modeling [20; 18; 19] but it is the first time, in the present study, that this tool is used in pyelocalyceal system analysis. Further work is needed to obtain local forces/displacement information in pyelocalyceal morphological changes, using finite element analysis.

The main goal of the present study was to evaluate the morphometric changes after pyeloplasty intervention introducing the K index as a tool for pyeloplasty follow-up. A drawback of the present study is lack of a correlation with renal function quantitative assessment. In our study, the success of the pyeloplasty intervention was clinically assessed by the relief of pain and resolution of the pyelocalicectasis evaluated by IVP and ultrasound exams. It is very possible that K index be related to renal function and further studies focusing on this relationship might be of interest.

In conclusion, the K index is proposed for the pyelocalyceal distension assessment in patients following pyeloplasty intervention. The gradual improvement of K index correlates well with other group’s findings concerning the kidney anatomy/function changes after pyeloplasty. Pyelocalyceal system meshes are proposed for a further finite element analysis of the local forces and displacements.

References
Rezumat

Obiective: Scopul acestei lucrări este acela de a evalua modificările morfologice post pieloplastie folosind modelarea tridimensională a sistemului pielocaliceal, introducând raportul volum-suprafață a sistemului pielocaliceal ca marker de evaluare a distensiunii pielocaliceale. Propunem pentru analiza sistemului pielocaliceal metoda de generare a ochiurilor de reflea (“meshing”).

Material și metodă: Opt pacienți diagnosticați cu sindrom de joncțiune pielo-ureterală (JPU) au fost supuși pieloplastiei deschise. Câte trei examinări RMN au fost efectuate fiecărui paciente: prima, anterior pieloplastiei, iar cea de-a doua între două și patru săptămâni post pieloplastie, iar cea de-a treia între trei luni și un an de la pieloplastie. Imaginile au fost procesate cu “3DSlicer”, un program special pentru segmentare, cu generarea de modele tridimensionale a sistemului pielocaliceal, introducând raportul volum-suprafață a sistemului pielocaliceal ca marker de evaluare a distensiunii pielocaliceale. Propunem pentru analiza sistemului pielocaliceal metoda de generare a ochiurilor de reflea (“meshing”).

Rezultate: Comparativ cu valorile pre-pieloplastie, indicii pielocaliceali K au fost semnificativ modificată spre mai mici. La examenele uriale (p = 0.017), „Mesh”-ele (modelele) pielocaliceale au fost obținute.

Concluzii: Folosind indexul volum-suprafață, succesul intervenției de pieloplastie este cel mai bine evaluat la examenele uriale. Indexul volum-suprafață este propus ca un parametru important în evaluarea succesului terapeutic post pieloplastie. „Mesh”-ele pielocaliceale au fost obținute și propuse pentru o analiză eventuală finită a elementelor.

Cuvinte cheie: rezonanță magnetică nucleară, „mesh”, modelare tridimensională, pieloplastie