Semi-automatic assessment of pediatric hydronephrosis severity in 3D ultrasound

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Semi-Automatic Assessment of Pediatric Hydronephrosis Severity in 3D Ultrasound

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ABSTRACT

Hydronephrosis is the most common abnormal finding in pediatric urology. Thanks to its non-ionizing nature, ultrasound (US) imaging is the preferred diagnostic modality for the evaluation of the kidney and the urinary track. However, due to the lack of correlation of US with renal function, further invasive and/or ionizing studies might be required (e.g., diuretic renograms). This paper presents a computer-aided diagnosis (CAD) tool for the accurate and objective assessment of pediatric hydronephrosis based on morphological analysis of kidney from 3DUS scans. The integration of specific segmentation tools in the system, allows to delineate the relevant renal structures from 3DUS scans of the patients with minimal user interaction, and the automatic computation of 90 anatomical features. Using the washout half time ($T_{1/2}$) as indicative of renal obstruction, an optimal subset of predictive features is selected to differentiate, with maximum sensitivity, those severe cases where further attention is required (e.g., in the form of diuretic renograms), from the non-critical ones. The performance of this new 3DUS-based CAD system is studied for two clinically relevant $T_{1/2}$ thresholds, 20 and 30 min. Using a dataset of 20 hydronephrotic cases, pilot experiments show how the system outperforms previous 2D implementations by successfully identifying all the critical cases (100% of sensitivity), and detecting up to 100% ($T_{1/2} = 20$ min) and 67% ($T_{1/2} = 30$ min) of non-critical ones for $T_{1/2}$ thresholds of 20 and 30 min, respectively.

Keywords: Hydronephrosis, kidney, ultrasound imaging, computer-aided diagnosis, quantification.

INTRODUCTION

Hydronephrosis (HN), defined as dilation of the collecting system of the kidney, calices, and pelvis, is one of the most common genitourinary tract anomalies detected, reported in approximately 2-2.5% of children [1]. Ultrasound (US) imaging is the preferred modality used in diagnosis of HN, thanks to its non-ionizing and non-invasive properties, real time nature, safety, and relative low cost. However, the potential of US as diagnostic tool is limited due to the lack of direct correlation with functional imaging modalities, such as diuretic nuclear renography (DR), which is invasive and ionizing.

Currently, the most widely used US-based system for grading HN is the Society for Fetal Urology grading system. However, the subjectivity of this grading method results in significant inter-observer variation, especially for the most severe categories of HN [2]. Shapiro et al.[3] proposed one of the first objective measure of hydronephrosis severity, the
The hydronephrosis index (HI), defined as the ratio of the collecting system area to the total area of the collecting system and renal parenchyma. However, the practical utility of this index also remains unclear [4].

![Block diagram showing the principal elements of the proposed CAD system for pediatric hydronephrosis.](image_url)

Under the hypothesis that renal morphology is correlated with renal function, we have previously demonstrated the potential clinical value of quantitative image analysis in the assessment of pediatric HN [5]. From the manual segmentation of the renal parenchyma and collecting system in 2DUS, we defined a set of morphological descriptors able to predict the severity of HN. In spite of the promising results reported, methods working with 2D images can be affected by the subjective selection of a representative 2D sagittal slice that contains a longitudinal section of the kidney and the collecting system. 3DUS has the potential to reduce the operator dependence of 2D-based systems. However, the use of 3D quantitative imaging biomarkers requires significantly more user interaction to manually delineate the renal structures (up to several hours per case).

In this work, we present the first semi-automatic computer-aided diagnostic (CAD) framework for the assessment of pediatric HN using volumetric quantitative biomarkers from 3DUS (Fig. 1). First, an interactive model-based segmentation tool is used to delineate the contour of the kidney [6]. Once the kidney is segmented, the collecting system is automatically detected using an active contour-based method that mimics the propagation of fluid inside the kidney [7]. Finally, a set of 3D morphological descriptors of the renal system are automatically extracted and used as predictive features via a machine learning algorithm. A best-fit model is then derived to predict the severity of HN. The model is tuned to identify with maximum sensitivity the severe cases that require immediate medical attention, and detect non-critical cases where DR could be safely avoided.

**METHODOLOGY**

In this study, we consider a retrospective dataset (IRB approved) of 20 hydronephrotic consecutive patients of variable severity (defined by DR) and different ages (0-7 years). For each case, concurrent 3DUS (acquired using a Philips-iU22 system with X6-1xMatrix transducer) and DR (MAG-3) were acquired in order to study the correlation between renal function from DR and 3D renal morphological parameters from 3DUS. In particular, the DR parameter used to characterize the renal function was the washout half time \( T_{1/2} \) for urine in the kidney to drain, i.e., the time at which the washout curve decreases to half of its maximal value. Based on this DR parameter, urologists can define functional thresholds to identify hydronephrotic renal units where DR can be safely avoided. The main elements of the proposed framework are depicted in Fig. 1.

The input of the proposed CAD system is a 3DUS scan containing the entire volume of the kidney (Fig. 2.(b)). The segmentation of the kidney is obtained by means of a dedicated interactive segmentation tool with minimal user interaction (2-4 mouse clicks). The system incorporates an automatic kernel convolution-based kidney detector [6] that provides an initial estimation of volume, and thus, minimizes, or even suppresses user interaction. This initial segmentation is further refined by the user defining control points that constrain the deformation of the model. The system provides immediate visual feedback, which allows real-time response interactions for a fast and accurate kidney segmentation.

Once the kidney has been delineated, the collecting system is segmented using an active contour-based formulation designed to replicate the evolution of HN in the collecting system [7]. Using local phase analysis, the system incorporates a positive delta detector to identify the bands of adipose tissue that surround the collecting system. This allows creating specific probability positional maps to control the propagation of the contour. The detected adipose bands surround the dilated collecting system and constitute a key anatomical clue for its accurate delineation, allowing to...
differentiate the above from other hypoechoic structures (e.g., renal pyramids). The algorithm is automatically initialized by selecting the darkest 3×3×3 block within the region delimited by the detected adipose tissue.

Finally, the segmented renal structures (i.e., the kidney and the renal collecting system) are automatically processed using image analysis techniques to extract a set 90 3D morphological parameters. Following [5], these parameters can be divided in three different categories:

(i) **Size descriptors**: including the relative volume of the collecting system and the kidney (i.e., 3DHI), relative surface, and maximum and minimum parenchyma thickness (see Fig. 3(a)).

(ii) **Geometric shape descriptors**, such as the sphericity and the eccentricity of both, kidney and collecting system (see Fig. 3(a)).

(iii) **Curvature descriptors**, including the average curvature of the kidney, and the curvature dissimilarity between the calices and the kidney (see Fig. 3(b) and (c)).
Smallest Parenchymal Thickness
Large Parenchymal Thickness

1.0

Some of the morphological descriptors are depicted in Fig. 3. The aim of these parameters is to characterize quantitatively the anatomy of the hydronephrotic renal units, defining potential predictive variables of the functionality of the kidney (i.e., $T_{1/2}$).

From the high dimensional space of 90 predictive variables, an optimal subset of features is selected by means of the unsupervised feature selection framework proposed by Cai et al. [8]. Using a threshold of $T_{1/2TH}$ min to define severity, we use a support vector machine (SVM) with radial basis function kernel to classify each case as critical ($T_{1/2} > T_{1/2TH}$ min) or non-critical ($T_{1/2} \leq T_{1/2TH}$ min). Finally, receiver operating characteristic (ROC) curve analysis is used to identify probability thresholds that maximize the sensitivity of detecting severe cases of hydronephrosis; that is, no case with a washout time above the defined threshold is misclassified.

**RESULTS**

To evaluate the performance of the system, we studied two different threshold levels $T_{1/2TH}$ of half time considered clinically relevant: 20 and 30 min. The optimal set of predictive variables was selected using the area under the ROC curve (AUC) as criteria. For $T_{1/2TH} = 20$ min., the optimal performance was obtained with only two predictive variables: dilation of the collecting system (i.e., a shape descriptor that characterizes the distance of the collecting system to the renal pelvis), and the average curvature discrepancy between the calyces and the kidney. For $T_{1/2TH} = 30$ min, the system reached an optimal performance with 6 shape descriptors, adding the kurtosis, skew and entropy of the collecting system, and the sphericity of the kidney to the two aforementioned descriptors. The AUC, accuracy, sensitivity and specificity were 1, 1, 1, and 1 for $T_{1/2TH} = 20$ min (i.e., a perfect classifier is obtained), and 0.93, 0.94, 1, and 0.67 for $T_{1/2TH} = 30$ min, respectively (see Table 1).

The performance of the new 3D CAD system described above was compared with the original implementation described in [5] based on 2D morphological features. For this, a 2DUS slice containing a whole longitudinal section of the kidney and its collecting system was selected from the original 3DUS volume. The set of 2D planar predictive features were automatically extracted as described in [5]. The AUC, accuracy, sensitivity and specificity of this 2D CAD system is also shown in Table 1. As hypothesized, the use of 3D morphological features provides a better predictive capacity than the 2D features.
Table 1. Area under the curve, sensitivity, specificity, and accuracy obtained for two classifiers studied, 3D CAD, and 2D CAD.

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CONCLUSIONS

This paper describes for the first time the value of volumetric morphological analysis of the kidney in the assessment of pediatric HN, introducing the first semi-automatic CAD system based on the quantitative analysis of 3DUS. Besides the lack of studies on the characterization of the renal anatomy from US images and its relationship with renal function (DR), previous works in this field were limited by the subjective interpretation of 2DUS images. However, the kidney is a complex 3D structure. The proposed system includes dedicated segmentation tools for the accurate delineation and characterization of hydronephrotic kidneys, enabling the semi-automatic computation of new objective and reproducible morphological features of the complete renal structure in 3D. These tools were tailored for the particular challenges of 3DUS images, and provide an accurate segmentation with minimal user interaction, and the automatic extraction of 90 different anatomical features, including size, geometric, and curvature descriptors.

Using the washout half time from DR as clinical indicative of the severity of renal obstruction, an optimal selection of predictive anatomical features was extracted to identify, with 100% sensitivity, those critical patients with severe obstruction which would benefit from further invasive studies. Interestingly, the system identified new informative morphological parameters that correlate with renal function, such as the curvature dissimilarity between the calyces and the kidney, and the dilation of the collecting system, as alternative to the classical HI.

Using thresholds of 20 and 30 min for the washout half time, the system also identified 100% and 67% of the non-severe cases, respectively. These preliminary results obtained with a dataset of 20 hydronephrotic cases demonstrate how quantitative image analysis of the complete 3D anatomy of the kidney provides accurate and reliable diagnostic information of potential clinical utility in the assessment of pediatric HN.

The rationale behind the proposed CAD system is not to replace DR, but to permit more informed utilization of nuclear and invasive imaging modalities, thus limiting the use of ionizing tests and reducing clinical cost. In future work, we expect to continue the evaluation of the system on a larger number of cases, and study the potential of this methodology for clinical follow-up.

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REFERENCES


