Renal Volume Estimation by Ultrasound Parallel Scanning for Polycystic Kidney Disease Follow-up

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***Abstract*— Renal size provides information for the diagnosis and prognosis of kidney diseases. Volume measurement is usually based on semi-axis derived from Ultrasound (US) imaging. Complex pathologies such as Polycystic Kidney Disease (PKD) require complex imaging studies that include contrast media and ionising radiations (X Rays), which are not suitable due to toxicity and accumulation of radiation effects. We have developed NEFROVOL which is a low cost, non- invasive solution to reconstruct the renal structure and to estimate its volume. To do so, NEFROVOL processes parallel ultrasound images to generate a 3D kidney model. We suggest a way to record the set of images in a DICOM compatible way, since DICOM does not support multiple US slices, similar to CT scans. Tests on geometric solids, fruits and patients yield estimates within 10%, 17% and 25% of the real volume, respectively. NEFROVOL generates electronic medical record documents in CDA standard, as a single measure or as a trend over the years. NEFROVOL is compatible with 3D printing by generating files in STL format.**

***Keywords*— Polycystic Kidney Disease, Ultrasound, kidney volume, 3D printing.**

INTRODUCTION

Kidneys are a pair of organs located on both sides of the abdomen, that measure in the adult about l2 cm in length, 6 cm width and 3 cm thickness [l]. Inside the kidney, approximately one million nephrons perform blood filtration, disposing of waste and excess water in the form of urine. It is usual to record kidney volume in clinical practice, using ultrasound (US) equipment. The volume estimate is based on the geometric regularity of the normal kidney [4].

Polycystic kidney disease (PKD) is an inherited disorder in which clusters of cysts develop primarily within the kidneys, altering their geometry, their volume and their function. The cysts, as they accumulate fluid, can grow very large and since their location is random, the overall shape is altered resembling a fractal in some ways. One of the pieces of clinical evidence necessary for diagnostic and follow up is the volume growth rate [2].

But volume estimation in case PKD is present becomes difficult due to the irregular surface of the kidneys.

Available methods include the use of CT scans and MRI both with contrast injected. Proper image processing allows to estimate renal volume and thus to obtain a consistent follow up instrument. Accuracy is of the order of l0% [3] with 5% inter-operator variability in case of normal kidneys [4], when comparing the volume obtained by the ellipsoid formula to the contrast RMI image 3D processing.

Computed Tomography (CT) is an expensive and ionizing radiation-based method that cannot be repeated frequently, while Magnetic Resonance Imaging (MRI) could be used, albeit also an expensive procedure. In addition, for both methods, the contrast liquid used has a toxic effect on the kidneys, which have an already diminished renal function. A simple and non invasive volume estimation method is therefore needed.

Looking at the usual renal exploration available at the bedside, one sees US imaging, which can be repeated with no danger for the patient, and which gives an approximate idea of the size of each kidney. The clinician has nevertheless great difficulty in quantifying the volume to be recorded during PKD follow up, when the stage of the disease progresses. It is therefore difficult to formulate a prognostic judgment of the condition of the patient. Too much subjectivity is left to the interpretation of the US scan. Routine US scans does not show a 3D kidney reconstruction nor gives a reliable volume estimate.

We set ourselves the goal of developing an instrument which would take as much as possible from routine instrumentation and clinical habits, but capable of a clinically meaningful 3D reconstruction with a reliable volume estimation. We report in the present paper the theoretical and implementation details of a new instrument, called NEFROVOL, giving the first figures of volume estimation for regular geometric solid, fruit and vegetables, as well as normal kidneys. The gold standard is mathematical for regular solid, water displacement for fruit and vegetables and the semi-diametres formula for normal kidneys ""in vivo"".

Future publications will report on the measurement performed on PKD patients, having validated the method for increasingly complex bodies, simulating growing cysts.

DESIGN OF NEFROVOL

Basie Caneepts

The basic concept on which the design is based is that of obtaining a set of parallel US scans along the principal axis of the kidney. This axis can be difficult to determine in case of heavy renal deformation: we decide to take the principal axis in the anatomically original oblique direction of the normal kidney. This definition is not usual in clinical nephrology, as US scans are taken based on what the technician sees on the US screen. The 3D reconstruction is performed mentally by the health provider: we modify this aspect in order to obtain reproducibility and automatic 3D reconstruction, and thus volume estimation. To obtain a quantitative measurement of volume, we decided to obtain "sections" of the solid, and that these sections would be taken at a given constant distance from each other.

Epidermie Grid

We have designed a soft US transducer placement Grid (Figure l) to ensure a constant distance between US scans and to ensure thay are parallel. The material is lightweight, may be sterilized and is hypoallergenic. We designed the slots of the Grid for a particular US scanning head. The distance between slots is also known and shared with the NEFROVOL software, programmed to calculate volume.

Blaek Diagram

A block diagram of NEFROVOL is shown in Figure 2. The Epidermic Grid (Figure l) is located on the patient's skin, following the main axis of the kidney to be explored. The transducer located successively in the slots allows the health provider to obtain US scans, saved in the memory of the equipment. These files, one per image and in DICOM format, are fed to the NEFROVOL software. The NEFROVOL software is an interactive application to determine the boundaries of the kidney under study. The application also includes the calculations, after the kidney sections are obtained and delimited.

The final part of the Block Diagram is the report generation, in CDA format for the Electronic Clinical Record. In case NEFROVOL detects in its database more than one point in time, i.e. two US scans separated by more than one month, then the user can create an additional report, showing the evolution of kidney volume.

Fig. 1 Soft transducer guide Grid for NEFROVOL. Transducer dependent, the Grid ensures all US scans are equidistant and parallel. The distance between slots (2 cm) is compatible with certain transducers, but not all.

DICOM image standard includes several attributes [5] but was not developed to reconstruct volume quantitatively as is, for instance, a series of CT scans. CT scans do have their mutual distance defined in DICOM standard, so we have taken the same criterium to group US images, and to record their mutual distance, because 3D reconstruction from separate US sections is only possible if the distance between sections if known. To be able to re-create a 3D solid, we have thus included extra attributes in much the same way CT scan series have [5]. To the best of our knowledge, this is done here for the first time.

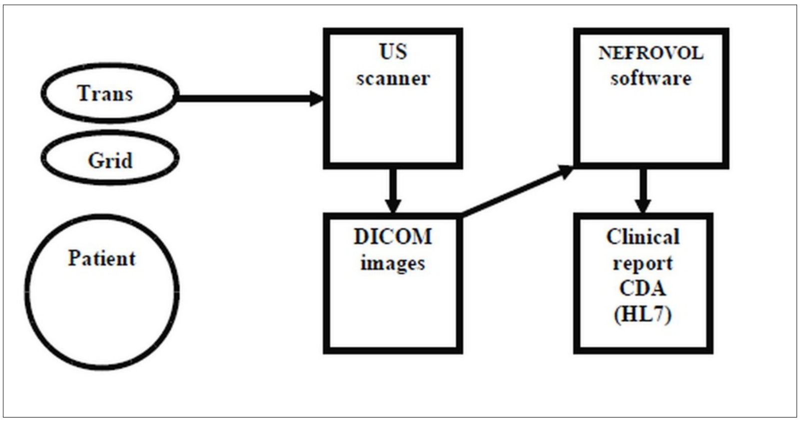

Fig. 2 Block Diagram of NEFROVOL. "Trans" is the US scanner transducer installed in the Grid located on the skin of the patient. The only hardware box if the US scanner, while DICOM images are transported to the NEFROVOL software for processing, CDA is the clinical report

RECONSTRUCTION OF KIDNEY VOLUME

We have developed a new method of measurement based on parallel and equidistant sections of the kidney, obtained by US scanning guided by a cutaneous soft grid. (Figure l).

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NEFROVOL handles from four to eight equally separated US scans in DICOM format. One of such scans is depicted in Figure 3, with a red contour drawn by the user, using the mouse. Clinical and physiopathologic expertise is important here, as any error at this stage will inevitably affect volume measurement later. From these images, NEFROVOL software extracts JPG images and keeps the contour in vector form. For volume reconstruction, we have considered two methods described as follows.

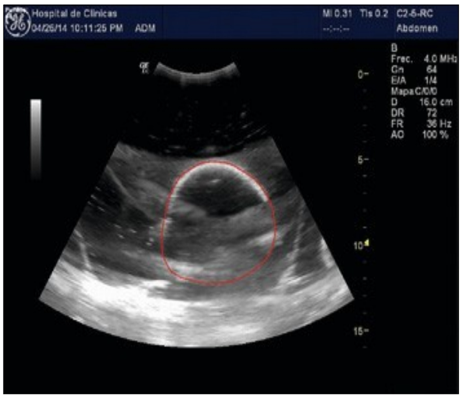

Figure 3: US scan processed by NEFROVOL.
The user has marked a contour around the solid whose structure is of interest.

Layered Canvex Hull

The Layered Convex Hull Method divides all points in layers horizontally displayed as in Figure 4 where each layer is shown in a different colour[6]. Every layer is structured as a convex container defined by Delaunay triangles. The total volume is the sum of layers.

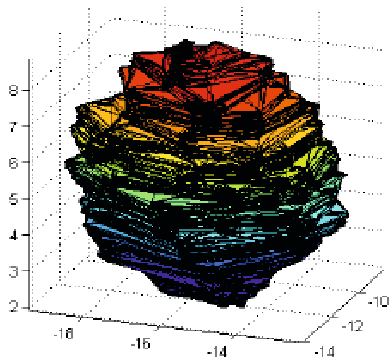

Figure 4: Layered Convex Hull applied to a structure. Taken from Fernández-Sarría et al. [6].

Valumetrie Pixel

The Volumetric Pixel Method is based on a three- dimensional matrix of [X, Y, Z] coordinates of the cloud of points conforming the volume. A voxel is defined as the elementary unit of volume. For every voxel, the method checks whether it intersects or includes any point of the solid. The total volume estimate is the sum of voxel volumes, respecting the scale [6].

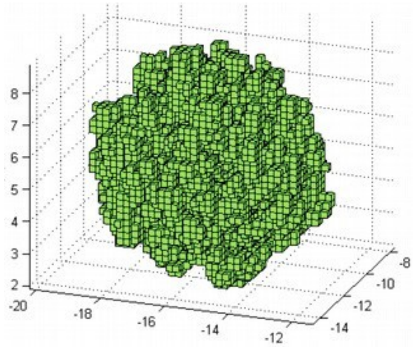

Figure 5: Volumetric Pixel Method. Volume is estimated as the sum of all voxels that belong to the solid.
Figure taken from Fernández-S et al. [6]

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Once the user has defined the contour of the kidney in all the US scan images, the points of the contour are used as vertexes of triangles formed by two adjacent contours. A mesh of triangles such as the one shown in Figure 6 is obtained [7]. The set of all such meshes represents the central part of the estimated volume of the kidney. The extremities are formed by a point at half the distance between cuts in the projection of the center of gravity of the last contour. In this way a practical and simple solution is suggested here for the kidney volume beyond the last US scan obtained. Fig. 8 shows one extrapolated extremity.

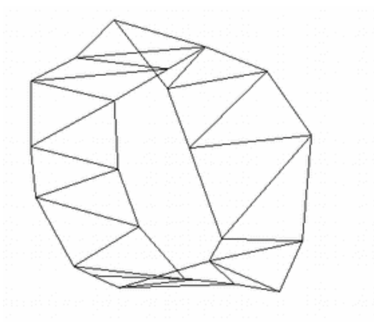

Figure 6: Two adjacent contours united by triangles, forming a 3D mesh.
Two parallel sections, roughly circular in shape, are shown

To calculate the volume of the mesh obtained as the set of two-contour meshes (Fig. 6) we use a combination of the methods described. The determination of the intersections with the kidney of all possible voxels is time consuming, and therefore we apply the Volumetric Pixel method only to the points included in one layer at a time. Each kidney layer was previously obtained with the Layered Convex Hull Method as a pair of contours. By doing so we keep both the precision of the Volumetric Pixel Method and the speed of the Layered Convex Hull Method.

The voxel was defined as a cube of one millimetre.

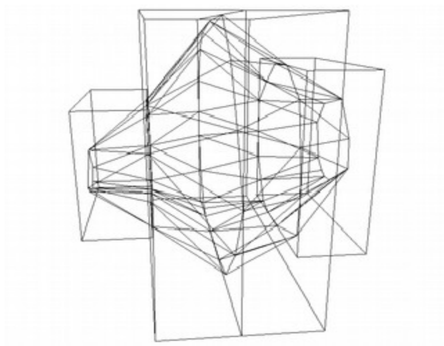

Figure 7: NEFROVOL method for volume reconstruction.
A combination of Layared Convex Hull and Volumetric Pixel methods, it is efficient.

To determine whether a voxel is included in the experimental structure (i.e. the kidney) a line is drawn (computationally) from an external origin of X,Y,Z space to the centre of the voxel. The intersections of this vector with all the triangles of the two-contour mesh are calculated. If the vector crosses the boundary of the solid an odd number of times, the voxel is included in the kidney, otherwise -if it is even- it is classified as external to the volume.

The volume of the extremities is calculated using the formula for triangle-based pyramids. If the contours have l2 points, there will be l2 pyramids sharing the same height.

3D Printing

Once the volume is defined by the meshes (Figure 8) and its capacity has been estimated, a standard file for 3D printing is created. NEFROVOL uses STL (Stereo Lithography) format [8]. A seldom used output, a 3D solid PVC object can be helpful in discussions on the organ being evaluated, along with screen 3D imaging. STL format allows to use a 3D printer developed by SAWERS [9].

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All clinical equipment tend to be connected in clinical networks to better documentation and to increase health care efficiency. NEFROVOL creates a Clinical Document Architecture

(CDA) standard output [l0] to be included in the patient clinical record. Two documents are available: one shows the US scans with the reconstructed 3D volume, including the relevant information of the images as DICOM variables. The main part of the report is shown in Figure 8.

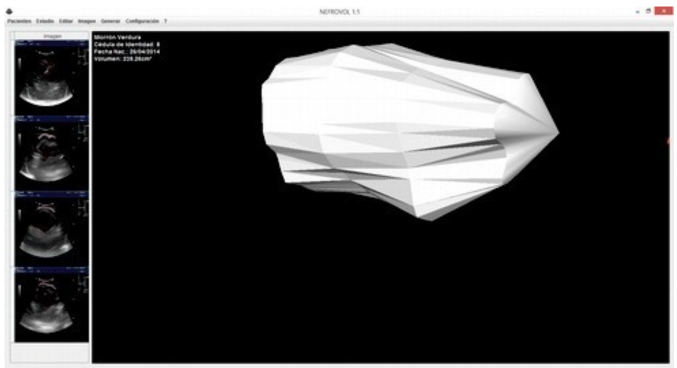

Figure 8: 3D reconstruction of a sweet potato in salt water. Four US scans are column wise at the left and a frozen view of the overall solid in the centre. Note the vertex extrapolated by NEFROVOL after the last contour.

The second document is an extension of the first when there is more than one 3D volume determination for the pa- tient, separated by a period of time set by the user. The evo- lution of kidney disease shows that one month or more could be appropriate. A graphical representation of kidneys volume (right and left) is shown in function of time, to help clinicians judge the rate of expansion of the organs.

TESTING METHOD

A General Electric GE LOGIQ C5 Premium with a C2-5 transducer [ll]was used to test NEFROVOL. Three conse- cutive protocols were followed to compare volumes as cal- culated by NEFROVOL and either real volume or volume calculated by other methods. The tests were:

l. Regular geometric volumes from a phantom

2. Irregular objects (fruit and vegetables)

3. Kidneys of volunteers

A formal approval request to the Ethics Committee of ***Hospital de Clínicas*** was filed prior to testing NEFROVOL with the usual US scanner to obtain follow up images.

A special phantom was designed and build for regular geometric solids out of transparent material with fine fishing cord fixed on opposite sides at given distances. The parallelepipedic box thus obtained was filled with salt water. This allowed to compare the geometrically calculated volume of trapezia or parallelepipedic volumes with the value obtained by NEFROVOL.

The true volume of fruit or vegetables was obtained by water displacement and then left in water to be US scanned.

RESULTS

For regular volumes, the results are shown in Table 1. Table 1 Test of NEFROVOL measuring

Table 1 Test of NEFROVOL measuring REGULAR volumes

N	Cuts	Dimensions	Real	**NEFROVOL**	Difference %
1	2	6x4x5	33.33	36.73	9
2	2	4x2x5	20.00	22.68	12
3	2	6x2x10	53.33	61.03	13

Volumes are given in cubic centimetres.

Regular volumes in a phantom are estimated by NEFROVOL with an error just over l0% which could be further refined looking at craftsmanship of the fishing string and its fixation to the inner sides of the box. These results were the basic check to further NEFROVOL reconstruction method to more complex structures.

For irregular volumes, such as fruit and vegetables, the results are shown in Table 2.

Table 2 Test of NEFROVOL measuring IRREGULAR volumes

Object	Type	Cuts	Real	**NEFROVOL**	Difference %
1	Boniato	8	400	338.39	-15
2	Morron	4	205	239.26	17
3	Orange	4	300	306.50	2
4	Potato	5	275	315.14	15

Volumes are given in cubic centimetres.

Irregular and oblong volumes such as the "Boniato" (sweet potato, object l) or the "Morron" (sweet pepper, object 2) seem to have higher error than spheroids such as Oranges, estimated with a small error of 2%. The most irregular object -sweet pepper- could be estimated to within l7% of true water displaced volume. For patients, NEFROVOL estimates were compared to the traditional US scanner method of the pseudo-sphere formula and are shown in Table 3.

Table 3 Test of NEFROVOL measuring KIDNEYS of volunteers

N	Cuts	Dimensions	Real	**NEFROVOL**	Difference %
1	3	10.74x4.99x6.56	184.08	138.05	25
2	3	9.30x4.56x6.41	129.85	164.01	21
3	4	11.84x5.04x5.49	171.39	172.76	1
4	3	10.35x3.73x5.50	111.18	109.0	2

Volumes are given in cubic centimetres.

In the case of patients with normal or transplanted kidney, Table 3 shows that the estimation is within 25% of the calculated value, as reported by the US scanner using the axes. Patient 1 had been recently kidney transplanted, while the other three were normal volunteers.

DISCUSSION AND CONCLUSIONS

NEFROVOL has addressed the problem of obtaining 3D reconstruction of organs from standard US scanner images with the particularity of estimating in addition its volume for follow up purposes. US scanners include measurements of areas of interest as well as distances between user defined points. But such distances and areas are managed in the realm of the US scan and not in a real world space or analogical space. NEFROVOL takes US scans as input and creates the 3D analogical representation of the volume defined by the user in a sequence of contours. Obstetric US scanners of some commercial providers do offer 3D reconstruction of fetal structures but with limited calibration capabilities. Their 3D images are adapted to the anatomical structure to be depicted, and therefore are based on heavy preconceived fetal shape assumptions. In contrast, NEFROVOL is a general purpose, simple and reliable processing method for 3D reconstruction and subsequent volume estimation.

The present state of the research has not reached the more challenging situation of evaluating polycystic kidneys (PKD), for which a protocol is in development. We expect the error to be of the same order or worse than for normal kidneys. This is not dramatic, since the goal of PKD volume estimation is mainly one of predicting kidney enlargement, rather than absolute figures. For exact volume measurement, MRI with contrast medium is still the best choice. The evolution of a PKD kidney volume with have the previous measurements as reference, and therefore enlargements of, say, 80% will be readily and objectively reported and documented for the first time.

The fact of generating a report to be included in the Electronic Patient Clinical Record (EPCR) System as a CDA, distinguishes NEFROVOL from regular US scanner use. Today normal practice has no documentation except pasting pictures to a written report or handing the DICOM images to the referring physician or patient as files. The engineering solution suggested with NEFROVOL respects the present use of US scanners in clinical settings, adding to it the benefit of transporting the DICOM images to a friendly computer environment where the user defines contours and literally sees a 3D kidney reconstruction, for both kidneys. Then our calculations create the report both in a PDF format for pre-electronic settings and in CDA format for the EPCR system.

To improve the estimation error of 25% in normal kidney (and hopefully also for PKD kidneys) we are addressing the problem by increasing the number of cuts or US images to twice or thice the number of scans allowed by the epidermic Grid. After the basic four cuts, the Grid could be displaced either half or a third of the distance between slots, to obtain more interpolations. This is more work for the user but probably a better precision to estimate the volume and to reconstruct the organ.

Another possible enhancement refers to the extremities of the organ, presently defined as half an inter-slot distance away. NEFROVOL could include an extra clinical measurement obtained longitudinally as the organ length.

Clinical use of NEFROVOL is now underway, collecting useful users' insight and experience while reconstructing kidney 3D structures and volume. The main difficulty reported so far is the limitation imposed by the grid when scanning the abdomen of patients. We hope that both training and use on one side as well as further technical enhancements on the other side may lead to a practical and reliable instrument, for the benefit of patients and their follow up.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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