Assessment of Kidney Volume Measurement Techniques for Ultrasound Images

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Abstract: This study intends to assess and compare the accuracy of different methods for estimating the kidney volume of ultrasound images consist of volume measurement from length-based, area-based and surface-based. For length-based method, the ellipsoid formula was used and for surface-based method, the volume can be automatically obtained from 3D ultrasound system after some manual contouring. For area-based method, sets of ultrasound images with different number of slices were used. After manual contouring, the slices were reduced to 2D representation and the enclosed area between slices is calculated as the volume of the kidney. For a better assessment, experiment was also performed using egg phantom. As results, for egg phantom, by using water displacement method as gold standard volume, length-based method underestimates the volume for about 6% and surface-based method overestimate the volume for about 4%. For area-based method, the volume is also underestimated but varies with total number of slices used and can be as low as 2.6% and as much as 4.5%. By applying the same analysis to the kidney, it is thus concluded that for kidney volume measurement, area-based and surface based methods are more accurate but an automatic technique for contour detection need to be developed for repeatability usage of the methods. Length-based method on the other hand needs to have a new correctional factor implemented to ellipsoid formula for more accurate volume measurement.

Keywords: egg phantom, kidney, three dimensional, two dimensional, ultrasound, volume

1. Introduction

Kidney sizes consist of length and volume are important parameters for clinical assessment and follow-up of patients with kidney transplants, diabetes, or renal arterial stenosis, as well as for evaluation of infection in urinary tract, or vesicoureteral reflux [1, 2]. Estimation of kidney length and volume are also helpful to differentiate between chronic and acute renal failure, and assist in decision making for renal biopsies and to predict the function of renal allograft after being transplanted [3]. As the size of the kidney is frequently used for therapeutic decisions, accurate and precise method for measuring the organ is essential [4].

Of several kidney parameters measured, kidney length was traditionally used as it is a simple, practical and reproducible measurement [5]. However, considering the complexity of the kidney shape, depending only on kidney length measurement to predict kidney disorders and diseases may not be accurate. Therefore, performing other kidney parameter measurement such as kidney volume can be helpful. Besides, there were some previous researches which emphasized kidney volume as a true predictor of kidney size in states of good health and disease [5]. Emamian *et al*. conclude that kidney volume is the most exact measurement of kidney size as it showed the strongest correlation with height, weight, and total body area [5]. Other research stated that kidney volume has shown a more sensitive means of detecting renal abnormalities than any other single linear measurement.

Recently, by using ultrasound, organ volumes such as kidney can be estimated using ultrasound from measurements of length as can be easily measured using 2D ultrasound. The volume can also be estimated from measurements of area or from surface reconstructions and can only be applied with 3D ultrasound systems. By using conventional 2D ultrasound, kidney volume was determined using ellipsoid formula which was based on the length, width as well as depth of the kidney. Some previous researches have emphasized on the use of other single linear measurement for calculating the volume of the kidney and there were also other studies that confirmed the accuracy of ultrasound measurements of the volume of kidneys using the ellipsoid formula [6-8]. However, there were also other studies which argued on the use of ellipsoid formula for volume calculation [4, 8]. Bakker *et al*. showed that ultrasound determination of kidney volume was not accurate as it underestimated kidney volume by 25% due to the ellipsoid formula. Therefore, they suggested the use of MRI technique where the volume was calculated based on voxel-count

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method [4]. Cheong *et al*. by using MRI data, also concluded that the kidney volume measured using ellipsoid formula underestimated the kidney volume by as much as 21–29% and the use of disk-summation method for volume estimation underestimated the kidney volume by no more than 4-5% [8]. Thus, under certain circumstances, three-dimensional reconstructive volume estimation can be a better and accurate method for kidney volume estimation.

The use of 3D ultrasound system allows the user to view in multiple planes slice-by-slice and if the surface of certain organ has been reconstructed, the volume can be calculated from this surface. For estimating the volume based on area measurement, the most common implementation is based on assumption that the image slices are parallel. There were numerous reports which indicated that estimation of volume using area-based was much more accurate than ellipsoid or other geometrical formula [9,10]. Few other researchers used 3D ultrasound system and they stated that 3D ultrasound methods are accurate to approximately 5%, and much more preferred over ellipsoid or similar equations [11].

This study will assess and compare the accuracy of different methods for estimating the kidney volume. We intend to evaluate the methods used for kidney volume measurement consist of volume measurement from length-based, area-based and surface-based. Based on the result, we will establish new criteria for choosing appropriate methods for kidney volume measurement using ultrasound.

2. Meterials and Methods

For this study, 20 volunteers have been chosen for ultrasound scanning purpose. The kidneys were scanned by using TOSHIBA *AplioMX* ultrasound machine with 3.5MHz transducer for two-dimensional (2D) images and 6MHz transducer for three-dimensional (3D) images. Under 2D ultrasound setting, the length, width and depth both in longitudinal and transverse section of the kidney were measured (Fig. 1, Fig. 2). 3D ultrasound setting was used to get image slices of the kidney for volume calculation.

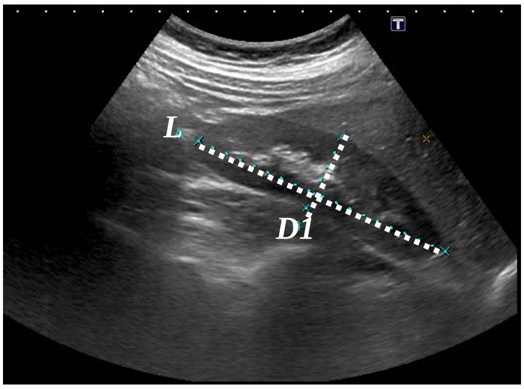

Fig. 1 Measurement of length, *L* and depth in longitudinal section, *D*1 in 2D ultrasound setting

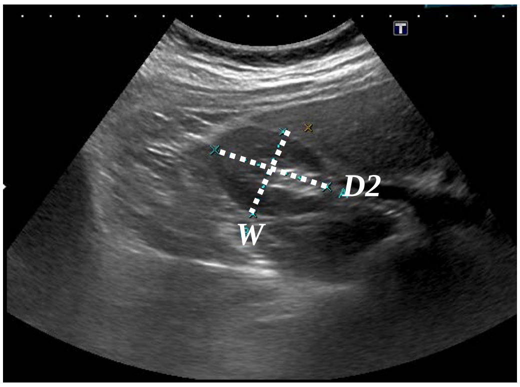

Fig. 2 Measurement of width, *W* and depth in transverse section, *D*2 in 2D ultrasound setting

Since the study of the kidney is performed on healthy volunteers, we do not know the exact volume of their kidney to be used as gold standard for comparing different methods of volume measurement. For a better assessment, therefore, we developed egg phantoms by using two different sizes of eggs (chicken egg and quail egg). The volumes of the eggs were first measured by using water displacement method (gold standard). Then, agar-based phantom were created. Both of the egg phantoms were scanned the same way as scanning the kidney by using both 2D and 3D ultrasound transducers.

All images that have been scanned were used as input to three main volume measurement techniques for ultrasound images namely length-based, area-based and surface-based. In length-based volume measurement, all parameters were manually measured. Details on each technique can be viewed in below section and the results were analyzed in next section.

2.1 Length-Based Volume Measurement

Conventional 2D ultrasound has been frequently used for volume measurement of organs in clinical practice nowadays. The organs of interest were approximated as a simple mathematical shape. As in this study, kidney has been approximated as an ellipsoid and the lengths of the major and minor axes were measured in selected 2D ultrasound images. In this study, kidney volume was determined by using the formula of Dinkel *et al*. (ellipsoid formula) and their study concluded that their volume calculation method showed good correlation to body weight. Solvig *et al*. also used the same formula but did some modification since they performed the volume measurement of transplanted kidney. Eq. 1 and Eq. 2 show the formula for measuring the kidney volume for Dinkel *et al*. and Solvig *et al*. respectively:

$$KV_{Dinkel} = 0.523 \times L \times W \times (D1+D2) / 2 \quad (1)$$

$$KV_{Solvig} = 0.612 \times L \times W \times (D1+D2) / 2 \quad (2)$$

where *L* is the maximum pole-to-pole diameter, *W* is the maximum width and *D* is the maximum depth in the longitudinal (*D*1) and transverse section (*D*2).

As can be seen from both Eq. 1 and Eq. 2, to obtain Eq. 2, correction has been applied to the result in Eq. 1, by adding some correctional factor. This study will analyze both equations and comparison will be made based on results to find any possible new correctional factor that can be used for a more accurate kidney volume measurement using 2D ultrasound.

2.2 Area-Based Volume Measurement

By using 3D ultrasound, area-based volume measurement can be performed where the volume is calculated from a sequence of image slices areas. For estimating the volume based on area measurement, assumption has been made that the image slices are parallel. There were numerous reports which indicate that estimation of volume using area-based was much more accurate than ellipsoid or other geometrical formula [9, 10]. Besides, there was also previous report that developed an area-based volume measurement method for calculating volumes from cross-sections that were overlapped and not parallel.

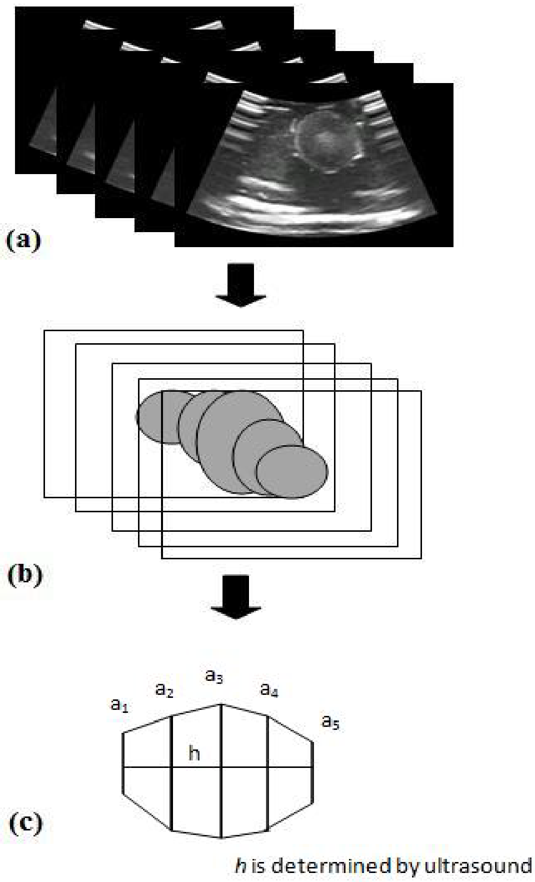

Fig. 3 Steps in area-based volume measurement method where set of ultrasound image slices in (a) are manually contoured as in (b) and being reduced to 2D representation as in (c)

In this study, all slices taken from 3D ultrasound images are assumed as parallel to each other. Different set of total number of slices has been made to investigate the relation between the number of slices and volume measured. Fig. 3 shows the steps involved in area-based volume measurement method. The image slices taken from 3D ultrasound will undergo manual boundary detection to contour the region of interest. Then, these slices will be reduced to a 2D representation, where the area of each contoured slice is represented by the length of each line, and the orientation of the lines is the same as the orientation of the slices. After that, the enclosed area between lines is calculated by using simple trapezoidal formula as in Eq. 3 and this value is equal to the volume of the real object.

$$KV = \sum_{n=2}^{m} \frac{1}{2} x \ h \ x \ (a_{n-1} + a_n) \quad (3)$$

where a is the area of contoured slice, h is the spaces between slices (SBS) (determined by ultrasound, 1mm=3.7795pixel) and m is total number of slices in a set of images.

2.3 Surface-Based Volume Measurement

In 3D ultrasound system, the volume can be calculated by summing the number of voxels inside the object which the surface has been reconstructed earlier. Then, the summation of the voxel is multiplied by the volume of one voxel to get the total volume of the object. In this *AplioMX* ultrasound machine, under the 3D setting, the volume can be obtained by contouring the object of interest in three different planes. Then, the system will automatically construct the surface of the object as well as giving the volume estimation of the object.

3. Results and Discussion

Table 1 shows the result of kidney volume for several ultrasound volume measurement methods consist of length-based, area-based and surface-based. The result shows the mean value of kidney volume for 20 volunteers. For length-based method, two formulas have been used for calculating the kidney volume and the kidney volume calculated is 88.7ml by using Eq. 1 and 103.8ml by using Eq. 2.

Table 1. Kidney volume for different ultrasound volume measurement methods

Methods		Kidney Volume (ml)
Length-Based Method	Dinkel et al. formula	88.7
	Solvig et al. formula	103.8
Area-Based Method	Longitudinal section	113.5
	Transverse section	115.1
Surface-Based Method		123.8

Based on the values, with respect to Dinkel et al formula, it showed that Solvig et al. use a correctional factor of 1.17. For area-based method, set of image slices of the kidney were scanned and saved in both longitudinal and transverse sections and the kidney volume were 113.5ml and 115.1ml respectively. Based on the values, for kidney volume measurement using area-based method, image slices in transverse section gave a higher value compared to image slices in longitudinal view. Kidney volume measured using surface-based method is 123.8ml and Fig. 4 shows an example of kidney image where the surface has been reconstructed automatically in 3D ultrasound system.

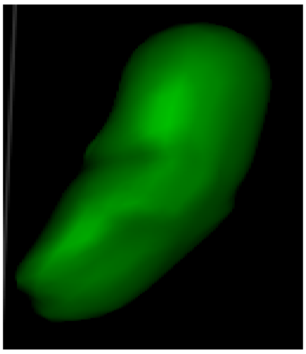

Fig. 4 Surface reconstruction of kidney in 3D ultrasound system

Table 2 shows the result of chicken egg and quail egg volume measured by different volume measurement methods as well as the percentage error of the volume compared to water displacement method (gold standard). The result shows 6% and 5.8% underestimation of volume for both eggs respectively when the volume is calculated using ellipsoid formula, even though the shape of egg is much more similar to the shape of ellipse. Surface-based method however overestimates the chicken egg volume for about 4.2% and quail egg volume for about 3.8%. For area-based method, different set of slices being used to investigate the effect of total slices number to the volume calculated using this method. For chicken egg, sets of 5 to 12 slices were used and for quail egg, set of 5 to 13 slices were used. Based on the result, the percentage error varies from 3.1% up to 4.5% for chicken egg and 2.6% up to 3.8% for quail egg. The result also concludes that as total slices number increase, the percentage error of the volume is decrease.

Overall, for egg phantom, with respect to water displacement method, length-based method by using ellipsoid formula tends to underestimate the volume for about 6% and surface-based method as measured in 3D ultrasound system tends to overestimate the volume for about 4%. By using area based-method, the volume is also underestimated but varies with total number of slices used and can be as low as 2.6% and as much as 4.5%. By assuming the real kidney volume as 25% underestimated by ellipsoid formula as in Bakker *et al*. [4], the real kidney volume should actually be around 120ml. Therefore, the use of area-based and surface based seem to be more accurate.

Table 2. Volume measurement of chicken egg and quail egg

Volume Measurement Methods		**Egg Volume (ml)**	**Percentage Error**
Chicken Egg			
Water displacement method		55.2	-
Ellipsoid formula (Eq. 1)		51.9	- 6%
Surface-based method		57.5	+4.2%
Area-based method	5 slices (SBS=10mm)	52.7	- 4.5%
	9 slices (SBS=5mm)	53.1	- 3.8%
	12 slices (SBS=4mm)	53.5	- 3.1%
Quail Egg			
Water displacement method		7.8	-
Ellipsoid formula (Eq. 1)		7.35	- 5.8%
Surface-based method		8.1	+ 3.8%
Area-based method	5 slices (SBS=5mm)	7.5	- 3.8%
	7 slices (SBS=4mm)	7.55	-3.2%
	13 slices (SBS=2mm)	7.60	- 2.6%

*SBS= slices between space

However, these three volume measurement methods using ultrasound have their own limitations. Length-based methods need to be further analyzed to find a more accurate correctional factor to ellipsoid formula. For area-based and surface-based methods, we cannot say that they are better compared to length-based method for estimating the volume as they highly depends on the user to correctly contour the object of interest. Automatic contour detection might increase the repeatability of using area-based and surface-based methods but it is currently still a challenging task to contour the organ automatically in high speckle ultrasound images.

4. Summary

We have successfully perform some evaluation to the current methods used for kidney volume measurement consist of volume measurement from length-based, area-based and surface-based. For a better assessment, egg phantoms with known volume have been developed. As results, for egg phantom, with respect to water displacement method, length-based method by using ellipsoid formula tends to underestimate the volume for about 6% and surface-based method as measured in 3D ultrasound system tends to overestimate the volume for about 4%. By using area based-method, the volume is also underestimated but varies with total number of slices used and can be as low as 2.6% and as much as 4.5%. By applying the same analysis to the kidney, it is thus concluded that for kidney volume measurement, area-based and surface based methods gave a more accurate results but they are not easily repeated due to manual contour detection. Thus, developing an automatic technique for contour detection might be a solution.

Length-based method on the other hand needs to have a new correctional factor implemented to ellipsoid formula for more accurate volume measurement.

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