INVESTIGATIVE RADIOLOGY
Volume 37, Number 9, 489–495
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3D Versus 2D Ultrasound

Accuracy of Volume Measurement in Human Cadaver Kidneys

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Partik B, Stadler A, Schamp S, et al. 3D versus 2D ultrasound. Accuracy of volume measurement in human cadaver kidneys. Invest Radiol 2002;37:489–495.

RATIONALE AND OBJECTIVES. **Comparison of the accuracy of 3D and 2D ultrasound in assessing the volume of human cadaver kidneys.**

MATERIALS AND METHODS. **Before autopsy the volume of 22 kidneys was assessed from a 3D data set after manually tracing organ contours (3D volumetry) and by applying a 3D ellipsoid formula both on a 3D data set and 2D images. Measurements by water-displacement served as the gold standard.**

RESULTS. **3D volumetry showed a mean absolute deviation of 31 mL (18.5%) compared with the mean gold standard measurement (168 mL), yielding a concordance correlation (Lin's ρ_c) of 0.71. Calculation based on the ellipsoid formula revealed a mean absolute deviation of 37 mL (22.0%) when applied on the 3D data set ($\rho_c = 0.65$) and of 42 mL (25.0%) when applied on 2D images ($\rho_c = 0.61$), respectively.**

CONCLUSIONS. **3D volumetry showed a satisfactory concordance correlation and is superior to volume calculation based on the ellipsoid formula either applied to a 3D data set or to conventional 2D images in assessing the volume of human cadaver kidneys.**

KEY WORDS. **Kidney; ultrasound; measurement; concordance correlation; comparative studies.**

THE ASSESSMENT of kidney volume is an important task for clinicians in several diagnostic situations, such as in early pregnancy and in renal transplants with acute rejection.[1–7] Large kidney volumes are also seen as a morphologic marker for the subsequent development of diabetic nephropathy in patients with insulin-dependent diabetes mellitus and have been correlated with creatinine clearance.[8,9]

Kidney size and volume have been assessed both in experimental and clinical studies with different imaging modalities.[9–13] However, in clinical routine, kidney volume measurements are usually performed with two-dimensional (2D) ultrasound because of its availability and lack of ionizing radiation. Three-dimensional (3D) reconstruction of ultrasound images has become an option on ultrasound scanners and seems to have the potential to replace 2D-based kidney volume measurements.[14]

Successful 3D volume measurements of kidneys using mechanical[15–17] or electronic probes[18,19] have also been described in prior studies. However, those studies were subject to some limitations, including the in vitro setting of the examinations or the lack of an accurate gold standard. In the current study, we wanted to evaluate the accuracy of 3D versus 2D ultrasound for kidney volume measurements in human cadavers and to compare the results with the water displacement method as an accepted gold standard.

Materials and Methods

The study was performed in accordance with institutional guidelines. We prospectively examined 22 kidneys in seven male and four female corpses consecutively (mean age, 66.2 years; age range, 49–76 years) with an average body weight of 70.6 kg (range, 46–102 kg), which were scheduled for

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Bernhard L. Partik, MD is supported by a Max Kade Grant.

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Received February 21, 2002, and accepted for publication, after revision, May 4, 2002.

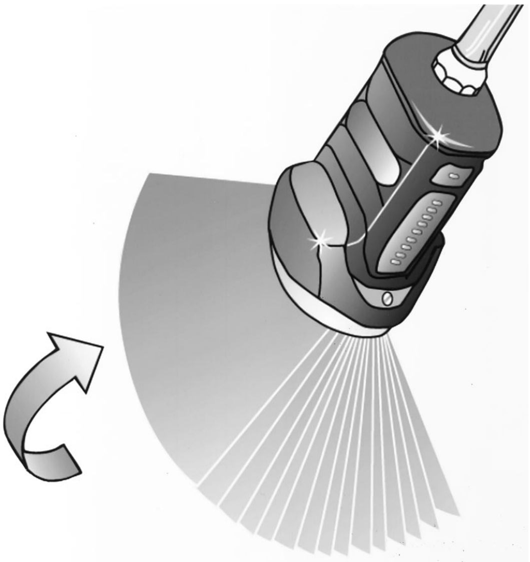

Figure 1. Schematic drawing of annular array transducer with integrated electromechanical device illustrating fan-shaped series of arbitrary sector scans during acquisition period of 3D volume scan.

routine autopsy in the pathology department. Corpses were stored at two degrees Celsius after death and removed from the storage facility 30 minutes before the ultrasound examinations. Ultrasound examinations were performed at an average time of 12.2 hours (range, 6–48 hours) post mortem immediately before the autopsy.

Data Acquisition

All image data were independently obtained by two observers (A: board-certified radiologist; B: three-year resident well trained in abdominal ultrasound). A third observer (C: research fellow with no experience in abdominal ultrasound) was not involved in data acquisition but was involved in the assessment of all 3D-volume measurements to evaluate the measurement accuracy of an inexperienced observer.

Image acquisition was accomplished using a maintained and calibrated ultrasound unit (Voluson 530D, Kretztechnik, Zipf, Austria) equipped with an abdominal 3.5/5 MHz annular array transducer with an integrated electromechanical device for volume scanning (Fig. 1). Corpses were examined in the supine position. For consistent measurements, the ultrasound scanning technique was standardized.

First, observers A and B acquired a 3D data set with the probe positioned in a fixed location displaying the maximal midsagittal plane of the kidney. By activating the volume transducer, volume data were acquired using the slow velocity mode, which provides the best spatial resolution. With this volume scan, a data set from a pyramid-shaped tissue volume can be acquired and stored in the random access memory. Archival storage of data are accomplished with removable cartridge hard disks.[20]

Second, conventional 2D images were independently obtained by the same two observers. The superior and inferior poles of the kidney were visualized until the maximal midsagittal plane was determined. This represented the renal length (l). Subsequently, a transverse scan at right angles to the axis of the maximal midsagittal plane was obtained. The renal width (w) and transverse diameter (t) were measured perpendicular to each other at the level of the renal hilum.[21]

Autopsy was performed by one pathologist. The kidneys were removed and excised from their capsules and associated fatty tissue. After that, the kidneys were lowered into a water-filled measuring cylinder. Volume of the explanted kidneys was then determined by the water-displacement method to the nearest cubic centimeter.[21]

Data Analysis

Previous to the study, observers A, B, and C were trained in software handling for a period of 1 hour by an experienced technologist to minimize measurement inconsistency.

Calculation From the 3D Data Set Based on Semi-Automatic Volume Calculation (3D Volumetry). Observers A, B, and C independently evaluated the volume data and were blinded to the results of prior measurements. The two 3D data sets from each kidney were assessed in random order, resulting in a total of six measurements for each kidney.

The reconstructed volume data were displayed on a video screen in three orthogonal planes (sagittal, transverse, and coronal) exhibited simultaneously (Fig. 2). In contrast to 2D ultrasound, 3D ultrasound allows determination of organ volume by stepping through organs slice by slice. Organ contours were traced manually by means of a cursor in cross-section planes in full screen display perpendicular to the long axis of the kidney, where organ contours were best appreciated. Scrolling step by step through the volume data, measurements were performed at each level of the kidney, where organ contours differed from previously traced contours, resulting in an average of 7.3 measurements (range, 5–9 measurements) (Fig. 3). Calculation of the total volume was performed automatically by an integrated 3D software volume measuring method.[22] Time of measurement was noted from the moment when loading of data to the random access memory was finished to the last manually traced organ contour and automatic display of kidney volume.

Calculation From the 3D Data Set Based on the 3D Ellipsoid Formula (3D Volume Calculation). After a mean time interval of 4.5 days (range, 3–7 days) observers A, B, and C independently evaluated the volume data, blinded to prior results. In random order, measurements of length, width, and thickness were performed using both the data sets acquired by observers A and B, which also resulted in six measurements per kidney. Volume calculation was based on a 3D ellipsoid formula ($l \times w \times t \times 0.523$) and carried out manually on a notebook computer (ThinkPad 380XD, IBM, White Plains, NY).[23] Time

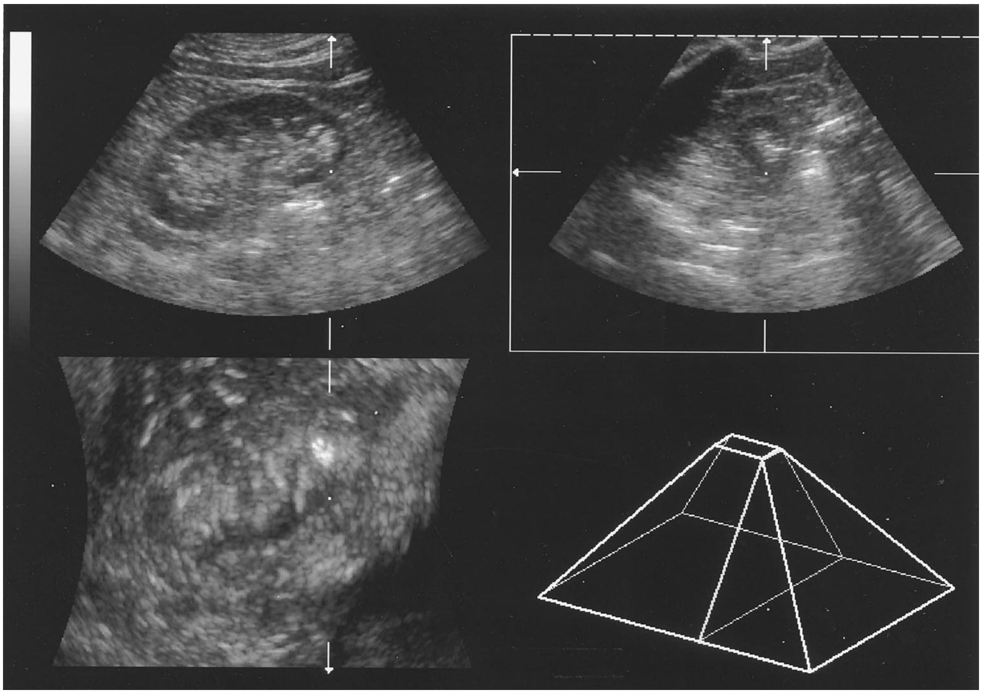

Figure 2. Monitor view of 3D ultrasound: three orthogonal planes of the kidney are displayed simultaneously. Note: dot indicates the same position in the x, y, and z-planes.

of measurement was noted from the moment when loading of data to the random access memory was finished to display of manually calculated kidney volume.

Calculation From 2D Images Based on the 3D Ellipsoid Formula (2D Volume Calculation). Finally, after four more days, observers A and B calculated independently, blinded to prior results, the kidney volumes based on their own 2D images using initially obtained values of length, width, and thickness. Volume calculation was carried out manually and based on the same three-dimensional ellipsoid formula as mentioned above.[23] Because of lack of additional information, observer C was not involved in 2D image analysis.

Statistics

We expressed results of volume measurements relative to the gold-standard measurements in terms of the mean ab-

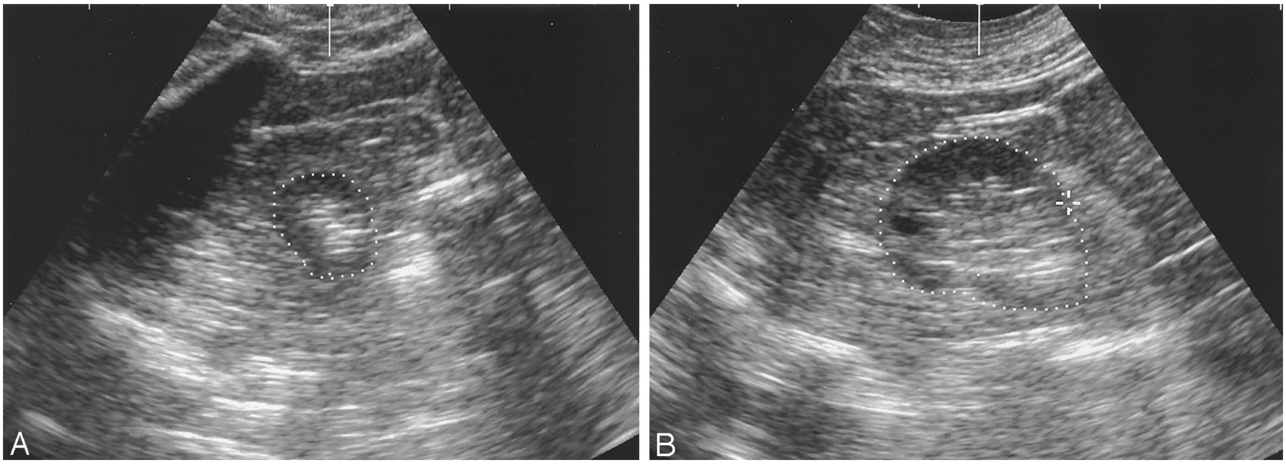

Figure 3. A 53-year-old male patient with 3D ultrasound of right kidney. (A) Ultrasound image in the axial plane at the level of the upper pole. Note: dots indicate manually delineated contour of the kidney. (B) Ultrasound image in the axial plane at a level between the hilum and the upper pole. Note: dots indicate manually delineated contour of the kidney.

solute deviation (MAD) of measurements.[24] The concordance of alternative-method measurements with gold-standard measurements was assessed with a statistical measure of agreement (or reproducibility) for continuous outcome variables, Lin's concordance correlation coefficient, ρ_c, along with measures for location shift, u, and scale shift, v.[25,26] Calculation and evaluation of components u and v (of which ρ_c is comprised) enables identification of the source of measurement error, primarily accounting for measurement discordance, in cases where ρ_c is less than unity, as elaborated in the following. u is the location shift parameter for measurement concordance between the gold-standard method and an alternative-measurement method. It quantifies the amount of measurement miscalibration. The ideal condition is $u = 0$, whereas $u > 0$ indicates that gold standard measurements are systematically larger than corresponding alternative-method measurements, and $u < 0$ indicates that gold standard measurements are systematically smaller. v is the scale shift parameter for measurement concordance between the gold-standard method and an alternative-measurement method. It quantifies the amount of measurement imprecision (ie, lack of accuracy). The ideal condition is $v = 1$, whereas $v > 1$ indicates that gold standard measurements produce more variation than corresponding alternative-method measurements, and $v < 1$ that they produce less variation. Lin's ρ_c takes into account both sources of measurement error (miscalibration, or u; and imprecision, or v). Lin's ρ_c is unity if, and only if, plotted data points of individual measurements from two measurement methods follow exactly a 45° line; in other words, when measurements are perfectly calibrated ($u = 0$) and perfectly accurate ($v = 1$). Consequently, in the context of measurement assessment, u and v provide valuable and different information about the causes for measurement discordance. Whereas location shift (u unequal to zero) indicates a calibration problem (ie, bias in measurements), scale shift (v unequal to unity) is indicative of a lack of precision (ie, overdispersion in measurements), and prevalence of both location shift and scale shift is indicative of more serious problems (eg, increasing lack of precision with increasing magnitude of measured objects). To our knowledge, conventional benchmarks for interpretorial evaluation of Lin's ρ_c have not yet been proposed. We hereby propose such a benchmark scheme. This grading and its verbal descriptors closely resemble the widely accepted propositions of Kaiser et al[27] for a statistical index in the context of factor analysis, as follows: "excellent" for values larger than 0.95, "very good" (> 0.90), "fairly good" (> 0.80), "middling/satisfactory" (> 0.70), "mediocre" (> 0.60), "poor" (> 0.50), and "unacceptable" (below 0.50). To test whether the concordance coefficients were statistically significantly different from mere chance agreement (a ρ_c of zero), we computed one-sided 95% confidence intervals (Elashoff JD, 1997; nQuery Advisor version 2.0, Los Angeles, CA).

Results

Mean volume of the kidneys evaluated with the water-displacement method was 168 mL (range, 48–240 mL). Compared with these results, measurements by 3D volumetry showed a mean absolute deviation (MAD) of 31 mL (18.5%), calculation by the ellipsoid formula from the 3D data set showed a MAD of 37 mL (22.0%), and conventional 2D measurements showed a MAD of 42 mL (25%). Volume measurements with the 3D volumetry method took an average of 5.1 minutes per kidney, whereas 3D volume calculation was finished after an average time of 2.3 minutes. All manual calculations of kidney volume in 2D images were accomplished within 30 seconds.

Results of the measurement concordance analysis are displayed in Table 1. Generally, averaged across specimens and across observers, the 3D volumetry method yielded the highest concordance ($\rho_c = 0.713$) relative to the 3D volume calculation method ($\rho_c = 0.651$) and to the 2D volume calculation method ($\rho_c = 0.611$). The concordance coefficients (u, v) for the various combinations of alternative-method measurements, specimens, and observers varied widely, ranging from as low as 0.327 to 0.822. A pattern for the specific concordance coefficients was not obvious, although the results suggest that concordance coefficients for the 3D volumetry method were somewhat higher than concordance coefficients for the 2D volume calculation and the 3D volume calculation method.

A comparison of the sources of discordance between gold standard measurements and alternative-method measurements, u and v, (Table 1) is revealing. Although most deviations from the desired property, $v = 1$, were negligible, most deviations from the desired property, $u = 0$, were positive, some considerably so. In other words, most of the alternative-method measurements were satisfactory with regard to measurement accuracy, ie, the alternative-method measurements did not systematically produce larger or smaller variation relative to the gold standard measurements. Conversely, the alternative-method measurements were negatively biased with regard to measurement calibration, ie, they systematically yielded too small measurements relative to the gold standard. However, the measurement error was consistent even in terms of MAD-based results. All lower confidence limits of the Lin coefficient were above zero, ie, all the Lin coefficients were statistically significantly different from chance agreement.

Discussion

The present study reveals that 3D volumetry is superior to volume calculation based on the ellipsoid formula, applied either to a 3D data set or to conventional 2D images, in assessing the volume of human cadaver kidneys. The mean absolute deviation was 31 mL (18.5%) compared with the mean gold standard measurement (168 mL), yielding a satisfactory concordance correlation (Lin's ρ_c) of 0.71.

TABLE 1. The Concordance of Kidney Volume Measurements Assessed by the 3D Volume Measurement Method and by a Three-Dimensional Ellipsoid Formula Applied on Both a 3D Data Set and Conventional 2D Images With the Gold Standard (Water Displacement Method)

Method of Volume Measurement	Data Acquisition by Observer	Volume Measurement by Observer	u	v	ρ_c
3D volumetry (averaged)			0.539	1.043	0.713
3D volume calculation (averaged)			0.209	0.840	0.651
2D volume calculation (averaged)			0.756	0.946	0.611
3D volumetry	A	A	0.551	0.891	0.585
3D volumetry	A	B	0.657	0.929	0.506
3D volumetry	A	C	0.404	0.972	0.770
3D volumetry	B	A	0.581	1.046	0.720
3D volumetry	B	B	0.694	1.200	0.630
3D volumetry	B	C	0.272	0.913	0.822
3D volume calculation	A	A	0.672	0.998	0.327
3D volume calculation	A	B	0.593	0.809	0.458
3D volume calculation	A	C	−0.163	0.607	0.590
3D volume calculation	B	A	0.269	0.755	0.657
3D volume calculation	B	B	0.273	0.807	0.564
3D volume calculation	B	C	−0.284	0.599	0.513
2D volume calculation	A	A	0.967	0.899	0.550
2D volume calculation	B	B	0.491	0.843	0.565

Observer A: board-certified radiologist; Observer B: a three-year resident (experienced in abdominal ultrasound); Observer C: a research fellow (no experience in abdominal ultrasound). ρ_c = Lin's concordance correlation coefficient, u = location shift, v = scale shift.

Previous studies have shown that 3D ultrasound allows more accurate measurements under experimental conditions.[16,28,29] Riccabona et al[16] found a mean accuracy of 3.95% for 3D ultrasound measurements in a phantom study. King et al[29] detected a mean error of 0.4% when 3D ultrasound and true volume were compared. This divergence from our results is most likely because of the in vitro setting of those studies. We hypothesize that tracing of organ contours for 3D volume measurements is enormously facilitated if kidneys are surrounded by homogeneous hypoechogenic media (saline 0.9%,[28] water,[29] starch containing water[16]). Matre et al[28] assumed that a clinical situation would introduce additional factors that would influence the accuracy of measurements, particularly when tracing the organ outline in relation to neighboring organs, which would be much more uncertain. Our data support this hypothesis, as, in some patients, delineation of kidney contours was complicated because of subtle blurring or overlaying "shadows" of the ribs. Another author showed that the mean difference in volume measurements of kidneys obtained by 3D ultrasound compared with MR imaging was 16.1 mL, yielding a Pearson correlation coefficient of $r = 0.82$.[17] To our knowledge, this was the only published in vivo validation of 3D ultrasound measurements on abdominal organs. However, this study had some major drawbacks. The estimation of measurement accuracy when different imaging modalities are compared remains problematic if none of the modalities is accepted as a gold standard. Furthermore, it has been shown that commonly used methods for the statistical assessment of agreement of continuous measures (ie, Pearson correlation coefficient, *r*; the coefficient of variation, *CV*; Student paired *t* test; and ordinary least squares regressional techniques, along with testing of the intercept if the linear regression line is zero and the slope of the linear regression line is unity) are not suited for this question.[25] All these methods produce misleading estimates of measurement agreement.

In general, previous studies indicated several limitations of ultrasound measurements in predicting renal volume.[30,31] Emamian et al[30] found that the relative observer variation in renal volume estimation is three times greater than that in renal length measurements, which demonstrates that renal volume estimation is less reliable than renal length measurement. A probable explanation is that renal volume estimation by the ellipsoid formula is based on the multiplication of the three dimensions and the result is therefore compromised by observer variation in three dimensions. Further, compared with measurements of renal length, measurements of the width and thickness of the kidney showed an even higher observer variability.[30] This can be attributed to the difficulty in obtaining an optimal and reproducible transverse image of the kidney. Our data support this hypothesis, as evidenced by better results for calculations based on the ellipsoid formula using the 3D data set with optimized visualization of kidney diameters in all three dimensions ($\rho_c = 0.65$) than by measurements from 2D images ($\rho_c = 0.61$). In a recent study, kidney volumes assessed by 2D ultrasound measurements based on the ellipsoid formula were found to be significantly less in normotensive patients compared with hypertensive patients.[32] However, our data show that volume calculation of kidneys based on the ellipsoid formula had only a mediocre concordance correlation, which is in accord with prior studies.[30,31] We hypothesize that volume calculation by 3D volumetry could increase the accuracy of such measurements.

Some studies have advocated a modified ellipsoid formula for calculating renal volume.[12,21] However, our results are not fully consistent with that reasoning because one observer overestimated kidney volumes in 3D volume calculations (Table 1; $u < 0$) compared with the gold standard.

No obvious differences in MAD and concordance coefficients were seen among the three observers, suggesting the possibility that, after adequate training, even inexperienced persons may perform 3D volumetry or calculations based on the ellipsoid formula when the 3D data set is obtained by an experienced observer. Measurements by 3D volumetry took an acceptable average time of 5.1 minutes per kidney, compared with 2.3 minutes for 3D volume calculation and below 30 seconds for 2D volume calculation, which is in accordance with data published by Riccabona et al.[16]

A possible limitation of our study is the fact that we could not exactly determine the reason for subtle blurring of kidney contours that contributed to the measurement error. Although corpses were stored at 2°C, one reason might be that the process of autolysis had begun, as examinations were performed at a mean interval of 12.2 hours postmortem. However, the effects of altered acoustic velocity because of temperature on ultrasound measurements are known.[33] Nevertheless, Hendrikx et al[34] found accurate results in measuring prostate volumes of human cadavers at a body temperature of 4°C. However, in our study we were unable to define exactly to which extent volume measurements were affected by autolysis, the effects of altered acoustic velocity, or both. We assume that in vivo measurements may be more accurate than in cadavers because of better delineation of kidney tissue. In addition, good patient compliance with breath-holding at an individual level of inspiration and a tailored examination position (eg, oblique) to avoid overlaying "shadows" of the ribs could facilitate acquisition of volume data. Another limitation is that we did not include an analysis of intraobserver variability in this study. However, because no obvious differences between MAD and concordance correlation were found among the three observers in a total of 308 volume measurements, we assume our data are valid also for repeated measurements by the same observer. We conclude that 3D volumetry of human cadaver kidneys showed a satisfactory concordance correlation and is superior to volume calculation based on the ellipsoid formula either applied to a 3D data set or to conventional 2D images.

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