Eur Radiol (2014) 24:1694–1699
DOI 10.1007/s00330-014-3162-5

ULTRASOUND

Assessment of renal tissue elasticity by acoustic radiation force impulse quantification with histopathological correlation: preliminary experience in chronic kidney disease

Liang Wang · Peng Xia · Ke Lv · Jie Han · Qing Dai · Xue-mei Li · Li-meng Chen · Yu-xin Jiang

Received: 23 January 2014 / Accepted: 21 March 2014 / Published online: 18 April 2014

Abstract
Objectives Chronic kidney disease (CKD), a progressive and irreversible pathological syndrome, is the major cause of renal failure. Renal fibrosis is the principal process underlying the progression of CKD. Acoustic radiation force impulse (ARFI) quantification is a promising noninvasive method for assessing tissue stiffness. We evaluated whether the technique could reveal renal tissue fibrosis in CKD patients.
Methods ARFI assessments were performed in 45 patients with CKD referred for renal biopsies to measure cortical shear wave velocity (SWV). During measurement, a standardized method was employed, which aimed to minimize the potential impact of variation of transducer force, sampling error of non-cortical tissue and structural anisotropy of the kidney. Then SWV was compared to patients' CKD stage and pathological fibrosis indicators.
Results ARFI could not predict the different stages of CKD. Spearman correlation analysis showed that SWV did not correlate with any pathological indicators of fibrosis.
Conclusion ARFI assesses tissue stiffness of CKD kidneys by measuring cortical SWV. However, SWV did not show significant correlations with CKD stage and fibrosis indicators despite using standardized measurement methods. We therefore suggest that it would be necessary to evaluate the effect of pathological complexity and tissue perfusion of the kidney on stiffness assessment in future studies.
Key points
- *Acoustic radiation force impulse (ARFI) can quantify tissue elasticity of CKD kidney.*
- *Despite standardized measurement, ARFI-estimated elasticity did not correlate with renal fibrosis.*
- *Effects of pathological complexity and tissue perfusion on renal stiffness warrant further study.*

Keyword Chronic kidney disease · Coustic radiation force impulse · Shear wave velocity · Ultrasound · Fibrosis

Introduction

Chronic kidney disease (CKD) is defined as a reduced glomerular filtration rate, increased urinary albumin excretion or both [1]. Prevalence is estimated to be 8–16 % worldwide. In the past decade, CKD has become an increasing public health issue. Particularly the risk for cardiovascular disease has notably increased in individuals with CKD. Diabetes and hypertension are the leading causes of CKD, although autoimmunity, atherosclerosis, infections, drugs and toxins, obstruction of the urinary tract, genetic defects and other insults may initiate the disease [2]. In all cases, CKD eventually compromises all renal structures and gives rise to a similar phenotype in pathology regardless of aetiology. Renal fibrosis is the principal process underlying the progression of CKD, which is a relatively uniform response involving glomerulosclerosis, tubular atrophy, interstitial fibrosis and changes in renal vasculature [3]. Therefore, renal fibrosis provides an excellent treatment target, and an effective management strategy including sensitive monitoring and specific treatment of renal fibrosis would have the potential to provide an immense medical, social and economical benefit.

Liang Wang and Peng Xia contributed equally to this study.

L. Wang · K. Lv (✉) · J. Han · Q. Dai · Y.-x. Jiang
Department of Ultrasound, Chinese Academy of Medical Sciences & Peking Union Medical College Hospital, 1 Shuaifuyuan Wangfujing, Beijing 100730, China
e-mail: lvke@163.com

P. Xia · X.-m. Li · L.-m. Chen
Department of Nephrology, Chinese Academy of Medical Sciences & Peking Union Medical College Hospital, 1 Shuaifuyuan Wangfujing, Beijing 100730, China

As sensitive laboratory markers are missing, renal biopsy is currently the best method to assess the severity of renal fibrosis and other pathologic changes. However, renal biopsy is invasive, susceptible to sampling errors and impractical for longitudinal monitoring [4]. Therefore, there is a critical need to develop noninvasive and reproducible alternatives. A newly emerging diagnostic imaging technique, acoustic radiation force impulse (ARFI), provides noninvasive assessment of tissue stiffness by quantitatively measuring shear wave velocity (SWV) of the tissue. This technique differs from strain elastography, as the operator does not need to apply any tissue deformation using the ultrasound transducer [5]. Some studies have verified ARFI as an accurate, repeatable and promising approach in liver fibrosis grading [6–8]. However, we are not aware of any study that has assessed ARFI as a noninvasive tool in detection of renal tissue fibrosis in CKD patients.

The purpose of this study was to investigate whether the stiffness value obtained by ARFI was associated with clinical stage and histological fibrosis indicators in patients with CKD.

Material and methods

Study population

The prospective study was approved by the ethics committee of our hospital. Between December 2011 and April 2012, 63 patients were enrolled after obtaining written informed consent. ARFI examinations were conducted on left kidney after renal biopsy (also on the left kidney) with a 3-day interval between biopsy and ARFI. The exclusion criteria were patients with evidence of post-biopsy renal subcapsular haematoma, impracticability for ARFI, acute kidney injury (AKI) and other elasticity-sensitive conditions including renal cyst, polycystic kidney disease, medullary sponge kidney, kidney stone, hydronephrosis, renal artery stenosis, renal vein thrombosis, nutcracker syndrome, nephrocalcinosis and renal tumour. In total, 18 patients were excluded from our study including one for failure of appropriate breath holding, one for AKI in pathology and 16 for presence of subcapsular haematoma. The remaining 45 CKD patients underwent ARFI measurement and comprised the study population.

ARFI ultrasound examination

All conventional and ARFI examinations were performed on a Siemens-Acuson S2000 ultrasound machine (Siemens Acuson, Mountain View, CA) equipped with ARFI (Virtual Touch™ Tissue Quantification package), using a curved array multifrequency transducer (4–1 MHz).

Patients were examined in the right lateral decubitus position. Before ARFI assessment, the length and interlobar arterial resistive index (RI) of the left kidney was measured by B-mode and Doppler ultrasound examination. Data are presented as means of three individual measurements. For RI assessment, colour Doppler gain and the pulse repetition frequency were adjusted individually. RI values were obtained from three different interlobar arteries.

During ARFI assessment, for standardization, the measurement was performed in the renal cortex in the middle third of the kidney on the sagittal plane (Fig. 1). Renal medulla and sinus were carefully excluded from the sample volume. The sample line was perpendicular to the surface of the kidney. Besides, the transducer was located as close to the kidney as possible, with a depth limitation of 8.0 cm. Once the location of transducer and sample volume had been determined, the operator maintained the same position during examination. The applied transducer pressure was minimized as much as possible during imaging to avoid mechanical compression on the kidney. All measurements were performed during breath holding. A total of 15 valid measurements were obtained. In the event of a non-valid measurement, a repeated measurement was carried out. This ARFI protocol was designed to minimize the potential impact of variation of transducer force, sampling error of non-cortical tissue and structural anisotropy of the kidney.

All ARFI examinations were performed by one experienced ultrasound physician, who was blinded to the patients' clinical and pathological data.

Pathological examination

Kidney tissue obtained by needle biopsy was fixed in 4 % buffered formaldehyde. After embedding in paraffin, 2-μm-thick serial sections were cut and haematoxylin and eosin staining and the periodic acid silver methanamine method were applied for assessment of the glomerulosclerosis and tubular atrophy. In addition, a Masson–Goldner's trichrome method was performed to quantify interstitial fibrosis. Stainings were performed according to standard protocols. The pathological lesions were evaluated semi-quantitatively

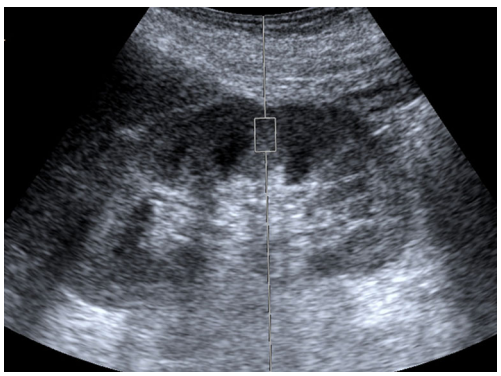

Fig. 1 Measurement of SWV in the middle third of the renal cortex on sagittal plane

by one experienced nephrologist, who was blinded to the patients' clinical and ARFI data. Glomerular sclerosis was expressed by glomerular sclerosis index (GSI), assessed according to the method stated in Chen's work [9]. Tubulointerstitial injuries, expressed by the percentage of the cortex showing tubular atrophy (TA) and interstitial fibrosis (IF), were evaluated on the basis of descriptions in the Oxford classification of IgA nephritis [10].

Clinical data

All patients were admitted to our hospital for renal biopsy. Clinical data, including serum creatinine, eGFR and BMI, were obtained from the patients' medical record.

Statistical analysis

For statistical data analysis, SPSS 16.0 for Windows (SPSS Inc., Chicago, IL, USA) was used. All descriptive results are presented as mean values with the standard deviation. To assess bivariate monotonous relationships, the Spearman correlation coefficient (rho) was calculated. Differences between groups were compared by one-way ANOVA. For the evaluation of intraobserver variability, the coefficient of variation (CV = standard deviation/mean × 100 %) of repeat SWV measurement was calculated for each patient. A two-tailed P value of less than 0.05 was considered statistically significant.

Results

Patients' characteristics

Patients' clinical, pathological and conventional ultrasound characteristics are summarized in Tables 1 and 2.

In clinical data, the most common aetiology of CKD was IgA nephropathy (31/45, 68.9 %). Over half the patients (26/45, 57.8 %) were classified into CKD 1 stage. In pathology, all pathological indicators (GSI, TA and IF) showed significant correlations with CKD stage (rho=0.339–0.617, $P<0.05$). On conventional ultrasound, renal length was negatively correlated with CKD stage. On one-way ANOVA, RI values in CKD 4 subgroup were significantly higher than in CKD 1 and 2 subgroups ($P<0.05$).

Table 1 Study population

Number of patients	45
Female	22 (48.9 %)
Male	23 (51.1 %)
Age (years)	37.1±13.4
Etiology of CKD	
IgA nephropathy	31
Membranous nephropathy	4
Malignant arteriolar nephrosclerosis	4
Diabetic nephropathy	3
Benign arteriolar nephrosclerosis	2
Lupus nephritis	1

ARFI clinicopathological correlation of SWV measurement

The results of ARFI SWV measurement are summarized in Table 2. Spearman analysis indicated no significant correlation of SWV measurements with CKD stage and pathological indicators (both $P>0.05$). However, renal length showed a weak correlation with SWV measurements (rho=0.369, $P=0.013$).

Influencing factors of SWV measurement

Some potential influencing factors of SWV measurement were assessed in our study.

For intraobserver variability, the overall CV of repeat SWV measurement was 23.0±8.3 % in our study. Specifically, CV was 22.5±9.0 %, 26.9±7.7 %, 22.3±5.4 % and 21.1±9.0 % in CKD 1, 2, 3 and 4 subgroups respectively (Fig. 2). There was no significant difference among subgroups ($P>0.05$).

For measurement depth, a strong correlation was found between patients' BMI and measurement depth (rho=0.701, $P=0.000$). However, no significant correlation was shown between SWV measurements and depth or BMI ($P>0.05$) (Table 2).

For renal tissue blood perfusion, the intrarenal arterial resistance was assessed. Interlobar arterial RI was calculated for each patient. No significant correlation was found between RI and SWV measurements.

Discussion

Chronic kidney disease (CKD), which comprises a group of pathologies, is a progressive and irreversible pathological syndrome that starts silently, continues through renal dysfunction and ends up in renal failure. The incidence of CKD has increased significantly over the recent decades [1, 2]. CKD treatment in earlier stages of CKD is effective in slowing the progression toward renal failure [11].

However, traditional markers of CKD, such as serum creatinine, urea nitrogen and proteinuria are insensitive and may result in extensive time lapse when successful interventions could be applied [12]. Some new biomarkers show promise, such as neutrophil gelatinase-associated lipocalin, but further validation is required before translation into clinical practice

Table 2 Study data of the 45 patients

Characteristic	CKD 1	CKD 2	CKD 3	CKD 4	Spearman rho (*P* value)	
Demographic data						
Number of patients (%)	26 (57.8 %)	7 (15.6 %)	6 (13.3 %)	6 (13.3 %)	–	–
Males/females	12/14	4/3	3/3	4/2	–	–
Age (years)	33.0±9.3	45.7±14.5	32.7±8.5	46.0±20.5	–	–
BMI (kg/cm^2)	26.2±4.9	25.3±2.7	30.9±5.4	23.5±2.7	–	+0.097 (0.528)[b]
Laboratory data						
Creatinine (mmol/l)	69.4±14.2	92.7±14.2	160.2±25.8	251.2±70.7	+0.838 (0.000)[a]	−0.100 (0.514)[b]
GFR (ml/min)	109.0±13.3	76.4±9.2	42.4±2.6	24.3±4.0	−0.900 (0.000)[a]	+0.148 (0.331)[b]
Pathological data						
GSI	1.02±0.57	0.91±0.49	1.48±0.92	2.13±0.91	+0.339 (0.021)[a]	−0.007 (0.965)[b]
TA (%)	0.21±0.17	0.30±0.20	0.56±0.23	0.57±0.31	+0.519 (0.000)[a]	−0.030 (0.847)[b]
IF (%)	0.18±0.13	0.31±0.17	0.55±0.24	0.59±0.27	+0.617 (0.000)[a]	−0.125 (0.413)[b]
Ultrasound data						
Length (cm)	11.54±0.61	10.75±0.48	11.13±0.93	10.99±1.24	−0.392 (0.008)[a]	+0.369 (0.013)[b]
RI	0.56±0.05	0.59±0.05	0.53±0.06	0.63±0.07	+0.200 (0.187)[a]	−0.140 (0.358)[b]
SWV (cm/s)	2.74±0.57	2.30±0.27	2.85±0.26	2.60±0.40	−0.189 (0.208)[a]	–
SWV-depth (cm)	4.62±0.92	4.87±0.82	5.18±0.89	3.88±0.47	–	−0.083 (0.587)[b]

CKD chronic kidney disease, *BMI* body mass index, *GFR* glomerular filtration rate, *GSI* glomerulosclerosis indicators, *TA* tubular atrophy, *IF* interstitial fibrosis, *RI* resistive index, *SWV* shear wave velocity

[a] Correlation with CKD stage and [b] with SWV

[13]. So far, there is no CKD marker which could satisfy the requirement of progression prediction and early detection.

Elasticity measurements in various tissues have gained increased interest. In the last few years ARFI, a novel elasticity assessment technique, has been used in several experimental and clinical studies in various tissues. It has gained widespread use for the detection of fibrosis in chronic liver disease [6–8]. ARFI quantitatively assesses SWV of the tissue. Shear waves are created by a short-duration high-intensity acoustic pulse. The classic parameter to describe tissue stiffness is the Young's elastic modulus, which is directly proportional to the square of the SWV [14].

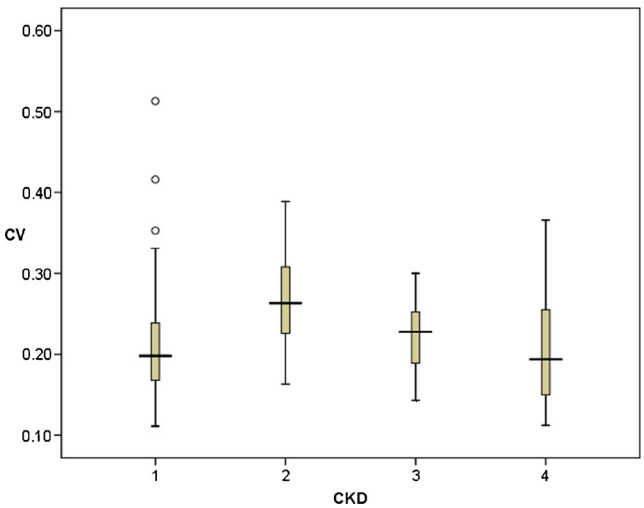

Fig. 2 The box and whisker plot of coefficient of variation (CV) of ARFI measurement in CKD subgroups. *Bottom*, *middle* and *top lines* of each box correspond to the 25th percentile, 50th percentile (median) and 75th percentile, respectively. The *whiskers* show 95 %/5 % confidential intervals. Points at a greater distance from the median than 1.5 times the interquartile range (IQR) are plotted individually as *circles*

In the field of nephrology, elasticity imaging has been applied in the assessment of cortical stiffness of renal transplants and native kidney [15–22]. However, studies have yielded conflicting results. In contrast, to our knowledge, the value of ARFI in noninvasive assessment of tissue fibrosis has not been studied in CKD patients. In the literature, only one study investigated the correlation of SWV value and the laboratory markers of CKD patients [23]. In our study, pathological fibrosis tended to deteriorate with increasing CKD stage. Cortical SWV value, however, did not show the same tendency with CKD stage, which is consistent with the findings in a previous study. Guo et al. [23] found that cortical SWV values did not differ in different CKD stages. The mean SWV values were 1.81±0.43 m/s, 1.79±0.29 m/s, 1.81±0.44 m/s, 1.64±0.55 m/s, and 1.36±0.17 m/s for stage 1, 2, 3, 4 and 5 in CKD patients respectively. Furthermore, no significant correlations were found between SWV values and pathological fibrosis indicators in the present study either. Similarly, Syversveen et al. [17] found that SWV measurements did not differ between kidney grafts with various degrees of fibrosis, whereas Stock et al. [16] described a positive correlation between SWV value and interstitial fibrosis in the renal allograft.

The reasons for these negative results in our study remain unclear. Syversveen et al. [17] found high inter- and intraobserver variation in ARFI measurement, and believed this to be the important factor that compromised the ability of ARFI in assessment of renal tissue stiffness. Furthermore, several studies indicated that a standardized measurement method is required to obtain reliable and reproducible results. Syversveen et al. [19] found that SWV measurements in kidney transplants are dependent on the applied transducer force. In animal experimental research, Gennisson et al. [24] found that cortical elasticity values were always higher when acquisitions were realized with the ultrasound main axis perpendicular to the main pyramid axis than when parallel, demonstrating an effect of renal anisotropy. According to these findings, a standardized ARFI protocol (details in "Material and methods") was employed in our study to minimize the potential affect of variation of transducer force, sampling error of non-cortical tissue and structural anisotropy of the kidney.

As a result, an acceptable level of CV (23.0±8.3 %) was achieved in our study. In addition, depth and patients' BMI had no significant affect on SWV measurements. Nevertheless, negative results were still obtained. Therefore, we presume that some intrinsic factors other than tissue fibrosis may have significant impact on renal parenchyma stiffness as well.

Compared to the liver, the kidney has a much higher tissue heterogeneity and anisotropy. Therefore, the pathological status in such a complex organ may not be fully reflected by one or more parameters. In the renal allograft study by Grenier et al. [18], renal cortical stiffness did not correlate with any single semi-quantitative Banff score or the level of interstitial fibrosis; however, a significant correlation was observed between cortical stiffness and the total Banff scores of chronic lesions (four components) and of all the elementary lesions (11 components). In addition, non-fibrotic changes could also increase the tissue stiffness, e.g. acute injury. In the liver, tissue elasticity is unreliable for detection of cirrhosis in patients with acute liver damage [25]. To exclude this confounding factor, patients with evidence of AKI were not included in our study. These results suggest that the complexity of renal pathology should be considered during interpretation of elasticity assessments.

The kidney is a richly perfused organ, receiving 25 % of cardiac output. Its distension (and in turn stiffness) may be determined by renal perfusion pressure, blood flow and filtrate volume. In our study, interlobar arterial RI was calculated to assess the renal tissue blood perfusion in one aspect. Although no significant correlation was found between RI and SWV, the absence of impact of blood perfusion on tissue stiffness can not be concluded. Tissue perfusion is a complex issue. RI is just one of the evaluation parameters and is far from sufficient and representative. More importantly, as CKD progresses, renal fibrosis increases gradually, whereas intrarenal blood perfusion decreases simultaneously [26]. The two factors contribute oppositely to the stiffness of renal tissue. Renal perfusion impairment, therefore, may counterbalance to some extent the stiffness increase due to fibrosis. In the animal study of renal arterial stenosis (RAS), Warner et al. [27] found that acute stenotic cortex stiffness decreased as renal blood flow decreased. In a 6-week chronic RAS model, however, cortical stiffness was not significantly different from controls, despite histological evidence of renal tissue fibrosis. They conclude that hemodynamic variables modulate kidney stiffness and may mask the presence of fibrosis. These results suggest that the status of renal tissue perfusion should also be considered during interpretation of elasticity assessments.

There are some limitations of this study. Firstly, although the sample size of our study is similar to or even larger than that in previous renal allograft research, it is still relatively small in consideration of the complex entity of CKD. Studies with a larger sample size are needed to verify our study results in the future. Secondly, epidemiological studies indicate that diabetes and hypertension are now the leading causes of CKD in the general population, whereas IgA nephropathy accounted for most cases in our study population (31/45, 68.9 %). There were only nine cases related to diabetes and hypertension. However, as a radiology–pathology correlation study, this discrepancy seems to be reasonable. Renal biopsy is only required in the evaluation of CKD in special cases, e.g. difficult cases to diagnose; however, most CKDs caused by diabetes and hypertension can be successfully diagnosed without renal biopsy. Therefore, the biopsy population is essentially different from the general population in this CKD study. Nevertheless, this difference should not hinder the translation of study results from a biopsy population into understanding of CKD in the general population, because in all cases, CKD eventually compromises all renal structures and gives rise to a similar phenotype in pathology regardless of aetiology. Thirdly, in our study, ARFI measurements were conducted after renal biopsy. To minimize the impact of the interventional procedure on renal tissue stiffness, some measures were taken in our study: (1) ARFI measurement was applied at the middle third of the kidney, whereas renal biopsy was conducted at the lower pole of the kidney. (2) There is a 3-day interval between renal biopsy and ARFI assessment. (3) Patients with post-biopsy haematoma were strictly excluded from our study. Although it is still impossible to completely eliminate the impact, with these measures, it seems to be reasonable to expect the non-biopsied middle-third renal tissue to remain at the baseline level of elasticity after a 3-day recovery when post-biopsy haematoma was absent. Finally, all ARFI measurements were done by the same operator, thereby eliminating interobserver variation of the technique as a source of error. On the other hand, the interobserver variability of ARFI under our standardized protocol was not evaluated in our study. Further investigation is needed regarding this issue.

In conclusion, the ARFI technique can assess the tissue stiffness of CKD kidneys by measuring cortical SWV values. However, this study suggests that the quantification of tissue stiffness using ARFI is not able to correlate with clinical stage and pathological indicators in CKD patients. This failure may be attributable to several intrinsic and extrinsic influencing factors. Among them, it would be necessary to evaluate the effect of pathological complexity and tissue perfusion of the kidney on stiffness assessment in future studies.

Acknowledgements The scientific guarantor of this publication is Ke Lv, the lead author of this article. The authors of this manuscript declare no relationships with any companies whose products or services may be related to the subject matter of the article. This study has received funding by Key Project of Chinese National Program for Fundamental Research and Development (973 Program 2012CB517803 to C.L.), National Natural Scientific Foundation, China (81170674 to C.L). No complex statistical methods were necessary for this paper. Institutional review board approval was obtained. Written informed consent was obtained from all subjects (patients) in this study. No study subjects or cohorts have been previously reported.

Methodology: prospective, diagnostic, performed at one institution.

References

1. Levey AS, de Jong PE, Coresh J et al (2011) The definition, classification, and prognosis of chronic kidney disease: a KDIGO controversies conference report. Kidney Int 80:17–28
2. Jha V, Garcia-Garcia G, Iseki K et al (2013) Chronic kidney disease: global dimension and perspectives. Lancet 382:260–272
3. López-Novoa JM, Rodríguez-Peña AB, Ortiz A, Martínez-Salgado C, López Hernández FJ (2011) Etiopathology of chronic tubular, glomerular and renovascular nephropathies: clinical implications. J Transl Med 9:13
4. Bosmans JL, Ysebaert DK, Verpooten GA (2008) Chronic allograft nephropathy: what have we learned from protocol biopsies? Transplantation 85:S38–S41
5. Bamber J, Cosgrove D, Dietrich CF et al (2013) EFSUMB guidelines and recommendations on the clinical use of ultrasound elastography. Part 1: basic principles and technology. Ultraschall Med 34(2):169–184
6. Palmeri ML, Wang MH, Dahl JJ, Frinkley KD, Nightingale KR (2008) Quantifying hepatic shear modulus in vivo using acoustic radiation force. Ultrasound Med Biol 34:546–558
7. Lupsor M, Badea R, Stefanescu H et al (2009) Performance of a new elastographic method (ARFI technology) compared to unidimensional transient elastography in the noninvasive assessment of chronic hepatitis C. Preliminary results. J Gastrointestin Liver Dis 18:303–310
8. Friedrich-Rust M, Wunder K, Kriener S et al (2009) Liver fibrosis in viral hepatitis: noninvasive assessment with acoustic radiation force impulse imaging versus transient elastography. Radiology 252:595–604
9. Chen L, Faulhaber-Walter R, Wen Y et al (2010) Renal failure in mice with Gsalpha deletion in juxtaglomerular cells. Am J Nephrol 32:83–94
10. Roberts IS, Cook HT, Troyanov S et al (2009) The Oxford classification of IgA nephropathy: pathology definitions, correlations, and reproducibility. Kidney Int 76:546–556
11. Boor P, Sebeková K, Ostendorf T, Floege J (2007) Treatment targets in renal fibrosis. Nephrol Dial Transplant 22:3391–3407
12. Levey AS, Cattran D, Friedman A et al (2009) Proteinuria as a surrogate outcome in CKD: report of a scientific workshop sponsored by the National Kidney Foundation and the US Food and Drug Administration. Am J Kidney Dis 54:205–226
13. Cai L, Rubin J, Han W, Venge P, Xu S (2010) The origin of multiple molecular forms in urine of HNL/NGAL. Clin J Am Soc Nephrol 5: 2229–2235
14. Garra BS (2007) Imaging and estimation of tissue elasticity by ultrasound. Ultrasound Q 23:255–268
15. Arndt R, Schmidt S, Loddenkemper C (2010) Noninvasive evaluation of renal allograft fibrosis by transient elastography–a pilot study. Transpl Int 23:871–877
16. Stock KF, Klein BS, Vo Cong MT et al (2010) ARFI-based tissue elasticity quantification in comparison to histology for the diagnosis of renal transplant fibrosis. Clin Hemorheol Microcirc 46:139–148
17. Syversveen T, Brabrand K, Midtvedt K et al (2011) Assessment of renal allograft fibrosis by acoustic radiation force impulse quantification–a pilot study. Transpl Int 24:100–105
18. Grenier N, Poulain S, Lepreux S et al (2012) Quantitative elastography of renal transplants using supersonic shear imaging: a pilot study. Eur Radiol 22:2138–2146
19. Syversveen T, Midtvedt K, Berstad AE, Brabrand K, Strøm EH, Abildgaard A (2012) Tissue elasticity estimated by acoustic radiation force impulse quantification depends on the applied transducer force: an experimental study in kidney transplant patients. Eur Radiol 22: 2130–2137
20. Stock KF, Klein BS, Cong MT et al (2011) ARFI-based tissue elasticity quantification and kidney graft dysfunction: first clinical experiences. Clin Hemorheol Microcirc 49:527–535
21. Gallotti A, D'Onofrio M, Pozzi Mucelli R (2010) Acoustic radiation force impulse (ARFI) technique in ultrasound with Virtual Touch tissue quantification of the upper abdomen. Radiol Med 115:889–897
22. Bruno C, Caliari G, Zaffanello M et al (2013) Acoustic radiation force impulse (ARFI) in the evaluation of the renal parenchymal stiffness in paediatric patients with vesicoureteral reflux: preliminary results. Eur Radiol 23:3477–3484
23. Guo LH, Xu HX, Fu HJ, Peng A, Zhang YF, Liu LN (2013) Acoustic radiation force impulse imaging for noninvasive evaluation of renal parenchyma elasticity: preliminary findings. PLoS One 8:e68925
24. Gennisson JL, Grenier N, Combe C, Tanter M (2012) Supersonic shear wave elastography of in vivo pig kidney: influence of blood pressure, urinary pressure and tissue anisotropy. Ultrasound Med Biol 38:1559–1567
25. Sagir A, Erhardt A, Schmitt M, Häussinger D (2008) Transient elastography is unreliable for detection of cirrhosis in patients with acute liver damage. Hepatology 47:592–595
26. Syversveen T, Brabrand K, Midtvedt K, Strøm EH, Hartmann A, Berstad AE (2011) Non-invasive assessment of renal allograft fibrosis by dynamic sonographic tissue perfusion measurement. Acta Radiol 52:920–926
27. Warner L, Yin M, Glaser KJ et al (2011) Noninvasive in vivo assessment of renal tissue elasticity during graded renal ischemia using MR elastography. Invest Radiol 46:509–514