

World Journal of *Radiology*

World J Radiol 2020 May 28; 12(5): 48-86





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INDEXING/ABSTRACTING

The *WJR* is now abstracted and indexed in Emerging Sources Citation Index (Web of Science), PubMed, PubMed Central, China National Knowledge Infrastructure (CNKI), China Science and Technology Journal Database (CSTJ), and Superstar Journals Database.

RESPONSIBLE EDITORS FOR THIS ISSUE

Responsible Electronic Editor: *Mei-Yi Liu*

Proofing Production Department Director: *Xiang Li*

Responsible Editorial Office Director: *Ruo-Yu Ma*

NAME OF JOURNAL

World Journal of Radiology

ISSN

ISSN 1949-8470 (online)

LAUNCH DATE

January 31, 2009

FREQUENCY

Monthly

EDITORS-IN-CHIEF

Venkatesh Mani

EDITORIAL BOARD MEMBERS

<https://www.wjgnet.com/1949-8470/editorialboard.htm>

PUBLICATION DATE

May 28, 2020

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INSTRUCTIONS TO AUTHORS

<https://www.wjgnet.com/bpg/gerinfo/204>

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<https://www.wjgnet.com/bpg/GerInfo/288>

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<https://www.wjgnet.com/bpg/gerinfo/208>

ARTICLE PROCESSING CHARGE

<https://www.wjgnet.com/bpg/gerinfo/242>

STEPS FOR SUBMITTING MANUSCRIPTS

<https://www.wjgnet.com/bpg/GerInfo/239>

ONLINE SUBMISSION

<https://www.f6publishing.com>

Diagnostic problems in two-dimensional shear wave elastography of the liver

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Author contributions: Naganuma H designed the report, collected the patient's clinical data, and generated the figures; Ishida H designed the report and wrote the paper; Uno A performed the computer simulation; Nagai H generated the figures; Kuroda H and Ogawa M collected the patient's clinical data.

Conflict-of-interest statement: The authors declare no conflicts of interest.

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Manuscript source: Invited manuscript

Received: February 25, 2020

Peer-review started: February 25,

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Abstract

Two-dimensional shear wave elastography (2D-SWE) is used in the clinical setting for observation of the liver. Unfortunately, a wide spectrum of artifactual images are frequently encountered in 2D-SWE, the precise mechanisms of which remain incompletely understood. This review was designed to present many of the artifactual images seen in 2D-SWE of the liver and to analyze them by computer simulation models that support clinical observations. Our computer simulations yielded the following suggestions: (1) When performing 2D-SWE in patients with chronic hepatic disease, especially liver cirrhosis, it is recommended to measure shear wave values through the least irregular hepatic surface; (2) The most useful 2D-SWE in patients with focal lesion will detect lesions that are poorly visible on B-mode ultrasound and will differentiate true tumors from pseudo-tumors (e.g., irregular fatty change); and (3) Measurement of shear wave values in the area posterior to a focal lesion must be avoided.

Key words: Two-dimensional shear wave elastography; Ultrasound; Artifacts; Liver cirrhosis; Liver tumor; Computer simulation model

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2020

First decision: April 7, 2020**Revised:** April 19, 2020**Accepted:** May 12, 2020**Article in press:** May 12, 2020**Published online:** May 28, 2020**P-Reviewer:** Lu Q, Shim J**S-Editor:** Zhang L**L-Editor:** A**E-Editor:** Liu MY

Core tip: Two-dimensional shear wave elastography is the most widely used diagnostic tool for liver but has many ultrasound artifact-related problems. Our computer simulation model suggests the following ways to minimize them: (1) In patients with chronic hepatic disease, especially liver cirrhosis, measure shear wave values through the least irregular hepatic surface; (2) The most useful application in patients with focal lesions is detecting lesions poorly visible on B-mode ultrasound and differentiating true tumors from pseudo-tumors (*e.g.*, irregular fatty change); and (3) Measurement of shear wave values in the area posterior to a focal lesion must be avoided.

Citation: Naganuma H, Ishida H, Uno A, Nagai H, Kuroda H, Ogawa M. Diagnostic problems in two-dimensional shear wave elastography of the liver. *World J Radiol* 2020; 12(5): 76-86

URL: <https://www.wjgnet.com/1949-8470/full/v12/i5/76.htm>

DOI: <https://dx.doi.org/10.4329/wjr.v12.i5.76>

INTRODUCTION

Although liver biopsy has long been the standard method for diagnosing chronic liver disease, it is associated with many problems, such as postbiopsy complications^[1], sampling error^[2], and interobserver variability^[3]. In a positive aspect, these problems motivated the development of noninvasive techniques to assess liver fibrosis, including magnetic resonance elastography^[4-6] and ultrasound (US)-based elastography^[7-10]. The latter has attained preferential use because of its lower cost and easier manipulation of the instrument^[7-10]. Currently, there are four kinds of US-based elastography, namely strain elastography^[11], transient elastography^[12], point shear wave elastography^[13], and two-dimensional shear wave elastography (2D-SWE)^[9,14,15]. Among these methods, 2D-SWE has emerged as the most frequently used diagnostic US tool for hepatic fibrosis quantification; this is due to its ability to sample a large area in the liver, changing the sampling area quickly under B-mode observation and displaying a color mapping of shear wave (SW) values over the B-mode image^[9,15]. Measurement of SW values can be easily performed but it is also well known that the obtained SW values change according to the instrument itself and the level of expertise of the operator; as such, the certitude of those SW results is not always satisfactory^[16,9,15]. The other reasons for this instability have not been clarified.

This review reexamines the variability, using a method that is different from those in the commonly reported studies. US artifacts are routinely encountered in clinical practice and include refraction artifacts^[16-18], attenuation artifacts^[16,19,20], reflection artifact^[16,21], reverberation artifacts^[22] and others^[16,23,24]. As use of 2D-SWE becomes more widespread, the problems related to US artifacts in it will be more important^[25-27]. The aim of this review was, thus, to present a wide spectrum of US artifacts in hepatic 2D-SWE and to provide the simplest way to minimize the effects of such.

THEORETICAL BASIS OF TWO-DIMENSIONAL SHEAR WAVE ELASTOGRAPHY

The push-pulse produces small tissue movements in the plane of the push-pulse. These tissue movements, in turn, produce SWs that propagate and produce other minimal tissue movements in the horizontal plane of the push-pulse. These movements in the horizontal plane further propagate through the tissue in a sideways direction, away from the push-pulse. These SW movements (strictly speaking, tissue movements produced by SWs) are tracked by the regular-interval tracking US pulses, which are used to measure the arrival time of SWs. The simple formula is arrival time of SW/distance from the push-pulse, used to determine the speed of SWs. Such a measurement is possible because the speed of SWs is very slow (< 1-10 m/s) compared to the speed of US pulses (around 1540 m/s) (Table 1)^[28,29]. There are two ways to quantify the relative tissue stiffness: SW speed expressed as m/s; and, kilopascal (kPa). Mostly, the SW speed is converted automatically to kPa, using the equation $1 \text{ kPa} = 3 \times P \times (\text{SW speed m/s})^2$, with the assumption that the examined tissue is always homogeneous, and where P is the tissue density and defined as 1.00 kg/m³.

Table 1 Acoustic characteristics of human tissues^[28,29]

Tissue	Sound velocity (m/s)	Acoustic impedance ($\times 10^6$ kg/m ² ·s)	Density ($\times 10^3$ kg/m ³)
Liver	1555	1.65	0.001
Fat	1460	1.38	0.0009
Muscle	1600	1.70	0.001
Water	1480	1.48	0.007

Cited from references 28 and 29, with minimal modification.

The 2D-SWE method uses emission of multiple acoustic push-pulse to generate SWs from multiple lines in the tissue (Figure 1). As the SWs propagate, they cause tissue displacement, and this very minimal displacement is tracked by conventional pulse-echo US beams^[6,30,31]. The US machine measures the propagation speed of SWs as they travel in tissue, and the measured SW speed at each point is displayed in color^[6,32]. The reconstructed 2D color mapping of SWs is called “2D-SWE” and facilitates recognition of global distribution of tissue elasticity of the area.

FACTORS THAT DEGRADE QUALITY OF TWO-DIMENSIONAL SHEAR WAVE ELASTOGRAPHY IMAGES

For all, these US artifact-related problems are more clearly shown upon use of propagation mode, which can determine the causal artifact.

Reverberation artifact

Acoustic reverberation of the push-pulse at the liver capsule results in a false increase in SW speed. Reverberation artifacts arise when the US signals reflects repeatedly between two interfaces of largely different acoustic impedance, resulting in delayed echoes returning to the transducer at regular intervals. This can lead to reverberation artifacts on grayscale US image^[33]. The same phenomenon of the push pulse is considered to occur between the liver capsule and the transducer. This phenomenon usually appears in the upper part of the cursor, presenting as a band of red (*i.e.* very increased SW speeds) (Figure 2). Thus, it is highly recommended to avoid this area when measuring SW values with SWE; if not, the results will be overestimated.

Attenuation artifact

Attenuation frequently occurs in a clinical setting and most commonly in obese or overweight patients. In these patients, a strongly attenuated push-pulse passing through the tissue results in poor creation of SWs at depth. This phenomenon usually appears at the distal part of the cursor, presenting as a colorless area (*i.e.* poor acquisition of SW data) (Figure 3). Thus, it is highly recommended to avoid this area when measuring SW values in obese or overweight patients.

Probe compression artifact

Excessive probe compression during image acquisition causes artificial compression of tissues just under the probe. This phenomenon is seen clearly when the liver is evaluated through subcostal scanning (Figure 4). SW measurement in the compressed area leads to a false elevation in SW values. A probe compression artifact appears near the probe, presenting as a reddish band. Thus, it is recommended not to compress the liver too much. The simplest way to avoid this artifact is to perform measurements through intercostal spaces only, where the liver tissue is less likely to be compressed by the probe.

Motion artifact

This phenomenon is seen clearly when the patient is unable to hold his/her breath or to change position quickly. Besides these extreme conditions, a motion artifact is usually seen when observing the left lobe of the liver, due to cardiac motion. Motion artifacts give rise to the characteristic image of a colorless area or a reddish area in the cursor, suggesting that SW values cannot be measured accurately in this area (Figure 5; see also, the section on tracking US beam-related problems below).

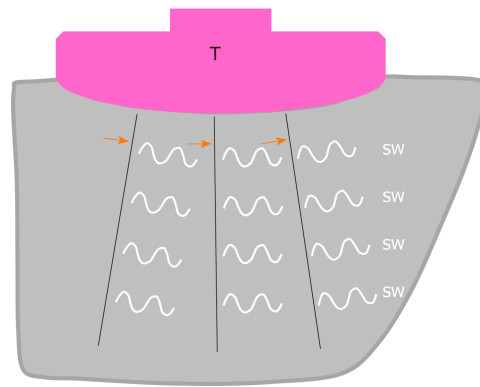


Figure 1 Schematic drawing of two-dimensional shear wave elastography in a healthy individual. Multiple push-pulses (arrows) are emitted from the transducer to create shear waves. T: Transducer; SW: Shear wave.

MECHANISMS UNDERLYING ULTRASOUND ARTIFACT-RELATED PROBLEMS IN TWO-DIMENSIONAL SHEAR WAVE ELASTOGRAPHY DETERMINED BY A COMPUTER SIMULATION MODEL

US scanners reconstruct US images on the assumption that sound passes through all parts of the human body in a straight line and at a constant velocity, and apply this assumption to all scanning planes. Actually, however, these sound velocity in the human body varies with the composition of the tissue scanned. When a plane containing tissues with different velocities is scanned, sound refraction occurs at the interface of the tissues, according to Snell's law (see later in "Discussion"). Computer simulation analysis helps understand the global images of refraction in the plane, measuring the degree of refraction at each point of the interface, not only in grayscale US image but also in 2D-SWE image.

2D-SWE in diffuse liver disease

2D-SWE has been reported as useful for assessing liver fibrosis with high accuracy^[8,9,34-36]. It is generally reported that SW speed increases as fibrosis advances^[15,37-39]; thus, heterogeneous distribution of different degrees of fibrosis will create a heterogeneous color mapping in 2D-SWE. Measurement of liver stiffness is based on the following assumptions: (1) All push-pulses emitted from the transducer advance directly without deviation, at an even distance from each other; and (2) All SWs created from these push-pulses propagate horizontally at the same distance from the transducer. However, in reality, like conventional US beams, push-pulses refract at the liver surface (according to Snell's law) because there is a large difference between the liver and the surrounding tissue and the hepatic surface is irregular.

Figure 6 shows the mode of propagation of push-pulses in the liver. As a result, SWs propagate in unassumed directions. This computer simulation model clearly teaches us an important lesson about measurement of SW speeds in liver cirrhosis. Furthermore, this speculation is in accordance with the findings from some studies with 2D-SWE measurements of healthy volunteers in whom the liver surface was smooth^[40,41]. In those studies, measurements by novice operators were not significantly different from those of experienced operators^[31,40,42]. Our computer simulation model shows that studies of normal liver do not contribute to resolving the problem of significant variability of SW values in liver cirrhosis. Although the measuring error is minimal, it is recommended to measure SW values through the least deformed hepatic surface possible.

2D-SWE in liver tumors

2D-SWE findings have been reported as useful for predicting tissue characterization of liver tumor, with markedly contradictory results^[43-47]. The most widely accepted method for diagnosing liver tumors by 2D-SWE is measurement of maximal or median SW values within the lesion^[46-49]. This method has long been performed but, as is shown in Figure 7, this idea is compromised by a combination of US refraction and reflection. The reported SW measurement of tumor stiffness is based on the following assumptions: (1) All SWs created from the push-pulses advance directly, without deviation, from the surrounding tissue toward the tumor and within the tumor; and (2) No reflection occurs at the interface between the surrounding tissue and liver

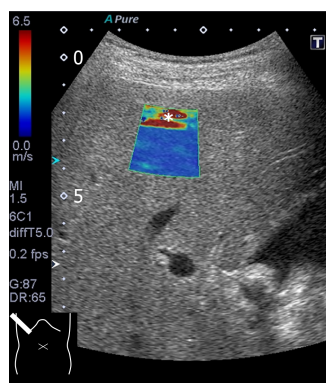


Figure 2 Reverberation artifact. The cursor contains a red (falsely increased shear wave) area (asterisk) at the top.

tumor.

However, in reality, like conventional US beams, SWs refract at the interface (again, according to Snell's law) because there is a large difference in propagation speed between the liver tumor and the surrounding tissue (Figure 7). Furthermore, the degree of refraction is thought to be more accentuated in 2D-SWE (1-10 m/s) than in conventional US (around 1540 m/s) (Figure 7B and C). The degree of reflection at the surrounding tissue-liver tumor interface is more accentuated in 2D-SWE, for the same reason. It is the deviation from the two above-mentioned assumptions that leads to the conclusion that accurate stiffness measurement of liver tumors is not possible by 2D-SWE, in most cases. This idea is in accordance with the American Institute of Ultrasound in Medicine recommendation that evaluation of liver tumor stiffness by 2D-SWE must be done with caution. Although, the SW value measurement inside the tumor is not highly accurate, this measurement is still valuable for judgement of relative stiffness of tumor and surrounding liver. However, conversely, this phenomenon helps in the detection of a liver tumor that is otherwise poorly visualized on B-mode (Figure 8) and in the differentiation of a pseudo-liver tumor (*i.e.*, focal fatty infiltration^[43] or chronic hepatic porphyria^[50]) from a true liver tumor.

Tracking US beam-related problems

Finally, we would like to briefly mention refraction of tracking US beams. We mentioned earlier the influence of US artifacts on 2D-SWE, on the assumption that the tracking US pulses occur at regular intervals and advance straight from the transducer through the tissue. However, they deviate in some instances. Figure 9 shows such a case. US beams deviate twice when passing through a focal lesion, with one at the upper surrounding tissue-focal lesion interface and the other at the lower focal lesion-surrounding tissue interface. As a result, US beams propagating in tissue posterior to the focal lesion deviate; however, the US machine calculates SW values on the assumption that there is no deviation of US beams. Thus, this phenomenon suggests that SW measurements must be done in a plane that does not contain focal lesions.

DISCUSSION

In many reported studies, 2D-SWE has been shown to have a sufficient level of sensitivity in evaluating the degree of hepatic fibrosis^[7-9,36] but with significant heterogeneity of results. This heterogeneity has been considered due to variations among patient populations, study design, and devices used^[49]. Some of these studies have pointed to technical flaws in earlier studies but recent studies also show some instable results^[45,46,51]. These studies have brought into question whether they included the influence of US artifacts.

This review has an important strength in that it is a theoretical analysis not found in similar trials reported in the literature. Computer simulation model yields a purely theoretical analysis. In the case of gray-scale US images, the sound refraction produces artifactual images, because the US scanner displays each point at the appropriate distance determined by the time taken for the echo to return to the transducer in the direction in which the transducer is pointing at the time, even when the US beam is refracted. In the case of 2D-SWE as well, the US scanner reconstructs 2D-SWE images on the assumption that SW passes horizontally in a straight line, without deviation, and the US scanner displays SW velocity mapping on the basis of data measured by tracking pulses (determined by the time/distance). Computer

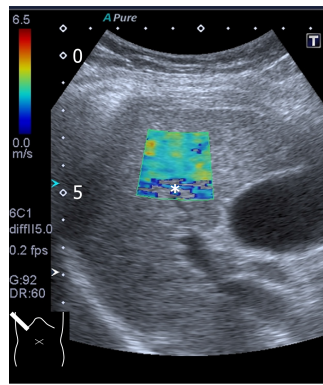


Figure 3 Attenuation artifact. The cursor includes a colorless area (asterisk indicating poor acquisition of shear wave data) at the bottom.

simulation model enables us to calculate accurately and automatically the degree of refraction at each point, and understand the global image of refraction in the plane. This method is especially useful for understanding the global mode of refraction at the curved interface (tumor-surrounding tissue interface or surrounding tissue-irregular hepatic surface interface) (Figure 10)^[52-54]. In short, it ensures that unfavorable factors, such as technical errors, differences in US machines used and different levels of 2D-SWE experience, or influence biased by additional clinical data, do not interfere in this analysis. It also maintains a high quality of interpretation. The SWE diagnosis is usually the so-called “final report” of the clinician and explains that it is necessarily correct. Our simulation model can be considered the basic thought of what the clinicians conclude. It is recommended, therefore, that as more practitioners are trained in 2D-SWE, our basic thought is used in clinical practice.

CONCLUSION

Two-dimensional shear wave elastography artifacts, although seen very frequently in a clinical setting, are poorly recognized. Our review emphasizes that interpretation of 2D-SWE images must incorporate knowledge of US artifacts.

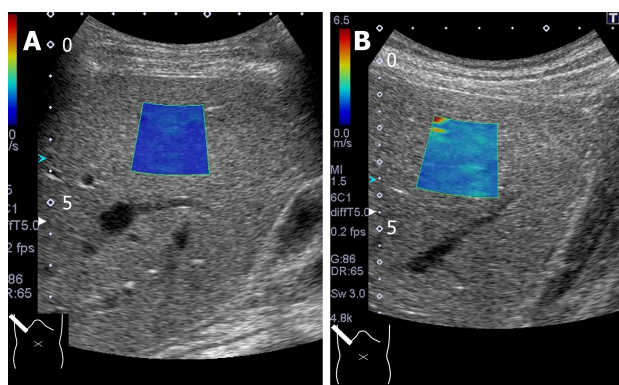


Figure 4 Probe compression artifact. Excessive probe compression gives rise to falsely increased shear wave values. A: Note that shear wave speed is 1.2 ± 0.06 m/s measured through an intercostal space; B: Changes to 2.0 ± 0.13 m/s through subcostal scanning under probe compression.

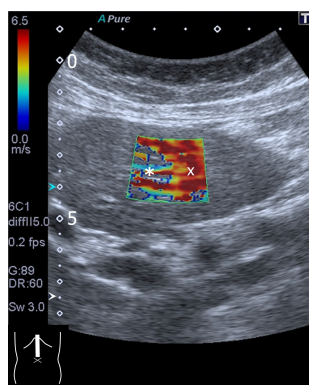


Figure 5 Motion artifact. Two-dimensional shear wave elastography of the liver left lobe shows this characteristic finding of a colorless area (asterisk), suggesting inaccurate measurement of shear wave values. The reddish part (x) of the cursor is also unreliable.

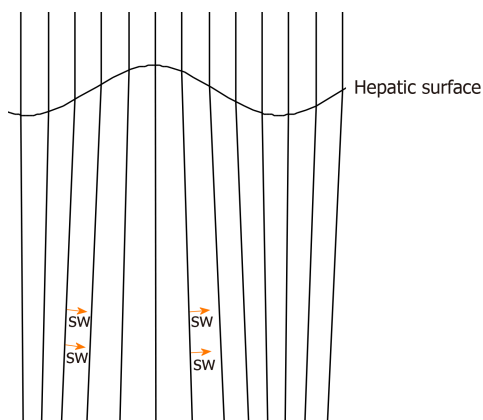


Figure 6 Computer simulation model of push-pulses in a cirrhotic patient. Push-pulses change direction at the irregular hepatic surface, according to Snell's law. Shear wave (arrow). SW: Shear wave.

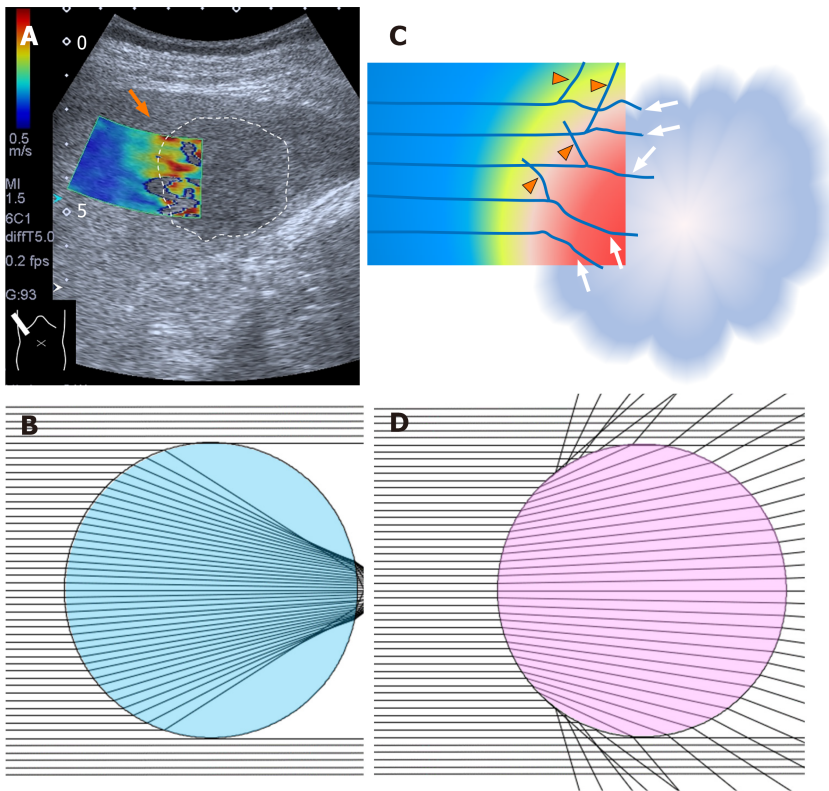


Figure 7 Two-dimensional shear wave elastography of liver tumor. A: Two-dimensional SW elastography of a liver tumor (encircled area) shows an irregular-shaped round area consisting of multiple layers of different colors (arrows); B: When the tumor has a lesser SW value than the surrounding tissue. Computer simulation model shows that all SWs deviate largely at the surrounding tissue (in this case, SW velocity 1.5 m/s) -liver tumor (in this case, SW velocity 1.0 m/s) interface; C: When the tumor has a greater SW value than the surrounding tissue. Computer simulation model shows that all SWs deviate largely at the surrounding tissue (in this case, SW velocity 1.5 m/s) -liver tumor (in this case, SW velocity 2.0 m/s) interface; D: Schematic drawing of mode of SWs around the surrounding tissue-liver tumor interface (arrows: deviated SWs; arrow heads: reflected SWs). SW: Shear wave.

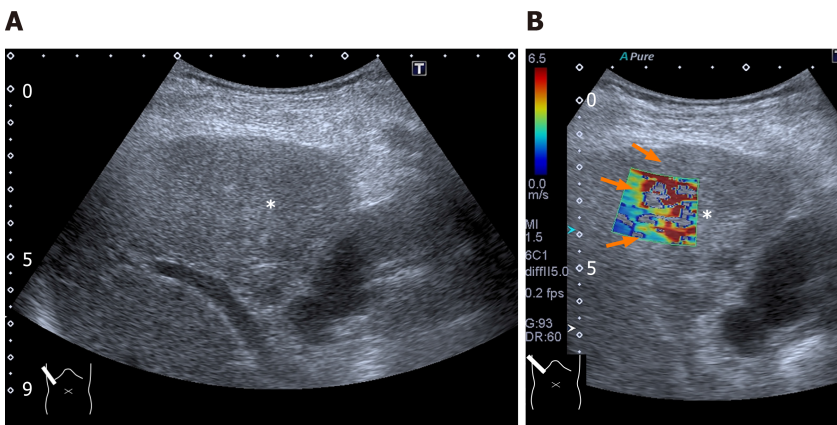


Figure 8 Representative case: intrahepatic cholangiocellular carcinoma. A and B: The lesion (asterisk) is poorly visible on B-mode (A) but it is well demarcated on two-dimensional shear wave elastography (B, arrow).

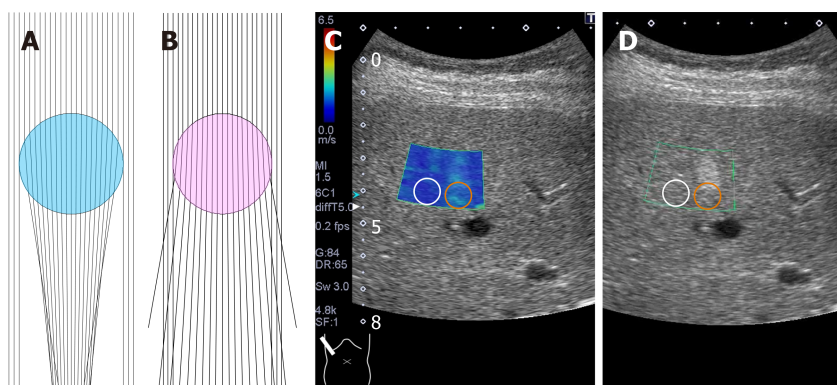


Figure 9 Computer simulation model of deviated push-pulses. A: Surrounding tissue acoustic speed is 1540 m/s and that of tumor (blue) is 1480 m/s; B: Surrounding tissue acoustic speed is 1540 m/s and that of tumor (pink) is 1600 m/s [A and B — the push-pulses change direction twice at two interfaces (upper and lower) of the surface of the lesion]; C: Two-dimensional shear wave elastography shows the posterior zone behind the lesion (red circle) to have a greater shear wave velocity (1.67 ± 0.19 m/s) than the surrounding hepatic tissue (1.07 ± 0.08 m/s) (white circle); D: Hepatic ultrasound reveals a 2 cm × 2 cm echogenic mass (hemangioma) in segment 5.

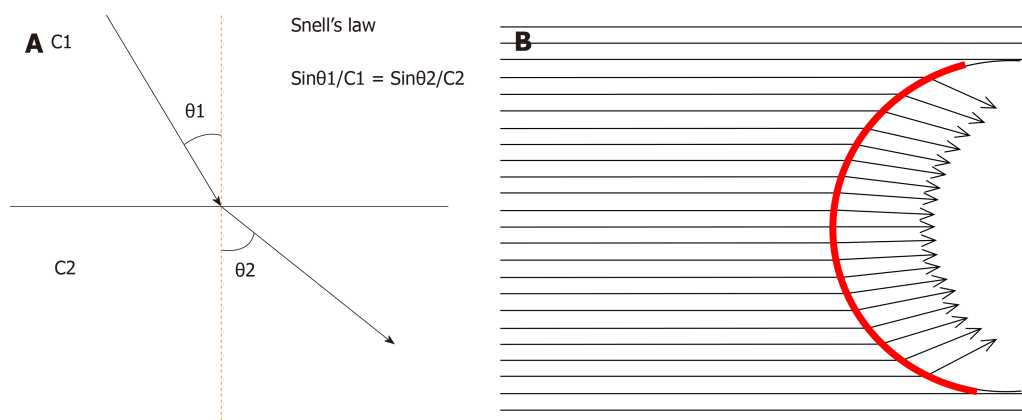


Figure 10 Sound refraction at the interface. A: Sound (or shear wave) refraction occurs at the straight interface between two structures of different acoustic (or shear wave) velocities, depending on Snell's law. The degree of refraction is always the same. θ_1 : Angle of incidence, θ_2 : Angle of refraction, C1: Sound (or shear wave) velocity in tissue 1, C2: Sound (or shear wave) velocity in tissue 2; B: Sound (or shear wave) refraction at the curved interface. As the tumor (or cirrhotic liver surface) has a curved interface, the angle of incidence changes according to the incidental point. Thus, the angle of refraction changes also according to the incidental point. Red line: Curved interface.

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