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FULL PAPER

2D shear-wave ultrasound elastography (SWE) evaluation of ablation zone following radiofrequency ablation of liver lesions: is it more accurate?

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Objective: To evaluate the usefulness of two-dimensional quantitative ultrasound shear-wave elastography (2D-SWE) [*i.e.* virtual touch imaging quantification (VTIQ)] in assessing the ablation zone after radiofrequency ablation (RFA) for *ex vivo* swine livers.

Methods: RFA was performed in 10 pieces of fresh *ex vivo* swine livers with a T20 electrode needle and 20-W output power. Conventional ultrasound, conventional strain elastography (SE) and VTIQ were performed to depict the ablation zone 0 min, 10 min, 30 min and 60 min after ablation. On VTIQ, the ablation zones were evaluated qualitatively by evaluating the shear-wave velocity (SWV) map and quantitatively by measuring the SWV. The ultrasound, SE and VTIQ results were compared against gross pathological and histopathological specimens.

Results: VTIQ SWV maps gave more details about the ablation zone, the central necrotic zone appeared as red, lateral necrotic zone as green and transitional zone as light green, from inner to exterior, while the peripheral unablated liver appeared as blue. Conventional ultrasound and SE, however, only marginally depicted the whole ablation zone. The volumes of the whole ablation zone (central necrotic zone + lateral necrotic zone + transitional zone) and necrotic zone (central necrotic

zone + lateral necrotic zone) measured by VTIQ showed excellent correlation ($r=0.915$, $p<0.001$, and 0.856 , $p=0.002$, respectively) with those by gross pathological specimen, whereas both conventional ultrasound and SE underestimated the volume of the whole ablation zone. The SWV values of the central necrotic zone, lateral necrotic zone, transitional zone and unablated liver parenchyma were $7.54\text{--}8.03\text{ ms}^{-1}$, $5.13\text{--}5.28\text{ ms}^{-1}$, $3.31\text{--}3.53\text{ ms}^{-1}$ and $2.11\text{--}2.21\text{ ms}^{-1}$, respectively ($p<0.001$ for all the comparisons). The SWV value for each ablation zone did not change significantly at different observation times within an hour after RFA (all $p>0.05$).

Conclusion: The quantitative 2D-SWE of VTIQ is useful for the depiction of the ablation zone after RFA and it facilitates discrimination of different areas in the ablation zone qualitatively and quantitatively. This elastography technique might be useful for the therapeutic response evaluation instantly after RFA.

Advances in knowledge: A new quantitative 2D-SWE (*i.e.* VTIQ) for evaluation treatment response after RFA is demonstrated. It facilitates discrimination of the different areas in the ablation zone qualitatively and quantitatively and may be useful for the therapeutic response evaluation instantly after RFA in the future.

INTRODUCTION

As a minimally invasive and cost-effective procedure, radiofrequency ablation (RFA) has been widely used for the treatment of liver tumours in recent years.^{1–3} Rapid determination of the local treatment response instantly after RFA is a critical issue, which is essential for the subsequent treatment plan or follow-up strategy. When there is suspicious residual viable tumour after RFA, additional RFA can be applied in the same treatment setting if rapid assessment is achievable, without the need for the patient's

re-admission, repeat RFA and repeat anaesthesia in another treatment setting, which will highly reduce the medical cost and patient anxiety. Contrast-enhanced imaging studies such as contrast-enhanced MRI (CEMRI), contrast-enhanced CT (CECT) and contrast-enhanced ultrasound (CEUS) have been widely used to evaluate the treatment response.^{4–8} The disappearance of arterial enhancement in the treated tumour region and an adequate safety margin on contrast-enhanced imaging studies indicate a successful treatment.^{5,6} However, in general, the patients have to wait

1 month or more until the peritumoral hyperaemia reaction around the ablation zone disappears when these contrast-enhanced imaging studies are applied, and the immediate contrast-enhanced imaging studies after RFA have been regarded as insufficient. In addition, patients who are underage, older than 80 years or allergic to contrast agents are not suitable for these imaging studies.

Ultrasound elastography is a new method to display the stiffness of the organ tissue. It has been used to differentiate malignant nodules from benign ones in various organs, based on the fact that malignant nodules are always stiffer than benign ones.^{9–11} Moreover, ultrasound elastography is a convenient and cost-effective examination method in comparison with CEMRI/CECT and CEUS, since no contrast administration is needed. The stiffness of the ablation zone in the liver increases obviously and is harder than that of the peripheral liver tissue after ablation.⁶ Some studies showed that conventional strain elastography (SE) could display the stiffness of the ablation zone qualitatively and depict the ablation zone well.^{12,13} Quantitative two-dimensional shear-wave elastography (2D-SWE) such as virtual touch imaging quantification (VTIQ) is a novel technique that can show tissue stiffness quantitatively and qualitatively, which has already been used in the diagnosis of breast lesions.^{14–16} Until now, VTIQ has not been used in the stiffness measurement of liver. We hypothesized that VTIQ is useful to display the different changes in the ablation zone and surrounding unablated tissue quantitatively and qualitatively after RFA, which might be an alternative tool for rapid evaluation of the local treatment outcome after RFA. To confirm the hypothesis, this study was carried out to observe the usefulness of VTIQ in volume and stiffness assessment of ablation zone after RFA in *ex vivo* swine livers.

METHODS AND MATERIALS

Liver procurement and storage

All experiments were performed with approval from the Institutional Animal Care and Use Committee. 10 fresh, normal porcine livers weighing about 200 g per piece of livers were purchased from a local slaughterhouse. Each sample was preserved in a plastic utensil that was filled with a normal saline solution before the experiment.

Ultrasound system

Ultrasound examination was performed using a Siemens S3000™ ultrasound system (Siemens Medical solutions, Mountain View, CA). A linear-array transducer with a frequency range of 4–9 MHz was used for this study. The 2D-SWE function of VTIQ (Siemens Medical solutions) is incorporated in the system, which is a novel technique that can display the transverse shear-wave velocity (SWV) of the target tissue under push pulse from the transducer. The stiffness difference of the region of interest (ROI) can be shown with a coloured map. The SWV will be measured quantitatively with a range of 0.5–10 m s⁻¹. Compared with conventional SE under manual compression and decompression, VTIQ improves the reproducibility of the examination and is independent of the operator. For VTIQ, the transducer can generate a longitudinal push pulse, which causes minimal localized displacement and subsequent transverse

shear-wave (SW) propagation. It synthesizes the stiffness information from up to 256 sequential acquisition beam lines inside a two-dimensional user-defined ROI and then displays the information with a qualitative and quantitative map. The SW ROI (a square box) could be as small as 1 × 1 mm, in comparison with the 6 × 5-mm SW ROI in the virtual touch tissue quantification in the previous version (Siemens S2000™ Ultrasound system) of point SWE (Siemens Medical Solutions).

Radiofrequency ablation system

A bipolar RFA system (Celon AG Medical Instruments, Teltow, Germany) was used for all ablation procedures. A T20 (the conducting part of the applicator is 20 mm, including both the insulator and tip) electrode needle and 20-W output power were selected for the study. The output energy used was 9 KJ. The ablation procedure will stop automatically after the impedance increases significantly, which is designed to prevent the flow of the current, and the energy rises to 9 KJ. This system does not need grounding pads used in conventional RFA systems.

Ultrasound examination

To minimize interobserver variations, all the ultrasound and ultrasound elastography examinations were performed by one investigator (BX) with 2 years' experience in liver RFA and ultrasound elastography. A uniform liver tissue without great vessels was selected for RFA. The RFA electrode that was put along the longitudinal axis of the ultrasound transducer was inserted into the liver under ultrasound guidance. A single ablation was applied for each evaluation. Immediately after ablation, the electrode needle was withdrawn and then ultrasound elastography evaluation was started without the placement of the ablation electrode needle in the liver. Ultrasound elastography of the ablation zone was evaluated 0 min, 10 min, 30 min and 60 min after the ablation, respectively. The conventional ultrasound, SE and quantitative SWE images were recorded at every observation time point. Firstly, conventional ultrasound was used to display the maximum longitudinal section of the ablation zone, and usually the needle tract can be visualized. Afterwards, SE was applied at the same position with the quality value greater than 60. A slight external compression and subsequent decompression was needed. High, intermediate and low stiffness were coded in blue, green and red and respectively, on SE. VTIQ evaluation was then performed. The imaging mode was shifted to the SWV mode, in which the SW speed distribution in the lesion is shown in different colours from high SWV (red) to intermediate SWV (yellow or green) and to low SWV (blue). The scale of SWV was in the range of 0.5–10 m s⁻¹. The sizes of the ablation zone were measured according to the colour difference on the VTIQ SWV map, which were measured at each time point under each condition. The volume of the ablation zone (V) would be calculated with the following formula: $V = 4/3\pi \times (LAD/2) \times (SAD/2) \times (SAD/2)$ (LAD, long-axis diameter; SAD, short-axis diameter). In addition, the SWV values of different stiffness areas (coded in different colours on VTIQ SWV map) in the ablation zone were measured. The SW ROI can be as small as 1 × 1 mm², which was placed on different areas as mentioned above to obtain the SWV value. [Figure 1](#) shows the measurement method.

Figure 1. Virtual touch imaging quantification shear-wave velocity (SWV) measurements after radiofrequency ablation. (a) SWV measurement of the central necrotic zone. (b) SWV measurement of the lateral necrotic zone. (c) SWV measurement of the transitional zone. (d) SWV measurement of the normal unablated tissue.

Pathology

1 h after RFA, the selected swine liver was sliced through the maximum section of the ablated zone. Gross images of the tissue were acquired by using a digital camera, and the volume of the ablation zone was calculated using the same formula as above. All gross tissue samples were sent for histopathological examination with haematoxylin-eosin (H-E) staining.

Statistical analysis

The quantitative data were expressed as mean $\pm$ standard deviation. The volumes of the ablation zones visualized on conventional ultrasound, SE and VTIQ, with reference to the gross pathological findings, and the SWV values of any two adjacent ablation parts of the ablation zones were compared using independent-samples *t* tests. The Pearson's correlation coefficients between the volumes of the ablation zones visualized on conventional ultrasound, SE and VTIQ and gross pathological findings were calculated with Pearson's test. The volumes of the ablation zone at 0 min, 10 min, 30 min and 60 min after RFA and the SWV values of the various parts in the ablation zones at different time points were compared using analysis of variance or non-parametric tests. SPSS v. 20.0 (IBM Corp., New York,

NY; formerly SPSS Inc., Chicago, IL) was used for the analysis. A *p*-value <0.05 was considered statistically significant.

RESULTS

Pathology

On gross pathological specimens, the central necrotic zone (black zone), lateral necrotic zone (white zone) and transitional zone (red zone) were clearly differentiated in the ablation zone, which showed difference in colour (Figure 2c). Figure 3 shows the H-E staining of the ablated zone and the unaffected normal liver tissue. The complete and partial cellular destruction in the ablated zone (Figure 3a) and normal cells in the unablated tissue (Figure 3b) were seen clearly. These cellular destruction zones were visualized only in the vicinity of the electrode needle. The ablated areas were similar and comparable in terms of size and locations, the volumes of which were in the range of 2.94–4.41 cm³ (mean, 3.56 $\pm$ 0.43 cm³) (Table 1).

Ultrasound, SE and VTIQ findings

With conventional ultrasound, the whole ablation zone appeared as mixed echogenicity and central necrotic zone as hyper-echogenicity at the observation time point at 10 min, 30 min and

Figure 2. Conventional ultrasound, strain elastography (SE), gross pathological specimen and virtual touch imaging quantification (VTIQ) maps after radiofrequency ablation (RFA). Arrowheads indicate the whole ablation zone. (a) Conventional ultrasound map showing the central necrotic zone (white arrows). (b) SE map showing the whole ablation zone (arrowheads). (c) Gross pathological specimen of the hepatic tissue after RFA. The central necrotic zone (Cz), lateral necrotic zone (Lz), transitional zone (Tz) and normal unablated zone (Nz). (d) VTIQ shear-wave velocity map showing the central necrotic zone (red zone), lateral necrotic zone (green zone), transitional zone (light green zone) and unablated tissue (blue zone). For colour image see online.

60 min after RFA (Figure 2a). The borderline between the ablation zone and the surrounding unablated tissue was hardly visible, since insignificant difference in the echogenicity was

found on conventional ultrasound. In addition, the ablation zone was invisible on conventional ultrasound immediately after the ablation procedure because of the hyperechoic gas produced

Figure 3. Haematoxylin-eosin staining images of the hepatic tissue after radiofrequency ablation (original magnification, $\times 100$). (a) The necrotic zone around the electrode needle containing complete cellular destruction (black arrow) and partial cellular destruction (white arrow). (b) The surrounding normal liver containing normal liver cells.

Table 1. Mean volumes of ablation zones after radiofrequency ablation (RFA) was calculated by various methods

Different ablation zones	Different time points	Volumes on conventional ultrasound (cm ³)	Volumes on SE (cm ³)	Volumes on VTIQ (cm ³)	Volumes on gross specimens (cm ³)
Zone A	0 min	2.28 ± 0.42 ^a (1.66–2.86)	2.54 ± 1.0 ^a (1.59–3.95)	3.22 ± 0.52 (2.78–4.53)	3.56 ± 0.43 (2.94–4.41)
	10 min	2.71 ± 1.04 ^a (1.49–5.05)	2.81 ± 1.08 ^a (0.55–4.48)	3.32 ± 0.62 (2.60–4.79)	
	30 min	2.44 ± 0.61 ^a (1.75–3.76)	2.58 ± 0.53 ^a (1.80–3.53)	3.45 ± 0.99 (2.45–4.94)	
	60 min	2.27 ± 0.64 ^a (1.34–3.48)	2.99 ± 0.70 ^a (2.28–4.66)	3.38 ± 0.71 (2.81–4.92)	
Zone B	0 min	NA	NA	1.68 ± 0.43 (1.07–2.52)	1.69 ± 0.26 (1.05–1.91)
	10 min	NA	NA	1.46 ± 0.28 (0.89–1.82)	
	30 min	NA	NA	1.45 ± 0.33 (1.00–1.96)	
	60 min	NA	NA	1.62 ± 0.38 (1.03–2.21)	
Zone C	0 min	NA	NA	0.54 ± 0.16 ^a (0.35–0.82)	0.16 ± 0.03 (0.11–0.20)
	10 min	0.19 ± 0.06 (0.12–0.31)	NA	0.43 ± 0.18 ^a (0.23–0.68)	
	30 min	0.17 ± 0.03 (0.12–0.23)	NA	0.45 ± 0.18 ^a (0.24–0.75)	
	60 min	0.18 ± 0.05 (0.14–0.25)	NA	0.42 ± 0.16 ^a (0.23–0.72)	

NA, not applicable; SE, strain elastography; VTIQ, virtual touch imaging quantification.

^aSignificant differences in comparison with volumes on gross pathological specimens (all $p < 0.001$); otherwise, no significant differences are found. Zone A, central necrotic zone + lateral necrotic zone + transitional zone (*i.e.* whole ablation zone); Zone B, central necrotic zone + lateral necrotic zone (*i.e.* total necrotic zone); and Zone C, central necrotic zone.

during the RFA procedure. On the SE image, the whole ablation zone was displayed in blue, whereas the unablated tissue was displayed in green or red at every observation time point, and the clear borderline between them was visualized (Figure 2b). On VTIQ SWV image, three areas with different colours in the ablation zone were clearly visualized, which were red, green and light green from inside to outside. These three different areas on VTIQ, the central necrotic zone was displayed in red, lateral necrotic zone in green and transitional zone in light green, might correspond to the central necrotic zone, lateral necrotic zone and transitional zone on gross pathological specimens (Figure 2d). In addition, the unablated tissue around the ablation zone was displayed in blue. Therefore, VTIQ was able to depict the different areas within the ablation zone, as well as the borderline between the ablation zone and the unablated tissue, similar to the gross pathological specimen; however, SE was able to depict only the borderline between the ablation zone and the unablated tissue and conventional ultrasound failed to depict even the extent of the ablation zone.

Volume measurement

After all examinations, the volumes of the ablation zones were calculated and compared (Table 1). Three different ablation zones were defined: Zone A, central necrotic zone + lateral necrotic zone + transitional zone (*i.e.* whole ablation zone); Zone B, central necrotic zone + lateral necrotic zone (*i.e.* total necrotic zone); and Zone C, central necrotic zone. The volume of Zone A (whole ablation zone) measured by conventional ultrasound, SE and VTIQ did not vary significantly as the observation time changed ($p > 0.05$). However, at each observation time point after RFA, both conventional ultrasound and SE underestimated the volume of Zone A (whole ablation zone) ($p < 0.001$),

whereas VTIQ calculated the volume accurately ($r = 0.915$; $p < 0.001$), in comparison with that measured on gross pathology. The volume of Zone B (total necrotic zone) was also calculated accurately by VTIQ, with the volume measured on gross pathology as the reference ($r = 0.856$; $p = 0.002$). The volume of Zone C (central necrotic zone) was calculated relatively precisely with conventional ultrasound ($r = 0.77$; $p = 0.009$), while it was overestimated by VTIQ ($p < 0.001$).

Shear-wave velocities of different areas in the ablation zone

The comparisons of the mean SWV values of different areas in the ablation zone after RFA are shown in Table 2. At 0 min, 10 min, 30 min and 60 min after RFA, the mean SWV values of the central necrotic zone, lateral necrotic zone, transitional zone and unablated liver parenchyma were 7.54–8.03 m s⁻¹, 5.13–5.28 m s⁻¹, 3.31–3.53 m s⁻¹ and 2.11–2.21 m s⁻¹, respectively ($p < 0.001$ for all the comparisons), with a descending trend from inner to exterior. In addition, the mean SWV values of each part in the ablation zone did not change significantly at different observation time points ($p > 0.05$ for all comparisons) at 0 min, 10 min, 30 min and 60 min after RFA, which indicates that the stiffness change happened instantly after RFA and will not change thereafter.

DISCUSSION

Although RFA has been accepted as one of the curative therapy methods for liver cancer, substantial incomplete ablation or residual tumour is often encountered in the clinic. Improving the ability to evaluate the local treatment during or immediately after RFA is important, which is indispensable for determining whether to perform additional RFA in the same treatment

Table 2. Mean shear-wave velocity (SWV) value (m s^{-1}) of different ablation zones and unablated liver parenchyma after radiofrequency ablation (RFA)

Different ablation zones	SWV value at 0 min after RFA (m s^{-1})	SWV value at 10 min after RFA (m s^{-1})	SWV value at 30 min after RFA (m s^{-1})	SWV value at 60 min after RFA (m s^{-1})
Central necrotic zone	$8.03 \pm 1.46^{a,b,c}$ (4.50–10.00)	$7.63 \pm 1.60^{a,b,c}$ (4.00–9.90)	$7.81 \pm 1.22^{a,b,c}$ (4.06–9.96)	$7.54 \pm 1.36^{a,b,c}$ (3.71–9.99)
Lateral necrotic zone	$5.28 \pm 0.98^{a,b}$ (3.52–7.57)	$5.16 \pm 1.04^{a,b}$ (2.72–7.53)	$5.14 \pm 0.86^{a,b}$ (3.26–7.32)	$5.13 \pm 0.95^{a,b}$ (3.44–7.70)
Transitional zone	3.53 ± 0.58^a (2.48–5.48)	3.45 ± 0.59^a (2.35–4.78)	3.38 ± 0.57^a (2.15–6.08)	3.31 ± 0.57^a (2.20–5.09)
Unablated liver parenchyma	2.21 ± 0.44 (1.37–3.05)	2.11 ± 0.32 (1.38–2.73)	2.11 ± 0.36 (1.50–3.20)	2.21 ± 0.39 (1.51–3.20)

Data are expressed as mean $\pm$ standard deviation (range).

p -value, SWV value comparisons among 0 min, 10 min, 30 min and 60 min after RFA.

^aSignificant differences in comparison with unablated liver parenchyma (all $p < 0.001$).

^bSignificant differences in comparison with the transitional zone (all $p < 0.001$).

^cSignificant differences in comparison with the lateral necrotic zone (all $p < 0.001$).

setting. Recent studies have shown that ultrasound elastography might be an ideal supplement method for monitoring the RFA treatment and is superior to conventional ultrasound.^{12,13} As additional advantages, the administration of a contrast agent is not required for ultrasound elastography and real-time observation is possible. In comparison with conventional strain ultrasound elastography, the recently developed quantitative 2D-SWE method is highly reproducible and less operator dependent. In addition, 2D-SWE provides a quantitative method for treatment response evaluation, which is highly relevant in the clinic, since it is more objective.

In the present study, we firstly investigated the feasibility of 2D-SWE of VTIQ in assessing the volume and stiffness of the ablation zone affected by bipolar RFA compared with conventional ultrasound and SE. From the results, we found that VTIQ was able to differentiate the central necrotic zone, lateral necrotic zone and transitional zone from the unablated liver tissue qualitatively and quantitatively, based on the different colours in the VTIQ SWV map and SWV values. This may be helpful for the treatment response evaluation of RFA. On VTIQ SWV maps, the volumes of Zone B (*i.e.* central necrotic zone + lateral necrotic zone) and Zone A (*i.e.* central necrotic zone + lateral necrotic zone + transitional zone) were calculated accurately with reference to the gross pathological specimens ($r = 0.915$ and 0.856 , respectively). The results indicate that VTIQ is able to delineate the shape and volume of the ablation zone accurately. In addition, a clear demarcation of the transitional zone by VTIQ makes it a reliable method for the determination of the necrosis margin of the ablation zone after RFA. Our results were in accordance with a previous study,¹⁷ in which the ablation volumes depicted by three-dimensional SWE and those by gross pathological examination showed a high correlation ($r^2 = 0.953$). In the present study, the volume of Zone C (*i.e.* central necrotic zone) calculated by VTIQ was larger than that of gross pathological specimens. However, this has no influence on the necrosis margin assessment of the ablation zone, since it is located deep inside the ablation zone. The stiffness of the ablation zone may increase with temperature, and central carbonization may affect the stiffness evaluation.

From the SWV map of VTIQ, we found that the transitional zone always appeared in light green colour, while the necrotic zone appeared in green or red colour. In addition, the SWV value of the central necrotic zone or the lateral necrotic zone was significantly higher than the transitional zone. Therefore, the surrounding hyperaemia reaction (the transitional zone) can be depicted from the VTIQ SWV colour map and by the measurement of the SWV value. In addition, the mean SWV values of each part in the ablation zone did not change at different observation time points at 0 min, 10 min, 30 min and 60 min after RFA; thus, the stiffness change happened instantly after RFA and did not change thereafter. Therefore, in comparison with CEUS or CECT/CEMRI, there is no need to wait for 1 month to observe the treatment response of the ablation with VTIQ. The success rate of RFA would be higher, if the necrotic degree of the ablation zone after RFA can be displayed and assessed shortly after RFA, since the residual lesions can be treated quickly at the same session.

Similar to previous studies,^{12,13,18,19} conventional ultrasound and SE can only depict the size of the whole ablation zone including the transitional zone, whereas they cannot depict the different areas in the ablation zone. Varghese et al¹² found that the dimensions, areas and volumes of the thermal lesions resulting from RFA measured by elastographic images and digitized pathologic images had excellent correlation ($r = 0.937$ for area comparison and $r = 0.979$ for volume comparison). Van Vledder et al¹³ reported that the diameter of the ablated lesions on ultrasound elasticity imaging and the gross specimens had good correlation in *in vivo* animal studies ($r = 0.81$). From the results of our study, conventional ultrasound and SE underestimated the volume of the whole ablation zone, whereas VTIQ calculated the volume more precisely. Therefore, VTIQ is superior to conventional ultrasound and SE in revealing the ablation zone affected by RFA qualitatively.

Until now, no reliable quantitative method has been developed to evaluate the treatment response after RFA, although quantitative CEUS has been tentatively used to evaluate the treatment response after chemotherapy or systematic therapy. Quantitative

2D-SWE, however, is a potential method to achieve this goal. Sugimoto et al¹⁷ found that in the images showing the largest ablation area after RFA, the Young's modulus of the central zone, peripheral rim and non-ablated zone were 59.1 KPa, 13.1 KPa and 4.3 KPa, respectively. Therefore, it is anticipated that quantitative SWE would facilitate the development of a cut-off Young's modulus to determine the necrotic extent of the ablated lesion. For example, a Young's modulus greater than the cut-off value might indicate complete necrosis, otherwise incomplete necrosis. In addition, the peripheral hyperaemia around the ablated lesion and the unablated area can also be discriminated with quantitative 2D-SWE; besides that, the ablation margin could also be defined. In the present study, the tissue stiffness is denoted by SWV instead of Young's modulus. It was found that the SWV values of the different ablation zones were significantly different, with a descending trend from the central necrotic zone to lateral necrotic zones transitional zone and unablated liver tissue, which is consistent with the previous study. Therefore, it is potentially possible to reflect the different pathological changes after RFA using the quantitative parameter of SWV, which is relevant in future clinical works. Morimoto et al²⁰ found that in the transitional zone, no viable tumour existed by histochemical staining analysis. In the present study, the SWV values for the transitional zone were in the range of 3.1–3.5 m s^{-1} 0–60 min after RFA and higher than 2.1–2.2 m s^{-1} for the surrounding unablated liver tissue. A SWV value of 3.1–3.5 m s^{-1} might be the appropriate threshold value for the determination of irreversible tumour destruction, and the residual viable tumour might be softer than the threshold (*i.e.* SWV of 3.1–3.5 m s^{-1}), which may provide useful information to guide a second round of RFA to treat the residual tumour.

Some limitations existed in this study. First, the *ex vivo* swine livers and lack of tumour models might not reflect the real clinical practice. The transitional zone in our study might be not

consistent with the hyperaemia zone *in vivo*. Secondly, lack of blood flow at the periphery of the ablated zone in the *ex vivo* livers might affect the measurement of stiffness, which would finally affect the evaluation of the volume of the ablation zone. Furthermore, the previous study²⁰ reported that H–E staining was inferior to histochemical staining for the diagnosis of coagulation necrosis in the ablation zone; thus, the H–E staining of the ablation zone in our study might not correspond to the gross pathological specimen exactly. In addition, only one investigator evaluated the results to avoid interobserver variation. However, intervariations and intravariables should be evaluated in the future. To minimize the intervariations and intravariables, a standardized and unified operation process, sufficient training and enough experience about ultrasound elastography and RFA is essential. Finally, only one type of RFA system and electrode needle was applied in this study, and the initial results of this study should be validated in future experimental and clinical studies.

CONCLUSION

In conclusion, the novel quantitative 2D-SWE of VTIQ is able to display the complicated pathological changes in the ablation zone clearly after RFA. The central necrotic zone, lateral necrotic zone and transitional zone show different stiffness qualitatively and quantitatively, and the stiffness of all of them is higher than that of the surrounding unablated liver tissue. This elastography technique might be useful for the therapeutic response evaluation instantly after RFA in the future.

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