### VASCULAR-INTERVENTIONAL



# Feasibility of shear wave sonoelastography to detect endoleak and evaluate thrombus organization after endovascular repair of abdominal aortic aneurysm

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### Abstract

**Purpose** To investigate the feasibility of shear wave sonoelastography (SWS) for endoleak detection and thrombus characterization of abdominal aortic aneurysm (AAA) after endovascular repair (EVAR).

**Materials and methods** Participants who underwent EVAR were prospectively recruited between November 2014 and March 2016 and followed until March 2019. Elasticity maps of AAA were computed using SWS and compared to computed tomography angiography (CTA) and color Doppler ultrasound (CDUS). Two readers, blinded to the CTA and CDUS results, reviewed elasticity maps and B-mode images to detect endoleaks. Three or more CTAs per participant were analyzed: pre-EVAR, baseline post-EVAR, and follow-ups. The primary endpoint was endoleak detection. Secondary endpoints included correlation between total thrombus elasticity, proportion of fresh thrombus, and aneurysm growth between baseline and reference CTAs. A 3-year follow-up was made to detect missed endoleaks, EVAR complication, and mortality. Data analyses included Cohen's kappa; sensitivity, specificity, and positive predictive value (PPV); Pearson coefficient; and Student's *t* tests.

**Results** Seven endoleaks in 28 participants were detected by the two SWS readers (k = 0.858). Sensitivity of endoleak detection with SWS was 100%; specificity and PPV averaged 67% and 50%, respectively. CDUS sensitivity was estimated at 43%. Aneurysm growth was significantly greater in the endoleak group compared to sealed AAAs. No correlation between growth and thrombus elasticity or proportion of fresh thrombus in AAAs was found. No new endoleaks were observed in participants with SWS negative studies.

**Conclusion** SWS has the potential to detect endoleaks in AAA after EVAR with comparable sensitivity to CTA and superior sensitivity to CDUS.

#### **Key Points**

- Dynamic elastography with shear wave sonoelastography (SWS) detected 100% of endoleaks in abdominal aortic aneurysm (AAA) follow-up that were identified by a combination of CT angiography (CTA) and color Doppler ultrasound (CDUS).
- Based on elasticity maps, SWS differentiated endoleaks from thrombi within the aneurysm sac (p < 0.001).
- After 3-year follow-up, no new endoleaks were observed in SWS negative examinations.

Keywords Abdominal aortic aneurysm · Endoleak · Color Doppler ultrasound · Elastography · CT angiography

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AAA	Abdominal aortic aneurysm
CDUS	Color Doppler ultrasound
CEUS	Contrast-enhanced ultrasound
CT	Computed tomography
CTA	Computed tomography angiography
EVAR	Endovascular aortic aneurysm repair
kPa	Kilopascal
MRI	Magnetic resonance imaging
PPV	Positive predictive value
ROI	Region of interest
SWS	Shear wave sonoelastography

## Introduction

Due to a lower perioperative complication rate, endovascular aneurysm repair (EVAR) of an abdominal aortic aneurysm (AAA) represents the most common method of AAA repair in North America [1–3]. Although EVAR has a lower perioperative complication rate and a long-term survival comparable to open surgical repair, it has a higher rate of reintervention mainly due to endoleaks [4]. An endoleak represents an increased risk of rupture if not properly detected [5]. Endotension [6] that represents aneurysm growth without evidence of an endoleak on imaging [7, 8] can also lead to AAA rupture. Therefore, lifelong imaging surveillance is required after EVAR [4, 9]. Current guidelines recommend surveillance with CTA during the first year and then with color Doppler ultrasound (CDUS) if there is no documented endoleak or sac growth [10]. However, most teams are still using CTA as a primary modality for long-term surveillance [11]. This follow-up increases costs of EVAR and exposes patients to ionizing radiation and contrast-induced nephrotoxicity [4, 12].

CDUS has a lower sensitivity and reproducibility than CTA to detect endoleaks [13]. Conversely, contrast-enhanced ultrasound (CEUS) has shown comparable sensitivity to CTA [13, 14]. This dynamic examination is more time consuming and requires patient preparation. As CEUS hardly competes with CTA in terms of reproducibility, efficiency, and productivity, its use in North America is still low [15].

After endovascular exclusion of an AAA with a stent graft, its diameter tends to decrease unless there is a persistent flow or pressure in the aneurysm sac [16, 17]. The presence of fresh unorganized thrombus has been described in patients with endoleaks on MRI [16]. Little attention has been given to the temporal evolution of the thrombus organization and aneurysm regression after EVAR.

Shear wave sonoelastography (SWS) measures tissue elasticity [18, 19]. This approach has never been tested for EVAR surveillance in patients. Compression elastography has been attempted to detect and classify endoleaks but did not provide additional advantages compared to CEUS [20]. The potential of SWS to detect endoleaks and characterize thrombus was previously reported in a canine model after EVAR, where fresh thrombi reported lower elasticity values than organized thrombi [21].

The primary purpose of this study was to compare the endoleak detection rate of SWS to that of CTA and CDUS. The secondary purpose was to characterize thrombus organization in the aneurysm sac by correlating AAA growth and thrombus elasticity after EVAR.

## Materials and methods

#### **Design and subjects**

This single-center prospective study at the Centre Hospitalier de l'Université de Montréal (CHUM) was approved by the institutional review board, and written informed consent was obtained from all participants. Participants were included if (Fig. 1) (1) they underwent EVAR and had CTA follow-up imaging between November 2014 and March 2016 and (2) this follow-up was performed more than 1 year after EVAR and (3) within 8 months of the combined CDUS-SWS evaluation. The patients were then followed for 3 years to detect the occurrence of an endoleak or endotension. Participants were excluded if (1) no pre-EVAR CT was available or (2) reference standard CT was performed without contrast injection.

#### B-mode, CDUS, and SWS examinations

All CDUS and SWS examinations (SuperSonic Imagine, Aixplorer) were performed by a vascular technologist with 20 years of experience, with a 192-element curved array probe (Single Crystal SC6-1) at 6 MHz. Data acquisitions were performed in the following order: B-mode, CDUS, and SWS. The length of the aneurysm was measured in a longitudinal plane; diameters and areas were measured in three equidistant axial planes between the renal arteries and aortic bifurcation. Endoleak areas were detected on CDUS and delineated. The speed range scale was initially set at 10 cm/s, with a smoothing of 0 and low wall filter. SWS parameters were set as opacity of 50%, smoothing of 5, and acoustic power as low as reasonably achievable. SWS uses the same thermal and mechanical energy indices displayed in CDUS mode. Cine loops and static images were registered for each acquisition plane. Brachial blood pressure was measured by sphygmomanometry before and after US procedures.

#### SWS qualitative image analysis

On the acquired elasticity maps (elastograms), an endoleak area was defined as the absence of an elasticity value

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**Fig. 1** A study flow chart showing the recruitment process. The sample size is 28. Seven endoleaks were detected by the defined reference standard. Note: CTA = computed tomography angiography, SWS = shear wave sonoelastography, EVAR = endovascular aneurysm repair, CDUS = color Doppler ultrasound



(<3 KPa) within the aneurysm sac outside the stent graft. As previously reported [21], areas without a signal on the posterior wall of the aneurysm were deemed as non-diagnostic as shear wave transmission could be attenuated due to stent graft interposition or limited penetration. A thrombus was defined as everything else but endoleak or stent graft areas within the aneurysm sac. Elasticity was first measured on the entire thrombus (total thrombus). Then, based on a previous preclinical study, values ranging between 3 and 19 kPa on SWS elastograms were labeled as fresh thrombus, whereas organized thrombus had values above 19 kPa [21].

SWS elastograms were independently reviewed by 2 readers: an abdominal radiologist (A.T., 10 years of experience) and a graduate student in medical physics under the supervision of a vascular radiologist (G.S., 25 years of experience). They identified and delineated endoleak regions using three (proximal, mid, and distal) static axial SWS elastograms and corresponding B-mode images. They were blinded to the color map of the CDUS and CTA examinations.

#### SWS quantitative image analysis

Elastograms were manually segmented using ImageJ software to calculate elasticity of aneurysmal sac contents [22, 23] (Rasband, W.S., V.1.47b, Research Services Branch National Institute of Mental Health). Segmentation and region of interest (ROI) positioning were done by matching B-mode and SWS images. The aneurysms were divided into three ROIs, namely endoleak areas, fresh thrombus, and total thrombus (fresh + organized thrombus).

#### **CT** examinations

At least three CTs per participant were analyzed in this study. The exams were performed on various CT scanners (Siemens Healthineers, Sensation 4, 16, and 64; Philips Healthcare, iCT 256 and Brillance 64; GE Healthcare, ProSpeed and LightSpeed Ultra) according to the clinical standard of care.

All 30 CTs performed before EVAR were contrast-enhanced. The first post-EVAR CT (baseline) included 29/30 injected studies (1/30 without contrast) and were made on average  $6.7 \pm 9.5$  months (0.1 to 45.1 months) post treatment.

Reference standard CTAs were performed on average within 4.1  $\pm$  2.2 months (0.2 to 7.7 months) of the combined CDUS-SWS studies. Of these, 28/30 were injected and 2/30 were excluded because they had no contrast injection due to renal insufficiency. Reference CTAs were performed on average 39.5  $\pm$  31.2 months after EVAR (8.5 to 157 months)

Clinical data and imaging were reviewed after 3 years to account for undiagnosed leaks, aneurysm growth, EVAR complication, and mortality. A last follow-up examination was available in 18 participants including one non-contrast-enhanced and 17 contrast-enhanced CTs with a mean time period of  $5.0 \pm 3.5$  years post baseline CT (1.4 to 15.1 years).

Contrast-enhanced examinations were performed with intravenous contrast injection of 100–120 mL of iohexol (Omnipaque 350 mgI/mL or Visipaque, GE Healthcare) at 4–5 mL/s. Scan parameters were a collimation of 0.5 to 1.0 mm and a pitch of 0.75 to 1.00. Parameters were set at 120–140 kVp and 280–724 mAs, depending on the participant's weight. Aneurysms were segmented to compute maximal diameters and volumes using dedicated software [24].

#### **Endpoint definition**

The primary endpoint was the detection of endoleak type I, II, or III or endotension with SWS by 2 readers blinded to CDUS and CTAs.

The reference standard was defined either by the presence of contrast in the aneurysm sac at reference CTA, the presence of flow in the aneurysm sac on the CDUS examination performed before the SWS examination, or the presence of endotension. In case of negative CT and positive CDUS, the participant was classified as positive since the specificity of CDUS is in the high range (0.97 to 1.00) [13]. Endotension was defined as growth by a minimum of 5 mm in diameter between baseline and reference CTA. Matching between SWS and CT examinations to define true and false positives was based on the cranio-caudal level of acquisition, stent graft position, and aneurysm surface and diameter at each proximal, mid, and distal region on B-mode imaging.

The secondary endpoint was the correlation of the elasticity measurement with AAA growth. Relevant data to compute secondary endpoints included total thrombus elasticity (kPa), percentage of fresh thrombus relative to total thrombus area (%), aneurysm growth in diameter (mm) and volume (mL) and growth rate in diameter and volume (%).

Total thrombus elasticity measurements were obtained from color elasticity maps after stent graft and endoleak area exclusion. The percentage of fresh thrombus was computed as follows: area of thrombus with an elasticity modulus between 3 and 19 kPa over total area of thrombus in each axial plane and averaged [21]. Growth was estimated as the variation of maximum diameter and volume between baseline and reference CTA. Growth was assessed at year three when imaging was available.

#### **Statistical analysis**

SPSS Statistics 24.0 was used to perform statistical analyses. Sensitivity, specificity, and positive predictive value (PPV) for endoleak detection with SWS were calculated for each reader and averaged. Agreement between the two readers for endoleak detection with SWS was assessed by Cohen's kappa. Analysis comparing total thrombus elasticity, proportion of fresh thrombus, and growth between groups with and without endoleak was made using Student's *t* tests assuming equal variance and setting statistical significance to p < 0.05. The mean percentage of fresh thrombus and total thrombus elasticity were correlated with diameter and volume growth with a Pearson coefficient.

## Results

Three patients lacking appropriate CT reference imaging were excluded from the 41 potential participants recruited between November 2014 and March 2016. Out of 38 eligible participants, 28 underwent the study whereas others refused to participate or could not be reached (Fig. 1).

A total of seven endoleaks were detected with the reference standard imaging (Table 1): one type Ib, five type II, and one endotension. One was detected by CDUS alone, three by CTA alone, and two both by CTA and CDUS (CDUS sensitivity of 43%). The endotension with a 7-mm increase in diameter was detected on CT.

Given the small sample size, apart from age and mean diastolic pressure, risk factors and comorbidities were not statistically different between groups. The clinical and imaging characteristics of participants are summarized in Table 2.

As expected, the mean variations in diameter and volume between baseline and reference studies were different in participants with and without an endoleak (p < 0.001). A greater growth was observed in the endoleak group having a mean diameter and volume expansion of respectively  $10.1 \pm 14.5\%$ 

Table 1 Endoleak detection with various modalities

Participant	CDUS	СТА	Endotension	Reference standard	Reader 1 SWS <sup>‡</sup>	Reader 2 SWS <sup>‡</sup>
1	_	_	_	_	_	_
2	_	_	_	_	1	1
3	1	_	_	Type II	1	1
4	_	_	_	_	-	_
5	_	_	_	_	_	_
6	_	_	_	_	1	1
7	_	1	_	Type II	1	1
8	_	_	_	_	_	_
9	1	1	_	Type II	1	1
10	_	_	_	_	_	_
11	_	_	_	_	1	1
12	1	1	_	Type Ib	1	1
13	_	_	_	_	_	_
14	_	_	_	_	_	_
15	_	_	_	_	_	_
16	_	_	_	_	1	1
17	_	_	_	_	1	1
18	_	_	_	_	_	_
19	_	_	1	Type V	1	1
20	_	_	_	_	_	_
21	_	_	_	_	_	_
22	_	_	_	_	1	1
23	_	_	_	_	_	_
24	_	1	_	Type II	1	1
25	_	1	_	Type II	1	1
26	_	_	_	_	1	_
27	_	_	_	_	1	_
28	_	_	_	_	_	_
Total	3	5	1	7	15	13

*CDUS* color Doppler ultrasound, *CTA* computed tomography angiography, *SWS* shear wave imaging

<sup>‡</sup> Inter-observer Cohen's kappa = 0.858

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Table 2Characteristics ofparticipants and AAAs at baselineand reference CTAs

	Endoleak	No endoleak	p value	
	(n = 7)	(n = 21)		
Participants' characteristics at last follow-up				
Men (%)	7 (100)	18 (86)	0.308	
Women (%)	0 (0)	3 (14)	0.308	
$Age \pm SD$	$83.3\pm4.3$	$76.0\pm7.5$	0.022	
Weight $\pm$ SD (kg)	$73.9\pm6.8$	$82.1\pm16.1$	0.213	
Diabetes (%)	0 (0)	6 (29)	0.119	
CVA (%)	3 (43)	2 (10)	0.048	
Dyslipidemia (%)	6 (86)	17 (81)	0.786	
Active smoking (%)	0 (0)	5 (24)	0.166	
Past smoking (%)	2 (29)	10 (48)	0.397	
Mean systolic mmHg $\pm$ SD	$141\pm11$	$135\pm19$	0.424	
Mean diastolic mmHg $\pm$ SD	$77 \pm 10$	$68\pm8$	0.027	
Abdominal aortic aneurysm characteristics at refe	erence CTA			
Mean diameter $\pm$ SD (mm)	$63.0\pm5.8$	$47.3 \pm 11.5$	0.002	
[min; max] Mean volume ± SD (mL)	$[54.2; 72.1] \\ 190 \pm 107$	[28.5; 76.0] 114 ± 56	0.020	
[min; max] Mean total thrombus elasticity $\pm$ SD (kPa)	[108; 416] 26.9 ± 13.7	[55; 287] 21.7 ± 10.8	0.318	
Mean fresh thrombus $\pm$ SD (%)	$20.5\pm 6.3$	$25.2\pm8.7$	0.203	
Aneurysm growth between baseline (post-EVAR)	) and reference standard	CTAs*		
Diameter growth $\pm$ SD (%)	$10.1\pm14.5$	$-16.3\pm11.9$	< 0.001	
Diameter growth $\pm$ SD (mm)	$5.6\pm7.8$	$-9.8\pm7.8$	< 0.001	
[min; max] Volume growth ± SD (%)	[-2.0; 21.0] $39.0 \pm 50.2$	$[-31.0; 0,2] \\ -25.9 \pm 15.7$	< 0.001	
Volume growth $\pm$ SD (mL)	$57.7 \pm 86.6$	$-48.4 \pm 47.1$	< 0.001	
[min; max]	[-0.7; 244.5]	[-196.2; 0.8]		

Mean fresh thrombus = proportion of 3 to 19 kPa thrombus over total thrombus

CVA cerebrovascular accident, SD standard deviation

\*A negative growth represents an aneurysm shrinkage

and  $39.0 \pm 50.2\%$ . Conversely, participants without an endoleak demonstrated shrinkage with  $-16.3 \pm 12.0\%$  average variation in diameter and  $-25.9 \pm 15.7\%$  in volume.

#### **Endoleak detection**

All seven participants with endoleaks detected by reference standard were also categorized as having endoleaks by the two blinded SWS elasticity map readers. This finding brings the sensitivity of SWS for endoleak detection to 100% in this study. As depicted in Table 3, 6 to 8 participants were incorrectly diagnosed with endoleaks, lowering the SWS specificity to 62% for reader 1 and 71% for reader 2, an average of 67%. The PPV of SWS was 47% for reader 1 and 54% for reader 2, an average of 50%. Inter-observer Cohen's kappa was in the high range for agreement on endoleak diagnosis (k = 0.858).

Areas deemed non-analyzable on SWS due to the absence of a signal on the posterior wall were estimated to be 5.1% of the cumulated areas of SWS acquisitions. Examples of endoleak detection discrepancies with different imaging

Table 3	SWS	imaging	detection	rate by	two	readers	compared	to	the
reference	standa	rd							

		Reference s	Total	
		Endoleak	No endoleak	
SWS Reader 1	Endoleak	7	8	15
	No endoleak	0	13	13
	Total	6	21	28
SWS Reader 2	Endoleak	7	6	13
	No endoleak	0	15	15
	Total	7	21	28

SWS shear wave imaging

<sup>&</sup>lt;sup>+</sup> Reference standard is defined as the presence of contrast in the aneurysm sac in the reference CTA and/or CDUS signal in the aneurysm sac and/or endotension

modalities are given in Fig. 2 (endoleak missed on CDUS), Fig. 3 (endoleak detected with all modalities), Fig. 4 (false positive on SWS), and Fig. 5 (no endoleak in sealed aneurysm confirmed with all modalities).

### Thrombus elasticity and endoleak

In all participants, the ROIs labeled as endoleak with SWS had an elasticity modulus close to zero with an average of  $0.053 \pm$ 0.087 kPa. Significantly higher values of elasticity were found in the total thrombus, averaging at  $23.0 \pm 11.6$  kPa (p < 0.001).

However, total thrombus elasticity within aneurysm sac (after endoleak exclusion) was not statistically different between the endoleak group ( $26.9 \pm 13.7$  kPa) and the sealed aneurysm group ( $21.7 \pm 10.8$  kPa) with a *p* value of 0.318.

Likewise, averages of  $20.5 \pm 6.3\%$  and  $25.2 \pm 8.7\%$  of the area containing fresh thrombus were found in groups with and without endoleaks, which was not significantly different (*p* = 0.203).

#### Elasticity modulus and aneurysm growth

No correlation was found between the thrombus elasticity and diameter (R = 0.278) or volume (R = 0.333) change over time.

A weak negative correlation was found between the proportion of fresh thrombus and growth in diameter and volume. The correlation was -0.453 between the amount of fresh thrombus and diameter growth and -0.386 between the amount of fresh thrombus and volume growth.

#### Long-term follow-up

By March 2019, 18/28 participants had an additional CT: 15 contrast-enhanced in arterial phase, one in portal phase, and two unenhanced. No additional endoleak or significant increase in aneurysm sac size was detected. The remainder 12 participants either ceased to be followed by imaging with participant's agreement (due to old age and comorbidities) or were lost to follow-up.



**Fig. 2** An endoleak was detected with SWS and CT but missed with CDUS in participant 7. Axial B-mode (**a**) shows the stent graft (arrow). Axial CTA located slightly below the US acquisition (**b**) confirms a type II endoleak (arrow) from the median sacral artery. CDUS (**c**) shows no

signal outside the stent graft. An SWS elasticity map (**d**) demonstrates the absence of an elasticity signal in the right posterolateral sac (arrowheads) compatible with an endoleak. Note the absence of a signal in the left posterior sac wall indicating a non-diagnostic region (arrow)

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**Fig. 3** Endoleak detected with SWS, CDUS, and CT in participant 12. Axial B-mode (**a**) shows hypoechogenic posterior aneurysmal sac contents. Axial CTA (**b**) confirms a large contrast pooling (arrow) secondary to a type 1b endoleak. CDUS (**c**) shows a signal in the stent graft limbs

Out of the participants with type II endoleaks, one underwent an embolization while the four others were observed with a favorable outcome. A participant with endotension was eventually diagnosed with an infected prosthesis and was treated conservatively with antibiotics. A high mortality rate was noted, with five deaths at 3 years, two of metastatic cancer, one of terminal liver failure, and two of indeterminate cause. Out of the five deaths, three were in the endoleak group including the type Ib endoleak participant who died of indeterminate cause.

## Discussion

This first clinical feasibility study showed that SWS is highly sensitive and fairly specific to detect endoleaks and is reproducible. SWS provided mechanical information on the AAA sac contents that is complementary to B-mode and CDUS examinations. However, no correlation was found between

and in the aneurysmal sac outside the stent graft (arrow). The SWS elasticity map (d) demonstrates absence of elasticity signal in the endoleak region (arrowheads)

overall sac elasticity measurement and presence of endoleaks or AAA growth.

## **Endoleak detection**

Because liquid does not support shear wave propagation, endoleak regions were mapped close to 0 kPa. SWS thus provides opportunities to depict low-blood-flow endoleaks that are difficult to find with other techniques [25, 26]. Unlike CDUS which provides a velocity-dependent and angle-dependent signal, shear wave sonoelastography permits detection of areas with minimal flow and even stagnant liquid. The high sensitivity of SWS in detecting areas of endoleak has been shown in this study where all seven endoleaks or endotension diagnosed by the reference standard were also detected by the two independent elastogram reviewers. Although the study was not designed to assess CDUS sensitivity, it is interesting to note that it only detected 3 endoleaks compared to 7 with SWS. 3886



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Fig. 4 A false-positive endoleak on the SWS in participant 16. Axial Bmode (a) shows an AAA deeply located 12 cm below probe AAA at the level of stent graft limbs (arrowheads). Axial CTA (b) and CDUS (c) show no endoleak. Note the inferior vena cava signal (arrow in c) in the posterolateral right aspect of the AAA. An SWS elasticity map (d)

This high sensitivity comes to the detriment of specificity and positive predictive value that were averaged respectively to 67% and 50%. Both are expected to be low in a screening examination but should be improved to have a greater clinical impact. The number of false positives could be explained by the study design where both readers only had access to selected static axial elasticity maps and B-mode images. A dynamic examination with real-time feedback of thrombus mechanical properties combined with concurrent CDUS evaluation would probably improve the specificity. On the other hand, there was no apparition of endoleak or endotension in SWS negative patients on long-term follow-up.

#### Thrombus elasticity

No difference in total thrombus elasticity values or proportion of fresh thrombus in the aneurysm sac could be found between groups with and without endoleak. In addition to the small sample size, the accuracy of kPa measurements in a vessel

demonstrates low elasticity signal (arrowheads) in the left posterolateral sac without an endoleak in the corresponding region of reference standard imaging. A high elasticity modulus (> 80 kPa) in red indicates organized thrombus (arrow)

with anisotropic properties may have played a role. Other techniques, such as quasi-static vascular ultrasound elastography measuring the strain of vascular structures induced by the cardiac pulsation, seems to have a more direct correlation with elasticity relying on aortic thrombus displacement rather than shear wave speed propagation [27].

Although the endoleak group had a significantly higher growth in volume and diameter, no correlation has been found with the thrombus elasticity. This can be explained by the elasticity thresholds defining fresh thrombus (3 to 19 kPa) based on a preclinical study where a 7.5-MHz linear probe was used. This clinical study uses a lower-frequency (6 MHz) curvilinear probe to achieve deeper penetration but uses the same post-processing algorithm to compute the elasticity maps. Areas of null elasticity are most likely valid given the presence of a signal in its surroundings. However, we cannot confidently say that areas of 3 to 19 kPa represent fresh thrombus histopathologically as it was in a canine model [21]. Further evaluation of data translation between the higher- and

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Fig. 5 Sealed aneurysm in participant 23. Axial B-mode (a), CTA (b), and CDUS (c) show a small aneurysmal sac (arrowheads) without evidence of an endoleak. An SWS elasticity map (d) shows intermediate

signal (20–40 kPa) surrounding the stent graft (arrowheads). Except for the lumen (arrow), no signal void suggesting endoleak is found on SWS map

lower-frequency probes and studies of fresh thrombus thresholds should be made.

# Limitations

The small sample size represents the main weakness. At a feasibility stage, we considered this small sample was sufficient to evaluate if SWS should gain further attention. Elastograms were analyzed to favor a high sensitivity over specificity for the diagnosis of endoleaks. A real-time multimodal approach combining B-mode, CDUS, and SWS would likely result in more accurate diagnoses. In future clinical work-flow, we could reserve injection of contrast-enhanced ultrasound examination only in participants with positive SWS examination to improve the specificity.

Combined SWS-CDUS examinations were all performed after the reference CTA on average  $4.1 \pm 2.2$  months (0.2 to 7.7 months) which constitutes a long latency period during which endoleaks might have occurred. If such an event had

happened and went undetected, SWS sensitivity was overestimated. In an attempt to mitigate the risk of missing an endoleak, a 3-year follow-up was performed. Moreover, CDUS was acquired concomitantly with SWS (after reference CTA) and had the potential to detect a new endoleak occurring in this time interval. This might explain why in patient 3 no endoleak was detected in the CTA but one was diagnosed by both SWS and CDUS performed 4.93 months after.

Nearly 5% of the SWS signal had to be considered nondiagnostic because of the absence of a wave transmission to the posterior wall of the aneurysm (Fig. 2d). Without a signal on the posterior aspect of the aneurysmal sac, one cannot conclude if it represents an endoleak or if the region is not assessable by the focused ultrasound beam. Again, faster postprocessing with real-time feedback would permit multiple elastogram acquisitions in different angles and planes than the three axials (proximal, mid, distal) analyzed in this study. This could enable the analysis of the whole aneurysmal sac and increase SWS sensitivity and specificity for endoleak detection.

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# Conclusion

This first-in-man study demonstrates the potential of SWS to detect endoleaks in an abdominal aortic aneurysm after endovascular repair with an excellent sensitivity. SWS has shown its potential to characterize aneurysmal sac contents based on elasticity maps. Optimization of SWS thresholds to discriminate areas of soft and organized thrombus and testing SWS on a larger sample size constitute the next crucial steps to developing this screening tool. Addition of SWS is conceivable particularly using a multimodal approach with B-mode, CDUS, and, if needed, contrast-enhanced ultrasound examination.

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## **Compliance with ethical standards**

**Guarantor** The scientific guarantor of this publication is Gilles Soulez, MD, MSc.

**Conflict of interest** The authors declare that they have no competing interests.

**Statistics and biometry** Paule Bodson-Clermont kindly provided statistical advice for this manuscript.

**Informed consent** Written informed consent was obtained from all subjects (patients) in this study.

Ethical approval Institutional Review Board approval was obtained.

#### Methodology

· prospectively performed at one institution

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