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1 On the potential of ultrasound elastography for pressure ulcer 2 early detection

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14 **Purpose:** Pressure ulcers are areas of soft tissue breakdown induced by a sustained mechanical
15 stress that damages the skin and underlying tissues. They represent a considerable burden to the
16 society in terms of health care and cost. Yet, techniques for prevention and detection of pressure
17 ulcers still remain very limited. In this article, the authors investigated the potential of ultrasound
18 elastography for pressure ulcer early detection. Elastography is an imaging technique providing
19 local information on biological tissue mechanical properties. It is relevant for pressure ulcer detec-
20 tion as this pathology is associated with a gradual stiffening of damaged tissues, beginning in the
21 deeper tissues and progressing toward the skin surface.

22 **Methods:** A 2D ultrasound elastography method was proposed and its ability in terms of pressure
23 ulcer detection was validated through numerical simulations and physical acquisitions on pressure
24 ulcer mimicking phantoms. *In vivo* experiments on a rat model are also reported. A maintained
25 pressure was applied on the animal thigh, with a view to generate a pressure ulcer, and ultrasound
26 data were acquired and processed before and after application of this pressure.

27 **Results:** Numerical simulations demonstrated that a pressure ulcer can theoretically be detected at
28 a very early stage with ultrasound elastography. Even when the ulcer region was characterized by
29 a low stiffening (ratio of 1.8 relative to normal tissues), the corresponding elastogram clearly
30 underlined the pathological area. This observation was confirmed by the results obtained on a
31 physical phantom mimicking a pressure ulcer at an early stage. Computed elastograms showed
32 strain differences between areas mimicking healthy and pathological tissues. Results corresponding
33 to *in vivo* experiments revealed a difference in the way tissues behaved before and after the pressure
34 was applied on the animal thigh, which strongly suggests the presence of a pathological area.

35 **Conclusions:** Experiments demonstrated that ultrasound elastography is a promising technique for
36 pressure ulcer detection, especially at an early stage of the pathology, when the disease is still
37 visually undetectable. In the absence of any gold standard method, this is also a first step toward the
38 development of a quantitative technique. © 2011 American Association of Physicists in Medicine.
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40 Key words: pressure ulcer, ultrasound, elastography, medical imaging

41 I. INTRODUCTION

42 Pressure ulcers, or bedsores, are areas of soft tissue break-
43 down induced by a sustained mechanical stress that damages
44 the skin and underlying tissues. They often appear after a
45 prolonged period of immobility, during which biological tis-
46 sues undergo a maintained pressure from a support (gener-
47 ally a bed or a wheelchair). Pressure ulcers mostly affect
48 people with sensitivity loss or limited mobility, who are un-
49 able to feel and/or release the pressure. Elderly people, pa-
50 tients in hospital recovery and persons with spinal cord in-
51 jury are especially at risk.

52 Few statistics are available to estimate the extent of this

53 pathology. In 2001, wide variations were found for the
54 prevalence of pressure ulcer in the United States:¹ 10%–18%
55 in acute care, 2.3%–28% in long-term care, and 0%–29% in
56 home care. In the United Kingdom, prevalence was esti-
57 mated at 18% in 1993.² As life expectancy increases in west-
58 ern countries, this disease becomes a growing issue and rep-
59 represents a considerable burden to the society in terms of
60 health care and associated cost.^{3,4}

61 Despite these numbers, techniques for prevention and de-
62 tection of pressure ulcer still remain very limited. For in-
63 stance, risk scales do exist but they are mostly used for hos-
64 pitalized patients, and their efficiency is largely questioned.⁵

65 Thus, detection and prevention are mainly based on the ex-
 66 perience of the health-care personnel.
 67 Different approaches were developed to study skin
 68 wounds. A good review of wound measurement techniques
 69 can be found in Ref. 6. These techniques can be divided into
 70 two categories: Visual assessment tools, based on color and
 71 digital image analysis, and physiological-based tools (i.e.,
 72 blood flow, force, or pressure measurements). More recently,
 73 Weber *et al.*⁷ developed a device to map the electrical im-
 74 pedance of a wound in order to determine the wound sever-
 75 ity. Treuillet *et al.*⁸ also presented an original approach to
 76 build 3D models of skin wounds from digital camera snap-
 77 shots, allowing quantitative measurements of the wound,
 78 such as surface, depth, or volume.
 79 Attempts to develop quantitative techniques for detection
 80 or prevention of pressure ulcers are far less numerous. In
 81 Ref. 9, 15 pressure ulcers were examined using four different
 82 noninvasive techniques: Skin temperature, redness index,
 83 skin retraction time, and ultrasound (US) scanning. Results
 84 showed that temperature and retraction time could not alone
 85 characterize the ulceration stage, while a redness index was
 86 useful in some cases. Ultrasound image processing could de-
 87 tect a subepidermal layer, which may be a good indicator that
 88 the skin is at risk. One can finally cite Ref. 10, where pre-
 89 vention of pressure ulcer was based on both movement mea-
 90 surement and autonomous nervous system analysis. Even
 91 though these studies were constructive, it is still relevant to
 92 develop new quantitative approaches.
 93 This lack of quantitative assessment tools is likely the
 94 result of a limited understanding of the pathology itself.
 95 There is indeed very little literature on the process that trig-
 96 gers the formation of pressure ulcers.
 97 To date, the most established theory is that tissue com-
 98 pression locally results in the occlusion of blood
 99 capillaries.^{11–13} The mechanism leading to the formation of a
 100 pressure ulcer is linked with a shortage of blood supply,
 101 called ischemia, which prevents the natural exchanges of
 102 oxygen and nutrients. If the microcirculatory flow distur-
 103 bance remains for too long, the ischemic condition leads to
 104 cell death and tissue damages.
 105 It is also acknowledged that pressure ulcers are associated
 106 with a stiffening of damaged tissues, as shown in Refs. 14
 107 and 15 on a rat model and on a realistic numerical model of
 108 human buttocks, respectively.
 109 Finally, recent studies suggest that pressure ulcers can
 110 form either superficially or within deep tissues.^{11,16,17} Super-
 111 ficial pressure ulcers arise in the skin. They are mainly
 112 caused by shear stresses and are easily detected by careful
 113 skin inspection. On the other hand, deep pressure ulcers (also
 114 called deep tissue injuries) develop in deep muscle layers
 115 covering bony prominences and are caused by sustained
 116 compression of the tissues. They follow a “deep-to-
 117 superficial” pattern and progress toward the skin surface.
 118 Therefore, severe necrosis of subcutaneous tissues may occur
 119 while the skin shows only minor signs of tissue breakdown.
 120 Consequently, deep ulcers are very difficult to identify. Since
 121 deep pressure ulcers are characterized by stiffening and a

deep-to-superficial growing process, providing information
 on tissue local mechanical properties could be of major in-
 terest for physicians.

Accordingly, US elastography is proposed for pressure ul-
 cer early detection. US elastography^{18,19} is indeed providing
 to clinicians information on the local mechanical properties
 of soft biological tissues. This information, generally dis-
 played as an image, enables the detection of unexpected stiff
 area within healthy tissues. Typical applications of US elas-
 tography are targeted to diseases such as breast and prostate
 cancer,^{20,21} liver fibrosis,²² and atherosclerosis.²³

Potentially, pressure ulcer US elastography could be used
 for diagnosis and wound healing follow-up. US elastography
 also has the advantage of being noninvasive, low-cost, and
 portable.

In this paper, we investigated the potential of quasistatic
 US elastography for pressure ulcer early detection. The paper
 is organized as follows. Section II provides a description of
 the US elastography method, followed by its application to
 numerical data in Sec. III, and to a pressure ulcer mimicking
 phantom in Sec. IV. Section V is dedicated to the presenta-
 tion of results obtained during an *in vivo* experiment. The
 final section provides a critical discussion and concluding
 remarks.

II. METHOD

Depending on the mechanical excitation applied to the
 tissues, there are mainly two approaches in US elastography,
 termed quasistatic elastography^{19,24–26} and dynamic
 elastography.^{18,27–29} This paper falls into the category of qua-
 sistatic elastography, which investigates tissue deformation
 under compression. In quasistatic elastography, information
 on tissue local mechanical properties is deduced from a
 simple principle: Subjected to a given stress, soft areas will
 deform more than stiffer ones. In practical terms, for a tissue
 under investigation, two US radiofrequency (RF) data sets
 are acquired, corresponding to two different stress levels
 called pre- and postcompression states. Pattern changes in-
 duced by the stress within the RF signals are then analyzed
 to compute a map of local strains.

The different steps leading to this local strain estimation
 are briefly explained hereafter to make the paper self-
 contained. The interested reader can refer to Refs. 26 and 30
 for more details.

II.A. Image deformation model

To achieve a local estimation, images were divided into
 multiple small regions-of-interest (ROIs) and for each ROI,
 the effects of the tissue compression were analyzed. Most of
 the 2D techniques used in elastography model the
 compression-induced tissue motion as a local 2D translation
 and then compute strain as the gradient of the resulting dis-
 placement field. Contrary to these techniques, we considered
 that the effect of compression on each ROI can be modeled
 as an affine transformation. In addition to a 2D translation,
 a scaling of the ROI was also considered, which reflects more
 realistically the tissue deformation at this location.

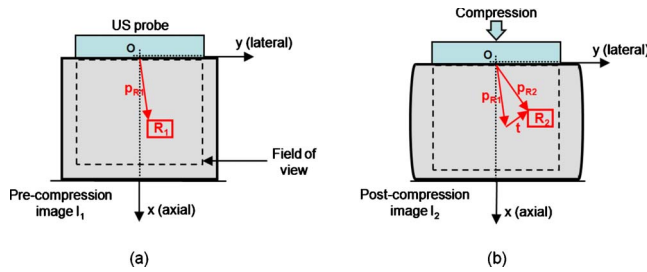


FIG. 1. Region of interest positioning in (a) the precompression image and (b) the postcompression image.

177 However, US data resolution is highly anisotropic. Owing
178 to US device characteristics, lateral resolution is much
179 coarser than the axial resolution, which makes an accurate
180 estimation of a scaling factor difficult in the lateral direction.
181 This has led us to consider only an axial scaling of the ROI,
182 the lateral deformation being taken into account in the lateral
183 translation of the ROI.

184 II.B. ROI displacement

185 Let us denote I_1 and I_2 the pre- and postcompression im-
186 ages, respectively. Let us consider R_1 a ROI of dimensions
187 $L_{x1} \times L_{y1}$, located at p_{R1} in I_1 . Finally, let us denote R_2 the
188 ROI in I_2 corresponding to the same tissue region after de-
189 formation. Its axial and lateral dimensions L_{x2} and L_{y2} are
190 such that $L_{x2} = \alpha \cdot L_{x1}$ (axial scaling) and $L_{y2} = L_{y1}$. The posi-
191 tion of R_2 in I_2 , namely, p_{R2} , is also different from p_{R1} , as
192 shown in Fig. 1. We therefore initialize R_2 at its most prob-
193 able position in I_2 as

$$194 \quad p_{R2ini} = p_{R1} + t, \quad (1)$$

195 with $t(t_{ax}, t_{lat})$ a 2D translation. This translation vector repre-
196 sents the effects of tissue deformation on the position of R_2 .
197 In particular, its axial component t_{ax} results from the axial
198 scaling of the regions located between the probe and the ROI
199 currently considered. It can therefore be entirely determined
200 from previous computations by beginning the estimation pro-
201 cess for the regions at the interface with the probe (where
202 $t_{ax} = 0$) and propagating this process to regions downward.
203 Similarly, the lateral shift t_{lat} is directly given by the previous
204 estimations, by beginning the estimation process for the re-
205 gions at the center of the probe and propagating this process
206 to the lateral sides.

207 II.C. Problem formulation

208 For the positions of R_1 and R_2 that have been determined,
209 two local parameters must now be estimated: An axial scal-
210 ing α and a residual lateral shift τ . This estimation is per-
211 formed through the minimization of an objective function f ,
212 which is defined as the opposite of the normalized correla-
213 tion coefficient between R_1 and R_2 , R_2 varying with these
214 parameters.

215 Since RF US data are oscillating signals by nature, the
216 function f may exhibit several local minima. To narrow the
217 optimization process around the area corresponding to the

global minimum, the range of values allowed for the param-
eters is reduced. This reduction in the parameter domain is
reasonable since in elastography, deformations induced by
the external load are of small magnitude (a few %). R_2 is
therefore sought in a small region immediately surrounding
its initial position. As a result, the optimization is subjected
to a set of linear inequality constraints on the parameters and
the problem to be solved can be formulated as

$$[\hat{\alpha} \quad \hat{\tau}] = \arg \min_{\alpha, \tau} f(\alpha, \tau) \quad \text{with} \quad \begin{cases} \alpha_{\min} \leq \alpha \leq \alpha_{\max} \\ \tau_{\min} \leq \tau \leq \tau_{\max} \end{cases}. \quad (2)$$

Typically, axial strain is restricted to the range [0%–6%] and
lateral shift is limited to three times the RF line interspacing
(i.e., $\alpha_{\min} = 0.94$, $\alpha_{\max} = 1$, $\tau_{\min} = -3$, and $\tau_{\max} = 3$).

In practical terms, this optimization process is imple-
mented, thanks to a sequential quadratic programming
methodology,³¹ together with an active set strategy. To en-
sure a reliable estimation and prevent the objective function
from being trapped in a local minimum, correction proce-
dures are also considered based on multiple initializations of
the process^{26,30}

II.D. Axial strain computation

In this paper, the mechanical parameter we are interested
in is the medium's axial strain. This information is directly
deduced from the estimated axial scaling factor $\hat{\alpha}$, according
to the following relation:

$$\varepsilon = \hat{\alpha} - 1. \quad (3)$$

It should be stressed that with Eq. (3), strain is negative for a
compression and positive for a dilatation. Because in this
study, all experiments were performed by applying a com-
pression to the observed media, computed strain values were
negative. For simplification purposes, we chose to display
the opposite of the strain, leading to elastograms with posi-
tive values, keeping in mind that they represent the percent-
age of medium compression.

III. NUMERICAL SIMULATIONS

Deep pressure ulcers develop at the deepest level and pro-
ceeds outward until they reach the skin.^{11,16,17} At an early
stage of the pathology, deep tissues are therefore damaged
while the epidermis is still intact. Besides, areas particularly
exposed to pressure ulcers are those over bony prominences,
such as the sacrum, hips, and heels, which represent 80% of
bedsores.³² From this background, a numerical phantom of
pressure ulcer was designed with regard to these observa-
tions, and the potential of US elastography for the early de-
tection of this condition was investigated.

The phantom of $30 \times 20 \times 4$ mm³ modeled a deep ulcer
at the very beginning of the pathological process (Fig. 2). It
was made of three different regions:

- Healthy soft tissues in contact with the US probe,
- A bony prominence at the bottom, which is a privileged configuration for pressure ulcer formation,

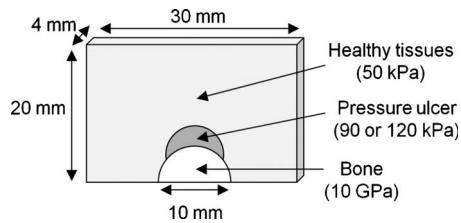


FIG. 2. Sketch of the numerical phantom mimicking a pressure ulcer at an early stage.

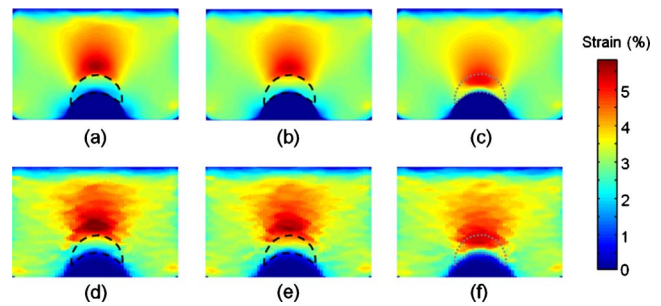


FIG. 3. Numerical phantom results. On the first row are the theoretical axial strain fields (given by the FEM) and on the second row are the estimated axial strain fields (in %). (a) and (d) are the fields for the configuration including a 120 kPa pressure ulcer. (b) and (e) are the fields for the configuration with a 90 kPa pressure ulcer. (c) and (f) are the fields for the configuration without pressure ulcer.

268 – And an intermediate layer mimicking the *in-*
 269 *development* ulcer, located above the bone, and whose
 270 limited size made it visually undetectable from the
 271 phantom upper surface.

272 The phantom mechanical properties were defined as fol-
 273 lows: The Young’s modulus of the bone was set to 10 GPa
 274 and that of healthy tissues was set to 50 kPa. These are
 275 orders of magnitude reported in literature.^{33–35} The modeling
 276 of the pressure ulcer was based on the following observation.
 277 During their experiments, Gefen *et al.*¹⁴ measured a 1.8–3.3-
 278 fold stiffening of tissues damaged by a pressure ulcer com-
 279 pared to normal ones. Accordingly, two different values were
 280 chosen for the Young’s modulus of the pressure ulcer: Either
 281 90 kPa, corresponding to the lowest ratio (1.8×50 kPa), or
 282 120 kPa, corresponding to a middle range value. In addition,
 283 a third configuration was considered for control. It repre-
 284 sented a “healthy” state, with no pressure ulcer (Young’s
 285 modulus of 50 kPa).

286 To obtain the postcompression configuration, a 1.5 kPa
 287 stress was applied on the upper surface of phantoms down-
 288 ward. The corresponding tissue deformations were computed
 289 through the use of a finite element modeling (FEM) package
 290 (COMSOL MULTIPHYSICS, Comsol Inc., USA).

291 From an acoustical point of view, tissues were modeled as
 292 a large number of punctual scatterers randomly distributed in
 293 the region-of-interest. In the absence of information related
 294 to pressure ulcer echogenicity and since our technique is
 295 based only on tissue’s stiffness differences, healthy and
 296 pathological tissues were considered as having identical
 297 acoustical properties. Consequently, a standard B-mode im-
 298 age did not allow seeing any difference between these two
 299 regions. On the other hand, the bone was designed to be
 300 hyperechoic compared to soft tissues.

301 US RF data were the result of the convolution between
 302 scatterers and a point spread function simulating the acous-
 303 tical response of the scanner.³⁶ Simulations were performed
 304 for both the pre- and the postcompression states, displace-
 305 ments of scatterers between the two states being given by the
 306 FEM.

307 The strain estimator described in Sec. II was applied to
 308 these simulated data. The corresponding results, together
 309 with theoretical fields, are given in Fig. 3. We can first ob-
 310 serve that the estimated elastograms are close to the theoret-
 311 ical fields provided by the FEM. They both exhibit similar
 312 patterns of strains, which is satisfying regarding the strain
 313 estimation method. The bone has a deformation close to
 314 zero, which is consistent with its stiffness, and it is clearly

identified in the three elastograms. Its position also matches
 the hyperechoic region of the B-mode image. Although the
 pressure ulcer cannot be detected in the B-mode scan, the
 presence of a hard pathological area is revealed in the elas-
 tograms [Figs. 3(d) and 3(e)]: Strain for the pathological area
 is indeed half that of its upper neighborhood (about 2.5% vs
 5%). Transitions from the healthy tissues to the ulcer and
 from the ulcer to the bone are very sharp. This underlines the
 hard region, with limits corresponding to the dotted line
 (area available from the FEM and added manually on the
 different maps). In contrast, the maps corresponding to the
 healthy model [Figs. 3(c) and 3(f)] show a relatively differ-
 ent configuration, with a smaller maximum and the region of
 highest strain overlapping the area of the ulcer.

IV. PRESSURE ULCER MIMICKING PHANTOM

In this section, additional tests are reported on a physical
 phantom designed to mimic an early stage pressure ulcer. A
 sketch of the phantom is shown in Fig. 4(a). It consisted of a
 $30 \times 60 \times 110$ mm³ parallelepiped, within which three
 regions can be identified: A bone, a region representing the
 in-development pressure ulcer, and the surrounding healthy
 tissues. The bone, of 10 mm in diameter, was a sample from
 the forward limb of a dog. Other regions were made of poly-
 vinyl alcohol (PVA) cryogel. PVA cryogel is a polymer that
 was introduced in the 1990s to build phantoms mimicking
 soft tissues.³⁷ Mixed with Sigmacell particles (Sigmacell
 Cellulose, type 20, Sigma-Aldrich, USA), its acoustical
 properties are close to those of soft biological tissues, and
 this material is suitable for US imaging. Moreover, the mat-
 erial stiffness increases with the number of freeze-thaw
 cycles applied. By varying this number of cycles, a wide
 range of elasticity values can be obtained, especially those
 commonly met for soft biological tissues.^{38,39} Since a pres-
 sure ulcer is stiffer than healthy tissues, the PVA cryogel for
 this region went through two freeze-thaw cycles, while the
 PVA cryogel for the healthy region underwent a single cycle.
 Such a pressure ulcer corresponds to a deep tissue injury.

RF US data were acquired with an *Ultrasonix Sonix RP*
 device (Ultrasonix Medical Corporation, Richmond, BC,
 Canada), equipped with a 7 MHz linear probe (reference

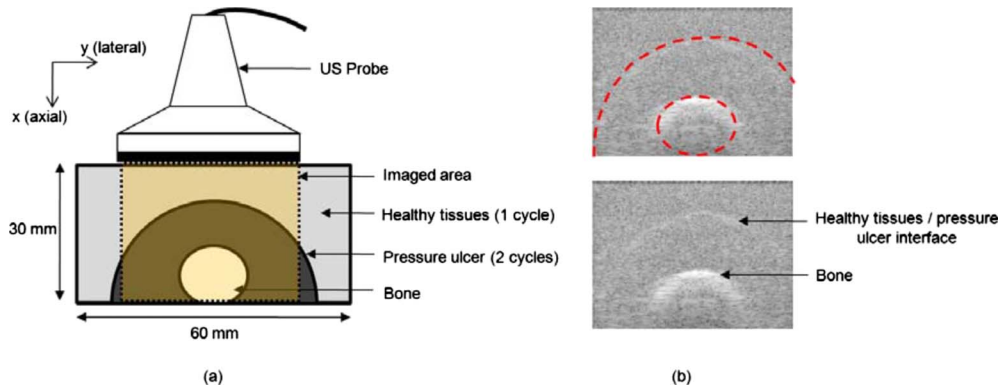


FIG. 4. (a) PVA phantom constitution. (b) B-mode image of the phantom.

355 L14-5/38). The postcompression data were acquired after
 356 uniform compression of the top surface of the phantom (ap-
 357 plied with a plate, while the bottom surface remained fixed).
 358 These data were then processed with our strain estimator.
 359 As it can be seen from the B-mode image of this region
 360 [Fig. 4(b)], the bone could be clearly identified from its
 361 specular reflection. However, the echography did not provide
 362 any information about the mechanical properties of the phan-
 363 tom. On the contrary, the estimated axial strain map (Fig. 5)
 364 was helpful for the detection of the three regions of the phan-
 365 tom. Even if strain values remained within a small range, it
 366 can be seen that pathological tissues exhibit a different pat-
 367 tern compared to the surrounding healthy soft tissues. Fi-
 368 nally, deformation of the bone is almost negligible, as ex-
 369 pected.
 370 Mean strain were calculated for the different tissue types.
 371 They were equal to $1.01 \pm 0.24\%$, $0.45 \pm 0.16\%$, and
 372 $0.06 \pm 0.06\%$ for the healthy, pathological, and bone regions,
 373 respectively.

374 **V. PRELIMINARY *IN VIVO* STUDY**

375 To further evaluate the contribution of elastography for
 376 pressure ulcer detection, *in vivo* acquisitions on an experi-
 377 mental rat model were performed. The intent of this study
 378 was to investigate *in vivo* the ability of elastography to detect
 379 strain, when the tissues under examination were subjected to
 380 a long-term unrelieved pressure.

381 The main reason for tissue breakdown is ischemia,¹¹⁻¹³ in
 382 connection with the interface pressure at the skin level. Tra-
 383 ditionally, the value of 32 mm Hg (4.3 kPa) is quoted for the
 384 pressure threshold that triggers capillary closure:⁴⁰ If main-
 385 tained, interface pressures higher than this value are sup-

posed to lead to tissue damage. However, a more recent
 386 study demonstrates that this value is not relevant since cap-
 387 illary closure mainly depends on the local pressure.⁴¹ To in-
 388 duce tissue breakdown, we therefore chose to adapt the pro-
 389 tocol described by Gefen *et al.*,¹⁴ where a maintained
 390 compression was applied on the thigh of rats to generate
 391 pressure ulcers. In the latter paper, it is shown that a pressure
 392 of 35 kPa maintained during 60 min leads to a twofold stiff-
 393 ening of tissues with cell death.
 394

The protocol for animal experimentation was approved by
 395 the Animal Care Committee of the Centre Hospitalier de
 396 l'Université de Montréal, in accordance with the guidelines
 397 of the Canadian Council of Animal Care. The animal was an
 398 18-week-old male rat from the Brown Norway breed and
 399 weighed 265 g. It was first anesthetized by inhalation of
 400 2.5% isoflurane, the hair of the hind limb was carefully
 401 shaved, and the animal was then immobilized. Its body tem-
 402 perature was monitored with a rectal probe (Thermalert
 403 TH-5, Physitemp Instruments, Clifton, USA) and maintained
 404 at 37 ± 1 °C with a heating surface. A first set of RF US data
 405

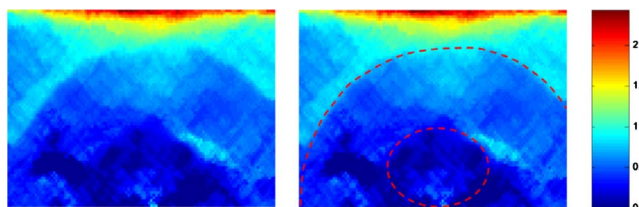


FIG. 5. Estimated strain map (in %) for the PVA cryogel phantom.

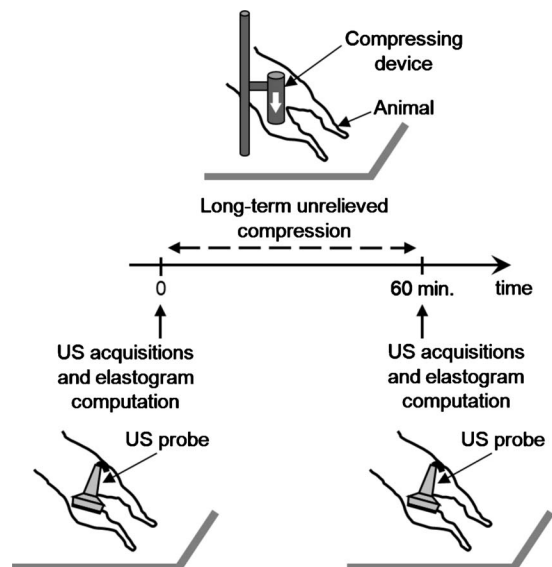


FIG. 6. Scheme of the *in vivo* protocol used to induce a pressure ulcer early detection on a rat and to acquire US data for elastography imaging.

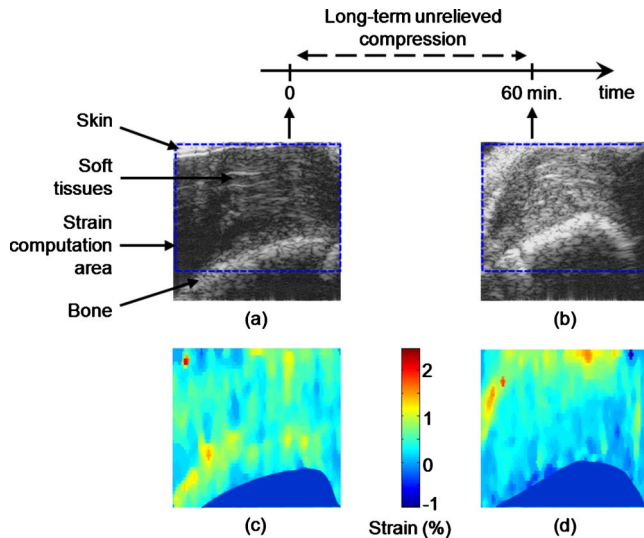


FIG. 7. B-mode images and elastograms for the *in vivo* experiment. (a) Initial B-mode image (showing the different tissues). (b) B-mode image after 60 min compression. (c) Initial elastogram. (d) Elastogram after 60 min compression.

406 was acquired, in a view to compute elastograms. A 35 kPa
407 pressure was then applied on the thigh of the animal during
408 60 min to generate a pressure ulcer. A second set of RF US
409 data was acquired after the 60 min compression. Once the
410 experiments were completed, the animal was euthanized by
411 inhalation of CO₂. Figure 6 summarizes the protocol.

412 RF US data were acquired with a *VisualSonics Vevo 660*
413 device (VisualSonics Inc., Toronto, Canada), equipped with a
414 35 MHz probe dedicated to small animal studies. US data
415 were acquired with the same settings of the scanner and were
416 processed to compute elastograms before the application of
417 the compression and after the 60 min compression. The com-
418 pression tool was a wooden stick, whose end was a 2-cm-in-
419 diameter disk in contact with the skin of the animal. Both the
420 US probe and the compression device were mounted on a
421 robotic arm (described in detail in Ref. 42). The latter was a
422 6 degrees of freedom industrial robot (F3 Articulated Robot,
423 CRS Robotics Corporation, Burlington, Canada), equipped
424 with a force sensor on its end (ATI, Industrial Automation,
425 Apex, USA), and controlled through a software interface (In-
426 tegral Technologies Inc., Laval, Canada). This enabled the
427 control of the pressure applied with the compressing device
428 and ensured an accurate positioning of the US probe.

429 Results of this experiment are presented in Fig. 7. Figure
430 7(a) provides a B-mode image of the investigated area where

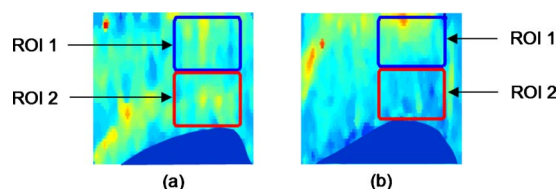


FIG. 8. Location of the ROIs for mean strain computation (a) on the initial elastogram and (b) on the final elastogram.

TABLE I. Mean strain and standard deviation, according to time and location of the ROI, for the *in vivo* experiment.

| ROI location | Mean strain (%) | Time | |
|-------------------|-----------------|-----------------|-----------------|
| | | 0 min | 60 min |
| Close to the skin | | 0.48 ± 0.22 | 0.50 ± 0.27 |
| Close to the bone | | 0.47 ± 0.19 | 0.13 ± 0.13 |

different tissues can be identified: The skin, the bone (both
hyperechoic), and soft tissues, which is the region that was
specifically analyzed. The corresponding B-mode image af-
ter the application of the 60 min compression is shown in
Fig. 7(b). Due to the 60 min compression, the B-mode im-
ages exhibit different patterns. However, these images alone
are not relevant to reveal or not the presence of a pathologi-
cal area. Computed elastograms are displayed in Figs. 7(c)
and 7(d), respectively. The initial elastogram appears homo-
geneous. Only the area immediately above the bone exhibits
a slightly higher strain. As a comparison, the same area on
the second elastogram (i.e., after 60 min compression) be-
haved differently, with a deformation smaller than the sur-
rounding tissues. A sharp evolution of the strain along depth
is also visible for the whole image: Shallow tissues seem to
exhibit higher strains compared to the tissues near the bone.
This evolution tends to show that the tissue area over the
bone became stiffer, which could be the indication of an
emerging pressure ulcer.

To support this visual impression, mean deformations
were calculated in two ROIs, as shown in Fig. 8. For a given
image, both ROIs have the same size. They are also located
at the same lateral position, but at different depths, either
near the skin or near the bone. Mean strain was estimated
over the pixels located within the perimeter defined by the
ROI. The corresponding results are given in Table I. Before
the compression was applied ($t=0$), the strain was almost
the same for both regions (0.48% for the top ROI and 0.47%
for the bottom ROI). On the other hand, mean strains were sig-
nificantly different after the compression of 60 min: While
the mean strain for the top ROI was 0.50%, that for the
bottom ROI dropped to 0.13%. The large decrease in strain
near the bone might be due to tissue stiffening in this region.
This observation allows to assume that the area near the bone
was pathological, corresponding to the presence of a pressure
ulcer or, at least, corresponding to tissues that underwent a
degradation such that they were significantly stiffer than
healthy tissues.

VI. DISCUSSION AND CONCLUSION

In this paper, we proposed a new approach based on ul-
trasound imaging to address the challenging problem of pres-
sure ulcer early detection. Even though US elastography usu-
ally finds its main application in cancer tumor detection, we
think it has great potential for pressure ulcer early detection.
Since this pathology is associated with a stiffening of dam-
aged tissues, highlighting abnormally hard areas could in-
deed be fundamental. Moreover, deep pressure ulcers are

478 characterized by a deep-to-superficial pattern: The ulcer de-
479 velops in deep muscle tissues and progresses toward the
480 skin. US elastography is therefore an interesting tool for
481 early detection, when the deep ulcer is still imperceptible by
482 visual inspection.

483 To investigate the usefulness of US elastography, different
484 types of data were processed. Numerical simulations demon-
485 strated that a pressure ulcer can theoretically be detected at a
486 very early stage with US elastography. Even when the ulcer
487 region was characterized by a low stiffening (ratio of 1.8
488 relative to normal tissues), the estimated elastogram clearly
489 underlined the pathological area.

490 This observation was confirmed by the results obtained on
491 a physical phantom mimicking a pressure ulcer at an early
492 stage. Computed elastograms showed strain differences be-
493 tween areas mimicking healthy and pathological tissues.

494 Compared to the results on numerical data, these elasto-
495 grams showed a different strain pattern, which could be at-
496 tributed to the different designs of the simulated and experi-
497 mental phantoms. Indeed, for building procedure reasons, the
498 area mimicking the pressure ulcer in the physical phantom is
499 much wider than those in simulations and completely covers
500 the bone. However, both numerical and experimental results
501 demonstrate that US elastography can detect an abnormally
502 stiff area corresponding to a deep pressure ulcer in develop-
503 ment, even though no particular symptom is visible on the
504 skin.

505 Finally, *in vivo* experiments were conducted on a rat
506 model. A maintained pressure was applied on the animal
507 thigh during 60 min, with a view to generate a pressure ulcer.
508 It has been shown in a previous study,¹⁴ based on histologies,
509 that the protocol used in our experiment (in particular, the
510 same compressing device and level of pressure were consid-
511 ered) leads to irreversible muscle cell death after only 15 min
512 of exposition. The same paper concludes that changes in me-
513 chanical properties follow morphological damages and cel-
514 lular death. RF US data, acquired before and after applica-
515 tion of this pressure, were processed with our strain
516 estimator. Elastograms revealed a difference in the way tis-
517 sues behaved before and after the pressure was applied,
518 which strongly suggest the presence of a pathological area.

519 These first results naturally require confirmation by per-
520 forming many other *in vivo* experiments. In particular, acqui-
521 sitions on human patients can be envisaged using lower fre-
522 quency probe to image a larger area of tissue.

523 Nevertheless, these first experiments demonstrate that US
524 elastography is a promising technique for pressure ulcer de-
525 tection, especially at an early stage of the pathology, when
526 the disease is still visually undetectable. In the absence of
527 any other technique, this is also a first step toward the devel-
528 opment of an objective and reliable tool.

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