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# Temperature Elevation in an Instrumented Phantom Insonated by B-Mode Imaging, Pulse Doppler and Shear Wave Elastography

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1 **Temperature elevation in an instrumented phantom**  
2 **insonated by B-mode imaging, Pulse-Doppler and Shear**  
3 **Wave Elastography**

4  
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26

27 **Abstract** — Diagnostic ultrasound is the gold standard for obstetric scanning and one of the  
28 most important imaging techniques for perinatal and neonatal monitoring and diagnosis.  
29 Ultrasound provides detailed real-time anatomical information, including blood flow  
30 measurements and tissue elasticity. The latter is provided through various techniques  
31 including Shear Wave Elastography (SWE). SWE is increasingly used in many areas of  
32 medicine, especially in detection and diagnosis of breast, thyroid, and prostate cancers and  
33 liver disease. More recently, SWE has found application in gynaecology and obstetrics. This  
34 method mimics manual palpation, showing the elastic properties of soft biological tissues.  
35 Despite its rising potential and expanding clinical interest in obstetrics and gynaecology (such  
36 as for assessment of cervical ripening or organ development and structure during pregnancy),  
37 its effects on and potential risks to the developing fetus remain unknown. Risks should be  
38 evaluated before recommendations are made on the use of SWE by regulatory bodies.  
39 Because ultrasound is known to produce thermal and mechanical effects, this study measured  
40 the temperature increase caused by B-mode, Pulse-Doppler (PD) and SWE, using an  
41 instrumented phantom with eleven embedded thermocouples. Experiments were performed  
42 with an Aixplorer® diagnostic ultrasound system (Supersonic Imagine, Aix-en-Provence,  
43 France). As expected, the largest heating was detected by the thermocouple closest to the  
44 surface in contact with the transducer (2.9°C for SWE, 1.2°C for PD, 0.7°C for B-mode after  
45 380-second excitation). Both conduction from the transducer face and direct heating due to  
46 ultrasound waves contribute to temperature increase in the phantom with SWE showing a  
47 larger temperature increase than PD and B-mode. This manuscript offers a methodological  
48 approach and reference data for future safety studies, as well as initial recommendations about  
49 SWE safety in obstetrics and gynaecology.

50

51 **Keywords:** Shear wave elastography; Ultrasound safety; Phantom; Thermocouple;  
52 Temperature change; tissue mimic; thermal damage; Obstetrics; Gynaecology; Fetus

53

54

## INTRODUCTION

55

56 Shear wave elastography (SWE) is a non-invasive diagnostic imaging technique used for  
57 mapping the elastic properties of tissues (Parker et al. 2011). This modality is being  
58 increasingly used in many areas of medicine, offering high-quality diagnostic examination, as  
59 it increases specificity and improves diagnostic accuracy, as discussed below. SWE provides  
60 the elastic properties of soft biological tissues, from the measurement of the speed of  
61 propagation of ultrasound radiation induced shear waves. Ophir et al. developed a strain-  
62 measuring compression elastography method (Ophir et al. 1991). Elastography was initially  
63 developed by Wilson and Robinson (1982) with the aim of quantifying Young's modulus for  
64 diagnostic purposes. Young's modulus quantifies the stiffness, defined as stress divided by  
65 strain, of a solid material. Tissue elasticity can be explored either by studying its deformation  
66 under the effect of constant pressure (*i.e.* the static method) or by studying the propagation of  
67 a mechanical shear wave induced by an oscillating source (*i.e.* the dynamic method)  
68 (Dickinson and Hill 1982). SWE represents an ultrasound-based approach to manual  
69 palpation medical examination (Fink 2013). Modern scanners like that used in this study  
70 generate the shear wave by producing a displacement in the tissue through a focused, high  
71 intensity and short duration ultrasonic push.

72 SWE has already been demonstrated that elastography is useful for characterizing malignant  
73 tumours in breast (Klotz et al. 2014), thyroid (Monpeyssen et al. 2013) and prostate (Dudea et  
74 al. 2011), as well as lymph nodes structure (Alam et al. 2008), and localized (Menten et al.  
75 2010; Sandulescu et al. 2012) or diffuse liver diseases (Kennedy et al. 2018).

76 The use of SWE has recently been extended to gynaecology diagnosis of uterine  
77 disorders (Metin et al. 2016; Stoelinga et al. 2014; Thomas et al. 2007) and to obstetrics  
78 (Ogawa et al. 2012) for cervix stiffness/ripening assessment (Duan et al. 2020; Egorov et al.  
79 2020; Hernandez-Andrade et al. 2013; Pereira et al. 2014). Potential indications of SWE in  
80 fetal and uterine imaging during pregnancy include placental examination (Akbas et al. 2019;  
81 Kılıç et al. 2015; Cimsit et al. 2015) and fetal organ development and structure. In fact, SWE  
82 has recently been explored to assess fetal brain (Diguisto et al. 2017), lung (Mottet et al.  
83 2019) and liver (Zheng et al. 2016), outside regulatory indication scopes. In obstetrics, the  
84 first use of this ultrasound technique was for the study of cervix (maturation, threats of  
85 premature delivery). The measurement techniques involving direct application of deformation  
86 (the only ones used until now) are not perfect, especially in terms of reproducibility.  
87 Histological modifications of the placenta in certain pathologies of pregnancy (*i.e.* pre-  
88 eclampsia) could have an observable effect in terms of tissue elasticity. In the same way, the  
89 evolution linked to the maturation of certain organs could also be of clinical interest. The  
90 examination of the fetal lungs (in particular in order to assess their spontaneous maturity or  
91 after preventive treatment of hyaline membrane disease by corticosteroid therapy) and the  
92 pre-implantation endometrium in assisted reproductive technology (ART) are typical  
93 examples. Few researchers have addressed the teratogenic effects of fetal elastography, one  
94 example was the discussion held between K. Preisand and G. Rus at the World Congress of  
95 Fetal Medicine in 2016 (Massó et al. 2017): although no apparent histological changes  
96 following ultrasound elastography have been reported, the absence all bioeffects could not be  
97 excluded (Sugitani et al. 2013). One of the first studies using SWE to assess cervical ripening  
98 in 2012 (Peralta et al. 2017), conducted in the lack of any regulatory framework, was the  
99 subject of comments (Massó et al. 2017) highlighting the need for follow-up of children  
100 exposed *in utero*. The potential teratogenic effects of elastography were subsequently

101 explored by a follow-up study of the children at 4 years of age, focusing on the results of a  
102 neonatal hypoacusis screening test and medical records. The exposed population was  
103 compared to the reference population using a contingency-table analysis to assess excess risk.  
104 Hypoacusis was reported in a late premature case (36 weeks, 1860 g), and was attributable to  
105 a Prader–Willi-like phenotype. No other case negative outcomes were observed, though a  
106 larger sample size would be beneficial. Some *in vivo* experiments have also shown that the  
107 threshold temperature increase for teratogenic effects induced by hyperthermia is estimated at  
108 1.5°C for an exposure of 5 min (Abramowicz et al. 2008).

109         Considering the increasing number of publications on elastography, the World  
110 Federation for Ultrasound in Medicine and Biology (WFUMB) first published guidelines for  
111 its clinical use in August 2011. The initial consensus meeting was held in March 2013 and led  
112 to the development of general guidelines for elastography (Shiina et al. 2015), and specifically  
113 for imaging of breast (Barr et al. 2015), liver (Ferraioli et al. 2015), prostate (Barr et al. 2017)  
114 and thyroid (Cosgrove et al. 2017). These guidelines did not distinguish between the different  
115 elastography modes. The European Federation of Societies for Ultrasound in Medicine and  
116 Biology (EFSUMB) later published guidelines and recommendations for the clinical use of  
117 ultrasound elastography (Dietrich et al. 2017; Săftoiu et al. 2018). Neither updated  
118 recommendation included obstetric application. The only British Medical Ultrasound Society  
119 (BMUS) recommendations regarding obstetrics focus on the use of B-mode and Pulse-  
120 Doppler (PD) imaging (BMUS Safety Group 2010). To date, SWE has not been approved by  
121 the Food and Drug Administration (FDA) for clinical applications in obstetrics.

122         Ultrasound can lead to two main types of potentially damaging effects on biological  
123 tissues, namely thermal and mechanical effects (Shankar and Pagel 2011). A developing fetus  
124 could be particularly sensitive to the aforementioned effects (Issaoui et al. 2018).

125 Previous studies have measured the temperature increase due to ultrasonic push used  
126 in SWE (Lui et al. 2014). A pre-clinic experimental approach is also required, and developing  
127 experimental techniques to measure the temperature rise in biological tissue caused by  
128 ultrasound is of great interest for a variety of diagnostic and therapeutic applications.

129 Previous (non-SWE) studies have been performed to assess whether the temperature  
130 increase in soft tissue mimicking materials can exceed the aforementioned safety limits  
131 (Miloro et al. 2017; Calvert et al. 2007; Clarke and terHaar 1997; Palmeri and Nightingale  
132 2004; Skurczynski et al. 2009). Thermocouples are known to generate artifacts (Morris et al.  
133 2008), the main source being the viscous heating. In the work, mitigating actions have been  
134 taken to reduce the artifacts. Different techniques that involve the analysis of ultrasound  
135 images have been developed (Alvarenga et al. 2017), but require a high level access to the  
136 raw data of the ultrasound scanners.

137 The present study aims to compare SWE imaging with two diagnostic imaging modes  
138 which are in routine clinical use for scanning of pregnant women (B-mode and pulsed  
139 Doppler (PD)). For this purpose, heating patterns caused by the three modalities were  
140 characterized in an instrumented phantom, composed of a well characterized Tissue  
141 Mimicking Material (TMM) with 11 embedded fine-wire thermocouples. It is important to  
142 note that a perspective of the study concerns the health risk of SWE for fetus in terms of  
143 temperature rises. The experimental program was carried out with a view to assessing health  
144 risks in order to meet a clinical objective in obstetrics in the future.

145

## 146 **MATERIALS AND METHODS**

147

148 *Instrumented Phantom*

149 An acousto-thermal phantom with embedded thermocouples was designed,  
150 manufactured and used to measure the temperature increase due to diagnostic ultrasound  
151 excitation. The phantom was developed at the National Physical Laboratory (NPL,  
152 Teddington, UK). The tissue mimicking material (TMM) used in the phantom was the agar-  
153 based gel described in the IEC 60601-2-37 (2007). The recipe, based on 3% w/w of agar,  
154 includes glycerol to match the speed of sound of soft tissues, as well as additives (silicon  
155 carbide and aluminium oxide) to adjust the attenuation and backscatter coefficients. A plastic  
156 frame mould was 3D-printed at NPL, in order to cast a 136×80×80 mm<sup>3</sup> block of TMM (see  
157 Fig. 1-a to 1-c). For use and storage, the phantom was kept in an aqueous solution of 11.9%  
158 w/w glycerol in order to prevent dehydration and glycerol leaching out of the TMM.

159 The main acoustic properties of the TMM were measured at NPL using the finite  
160 amplitude insertion substitution (FAIS) method described by Baêso et al. (2019): attenuation  
161 was almost linear with frequency ( $0.57 \pm 0.05 \text{ dB} \cdot \text{cm}^{-1} \cdot \text{MHz}^{-1}$ ) and speed of sound was 1540  
162  $\text{m} \cdot \text{s}^{-1} \pm 1\%$ . Thermal properties, measured using a hand held device (TEMPOS, Meter Group,  
163 Pullman, WA, USA), were: specific heat capacity of  $3770 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ , thermal conductivity of  
164  $0.58 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$  and thermal diffusivity of  $0.15 \text{ mm}^2 \cdot \text{s}^{-1}$ , with a quoted measurement  
165 uncertainty of 10%. The density of the TMM was  $1070 \pm 30 \text{ kg} \cdot \text{m}^{-3}$  (IEC 60601-2-37, 2007).  
166 These values are comparable to those of soft tissues. In particular, the IT'IS Database of  
167 Tissue Properties (Hasgall et al. 2018) reports values of  $3676 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ,  $0.53 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$  and  
168  $1105 \text{ kg} \cdot \text{m}^{-3}$  for the specific heat capacity, the thermal conductivity and the density of uterine  
169 tissues, respectively, while the IEC 60601-2-37 (2007) reports  $0.6 \text{ dB} \cdot \text{cm}^{-1} \cdot \text{MHz}^{-1}$  and 1575  
170  $\text{m} \cdot \text{s}^{-1}$  for acoustic attenuation and speed of sound in soft tissues.

171 Eleven 75  $\mu\text{m}$  diameter K-type insulated thermocouples from Omega Engineering  
172 (5SRTC-TT-KI-40-1 M, Manchester, UK) were embedded into TMM gel at pre-determined  
173 positions in the phantom using notches in the frame used to mold the gel. The carefully



174 designed wire matrix is shown in Fig. 1-d and 1-e. One of the 11 thermocouples (called ref in  
175 the figure), was used during the tests as a reference to track environmental thermal  
176 fluctuation. It was placed at the location ( $x = 0$  mm,  $y = 24$  mm,  $z = 74$  mm) to be outside the  
177 ultrasonic excitation, so that it can be reasonably assumed that it provides the externally  
178 affected TMM reference conditions. The present study is based on measuring temperature  
179 change due to ultrasound excitation at the locations of the ten other thermocouples whose  
180 coordinates are given in Table 1. The position of the thermocouples was chosen based on the  
181 results of a previous work (Issaoui et al. 2020) and assuming symmetry in the temperature  
182 field with respect to the two symmetry planes of the transducer. To limit the number of  
183 thermocouples and reduce the complexity of the instrument, it was decided to place all of  
184 them in one quarter of the phantom. Because the imaging probe can be orientated however the  
185 user prefers, this does not limit the flexible use of the phantom. Thermocouples Tc-1 to Tc-7  
186 were designed to be located in the transducer imaging plane ( $y = 0$  mm) with Tc-8\*, Tc-9\* and  
187 Tc-10\* outside this plane by either 10 or 13 mm (\*: symbol referring to thermocouples located  
188 out of the transducer plane).

189

### 190 *Experimental setup*

191 Preliminary tests were performed by three operators (MI, PM and IR) at the  
192 Institute of Cancer Research, London (ICR) to check the locations and the proper functioning  
193 of the TMM embedded thermocouples, and to validate the feasibility of using the  
194 instrumented phantom with an Aixplorer® scanner. Subsequently, the core of the study was  
195 carried out at the department of obstetrics and gynaecology of the University Hospital of  
196 Clermont-Ferrand (CHU), France. The test campaign was performed by five operators (MI,  
197 XB, BB, MG, DL). The echography system used was an Aixplorer® (Supersonic Imagine,  
198 Aix-en-Provence, France), featuring B-mode, PD and SWE imaging modes. Only a curved

199 SC6-1 probe (Supersonic Imagine, Aix-en-Provence, France) featuring 192 piezoelectric  
200 elements and a bandwidth of 1–6 MHz, typically used in obstetrics, was employed. The  
201 transducer face has a thickness of 15 mm, a radius of curvature of 100 mm and a frontal area  
202 of 73×15 mm<sup>2</sup>. The imaging transducer was clamped in placed in contact with the top surface  
203 of the phantom as shown in Fig. 2-a. Acoustic gel was employed to couple the phantom to the  
204 transducer. Figure 2-b shows a typical B-mode image of the thermocouple wires. Table 2  
205 provides the ultrasound settings used for each of the three imaging modes. For each of them,  
206 the “obstetric preset” option was chosen, and no other settings were changed during the tests.  
207 Ultrasonic imaging exposures lasted 380 seconds. This is a typical duration of an obstetric B-  
208 mode examination (Martin et al. 2015). Although not directly comparable to a clinical  
209 scenario, for comparison purposes, it was decided to consider the same duration for all the  
210 three modalities. Temperature measurements began twenty seconds before exposure and  
211 lasted 30 min so that the return to thermal equilibrium could be monitored. Temperature data  
212 from the thermocouples were recorded using a TC08 datalogger (PicoTech, St Neots, UK)  
213 connected to a computer. Recording frequency was set to 1 Hz. The standard deviation of the  
214 noise in temperature measurements was lower than 0.01°C (measurable for instance during  
215 the first 20 seconds before ultrasound excitation in Fig. 3). Ultrasound induced temperature  
216 changes were calculated by subtracting the reference thermocouple temperature to the value  
217 of thermocouples Tc-1 to Tc-10\* at every time. The variation of the temperature reading for  
218 the reference thermocouple was always below 0.05°C during the 400 s of insonation.

219

## RESULTS

220

221

222 Figure 3 presents the temperature change measured by the ten thermocouples as a function of  
223 time for (a) B-mode, (b) Pulse-Doppler (PD) and (c) Shear Wave Elastography (SWE). The  
224 first vertical dashed line indicates ultrasound activation, at time  $t = 20$  s. The second one  
225 corresponds to the end of exposure, at  $t = 400$  s. Values are shown until  $t = 750$  s in order to  
226 demonstrate initial cooling. Temperature increases at  $t = 400$  s are shown in Figure 4 using  
227 circles with diameters proportional to the maximum temperature change measured for each  
228 mode, which always occurs for Tc-1). This representation gives a better visualization of the  
229 temperature distributions for each mode but does not allow comparison between imaging  
230 modes. Finally, Figure 5 compares the temporal temperature variations of the three  
231 thermocouples closest to the transducer (Tc-1, Tc-10\* and Tc-7) for the three imaging modes.  
232 Some important features can be extrapolated from the graphs:

- 233 • the maximum temperature increase was about  $0.7^{\circ}\text{C}$ ,  $1.2^{\circ}\text{C}$  and  $2.9^{\circ}\text{C}$  for B-mode, PD  
234 and SWE respectively. After validation of the device and numerous preliminary tests,  
235 experiments were repeated twice and good reproducibility of the results was observed  
236 for each ultrasound mode (the maximum temperature variations between repeats was  
237 measured to be lower than  $0.1^{\circ}\text{C}$  for all thermocouples). It is worth noting that the  
238 objective of the study was not to perform a statistical analysis of the results, but to  
239 compare three ultrasound modalities among which two are already in routine clinical  
240 use for scanning of pregnant women;
- 241 • as expected from previous works (Miloro et al. 2017; Issaoui et al. 2020), the highest  
242 temperature rises were observed for Tc-1, which was just under the transducer. Large  
243 temperature changes were also observed for Tc-10\* (more than 50% of the peak

244 increase), which was superficially close to the transducer (4 mm below Tc-1) but  
245 10 mm away in the out of plane direction (see Fig. 1-d and 1-e);

- 246 • The temperature change at Tc-3 is smaller than the temperature change at Tc-2 and  
247 Tc-4, whatever the mode under consideration. In particular, Tc-4 readings at 400 s  
248 were about 0.04°C, 0.2°C and 0.4°C for B-mode, PD and SWE respectively;
- 249 • heating was also clearly detected out of the transducer plane for PD and SWE (see Tc-  
250 8\* to Tc-10\*).

251

252

## DISCUSSION

253

254 An instrumented phantom was developed for the assessment of the temperature increase  
255 during B-mode, PD and SWE ultrasound imaging. 10 thermocouples were used, and their  
256 positioning was not limited to being on the transducer axis. To our best knowledge, the  
257 present study is the first one to measure heating variations due to SWE with thermocouples  
258 inside a phantom. As expected from previous studies, the largest temperature rises were  
259 observed for the thermocouple which was just under the transducer. This is likely to be due to  
260 the self heating of the transducer and the effects are visible also for thermocouples outside  
261 the imaging plane (Tc-10). More in depth, direct absorption of ultrasound energy is expected  
262 to play a more significant role. The role of absorption is highlighted on the results by an  
263 immediate and measurable temperature rise from Tc-2 and Tc-7, more evident in SWE where  
264 a higher signal-to-noise ratio was achieved. Due to the proximity of these thermocouples to  
265 the transducer, heat transfer is likely to play a role in the temperature readings at the end of  
266 the insonation.

267 Furthermore, the temperature increase for Tc-4 was higher than the one observed for  
268 Tc-3 (which is closed to the transducer) for all the imaging modes. It is interesting to observe

269 that in SWE mode, Tc-4 is within the focus of the acoustic beam used for generation of the  
270 shear waves. Similar observations were made on a sample without embedded thermocouples  
271 using surface infrared thermography (Issaoui et al. 2020).

272 Future studies could advantageously couple embedded thermocouples and surface  
273 thermographic measurements in order to reconstruct the three-dimensional thermal field in the  
274 sample.

275 A limitation of our study is that it was performed on a phantom composed of soft  
276 tissue mimicking material only. The BMUS guidelines for the safe use of diagnostic  
277 ultrasound equipment (BMUS Safety Group 2010) suggests using the bone thermal index for  
278 obstetric scans after the 10<sup>th</sup> week. Many other studies have shown that heating of bones is  
279 much higher than that of soft tissues (Tabaru et al. 2012; Nitta et al. 2001). Further studies  
280 should be performed on phantoms containing soft tissues and bone mimicking materials.

281 On the other hand, in clinical practice, other factors such as the almost continuous  
282 movement of the transducer, freezing of the output and reviewing acquired data during the  
283 examination, blood perfusion and the presence amniotic fluid could reduce the temperature  
284 changes deeper in the tissue. The TMM used in the present study was selected to mimic the  
285 average acoustic and thermal properties of soft tissues. However, real tissues are  
286 inhomogeneous.

287 Thermocouples have been used in the past to measure temperature increases in tissue  
288 mimicking materials despite well-known artifacts in the measurements, the most relevant  
289 being the viscous heating. Precaution have been taken to minimize these artifacts. The  
290 sensitive element of the selected thermocouple was 3.5 times be smaller than the shortest  
291 wavelength (257  $\mu\text{m}$  at 6 MHz), following the indications of the IEC committee (IEC 60601-  
292 2-37, 2007). The thermocouples were positioned such that the wires were on a plane  
293 perpendicular to the acoustic propagation axis (Suo et al. 2019). Furthermore, diagnostic

294 imaging modes are characterized by small duty cycles, thus reducing the effects of viscous  
295 heating (Morris et al. 2008).

296 Despite the limitations, a clear trend was observed: temperature rise is faster and  
297 higher for SWE than by PD and B-mode, with the last two modes already in use in obstetrics  
298 for decades. Although all the measured values, including MI and TI, fall within the safety  
299 guidelines of BMUS, these are in the category of time limits.

300 The temperature rise due to SWE was the highest: about 2.5 times greater than that  
301 due to PD, and more than 4 times greater than that due to B-mode. These results also indicate,  
302 consistently with previous works (Miloró et al. 2017) that TI is a poor indicator of the actual  
303 temperature rise in tissues. If TI is not displayed, like for B-mode and PD, it indicates values  
304 below 0.4. These are at least 4 times lower than the TI indicated for SWE, which is not in  
305 agreement with the results of this work.

306 However, recently released EFSUMB guidelines (Kollman et al. 2019), recommend  
307 that Pulsed Doppler ultrasound should not be used routinely in early pregnancy (before the  
308 14<sup>th</sup> week) and when used driven by a clear clinical motivation, the displayed Thermal Index  
309 should be less than or equal to 1.0, and exposure time should be kept as short as possible.  
310 BMUS guidelines (BMUS Safety Group 2010) also suggest that Pulsed Doppler should not be  
311 used without a risk-benefit analysis (and always monitoring the TI) on the head, brain or spine  
312 of any fetus or neonate or the eye of a subject of any age.

313 Based on the existing guidelines, the results of this work suggest that the risks  
314 associated with SWE are higher than those associated with B-mode and PD. More in general,  
315 the results raise questions about the health risk associated with obstetric SWE, as well as  
316 about the approach to be put in place and the standards to be considered when certifying this  
317 technique for obstetrical use.

318

319

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324

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488

## Figure Captions List

489

490

491 **Figure 1.** 3D-printed frame showing thermocouple placement: a) CAD drawing of the frame  
492 showing notches used to control horizontal thermocouple placement; b) photograph of the  
493 frame; c) front view of the frame with mounted thermocouples. The front and side walls of the  
494 frame were removed in the photographs; d) schematic view of the thermocouple locations  
495 (labelled 1 to 10 and ref) and definition of the x, y, z axis directions; e) same in top view, with  
496 imaging plane highlighted.

497

498 **Figure 2.** a) Picture of the experimental setup showing the clamp arrangement used to hold  
499 the imaging probe in a static position; b) B-mode image of the phantom showing  
500 thermocouple wires.

501

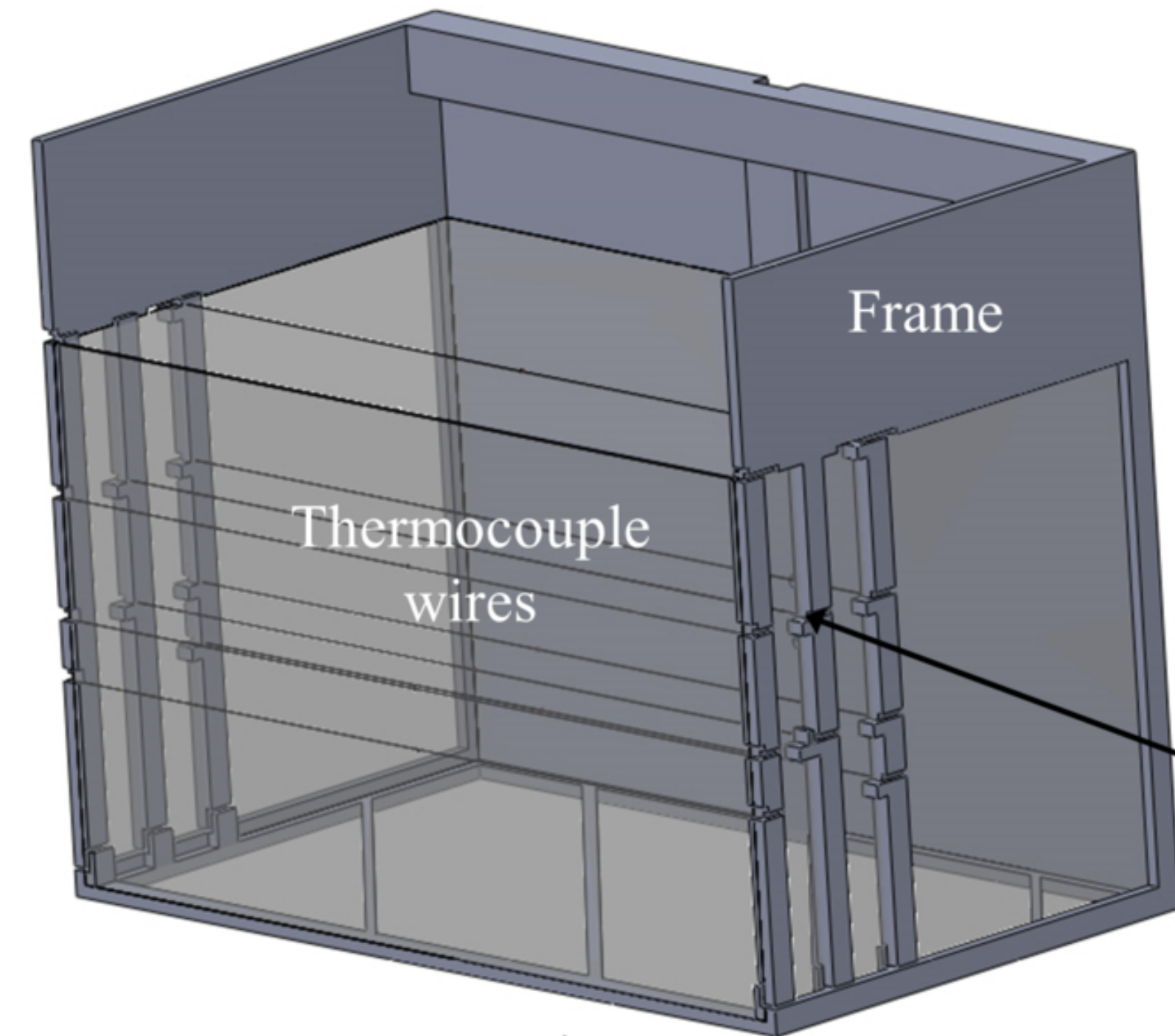
502 **Figure 3.** Temperature change of the ten thermocouples as a function of time: a) for B-mode;  
503 b) for PD; c) for SWE. For a better visualization of the lowest thermal responses, temperature  
504 changes at 400 s can be seen in Fig. 4.

505

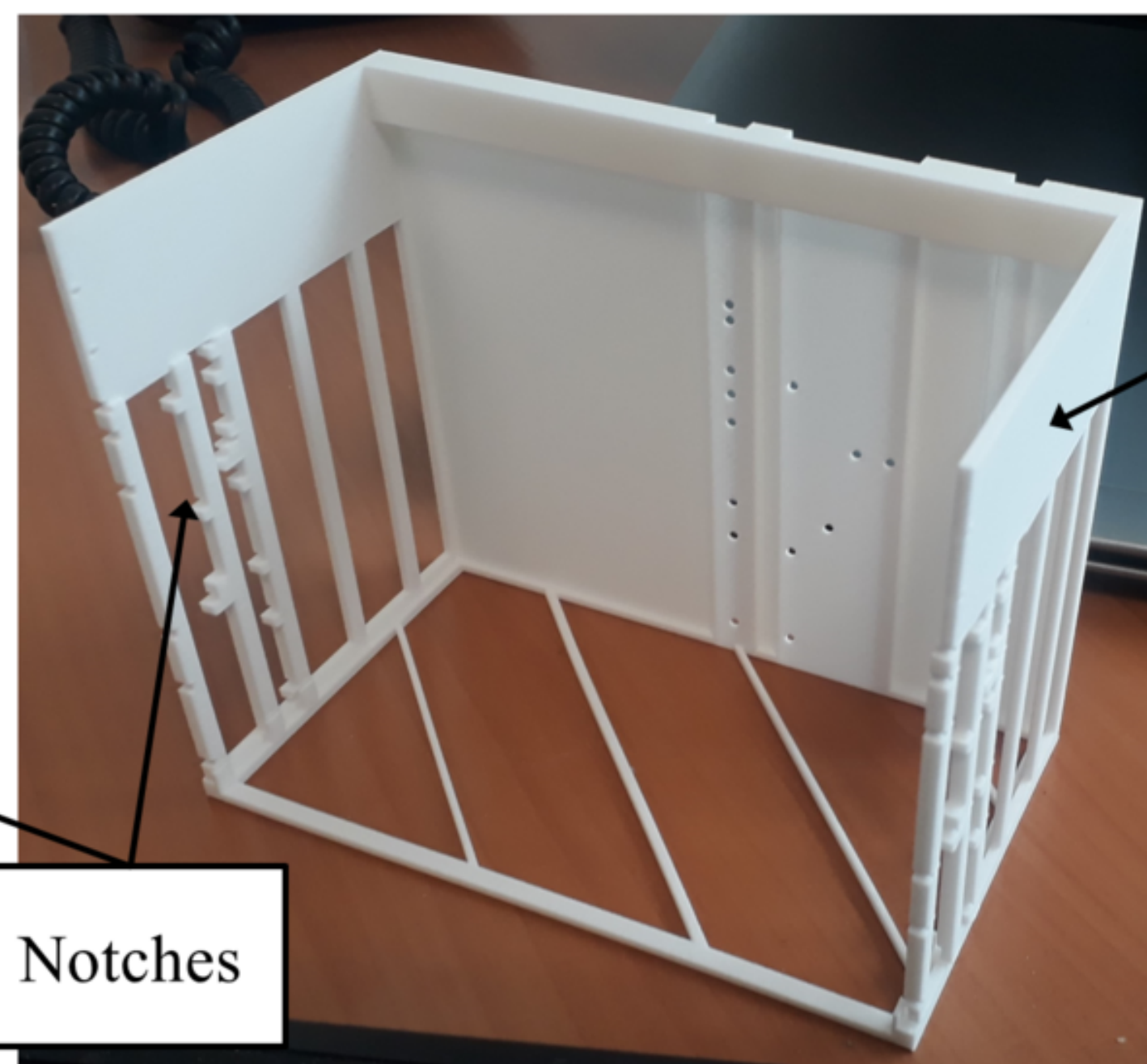
506 **Figure 4.** Temperature change for the three tested ultrasound imaging modes at 400 s  
507 (corresponding to the end of the 380 s exposure duration). For each mode, the circle diameter  
508 is proportional to the temperature change with the diameter for Tc-1 (maximum temperature  
509 change) being set to be the same (normalized) for the three modes in order to reveal relative  
510 temperature distributions within each mode.

511

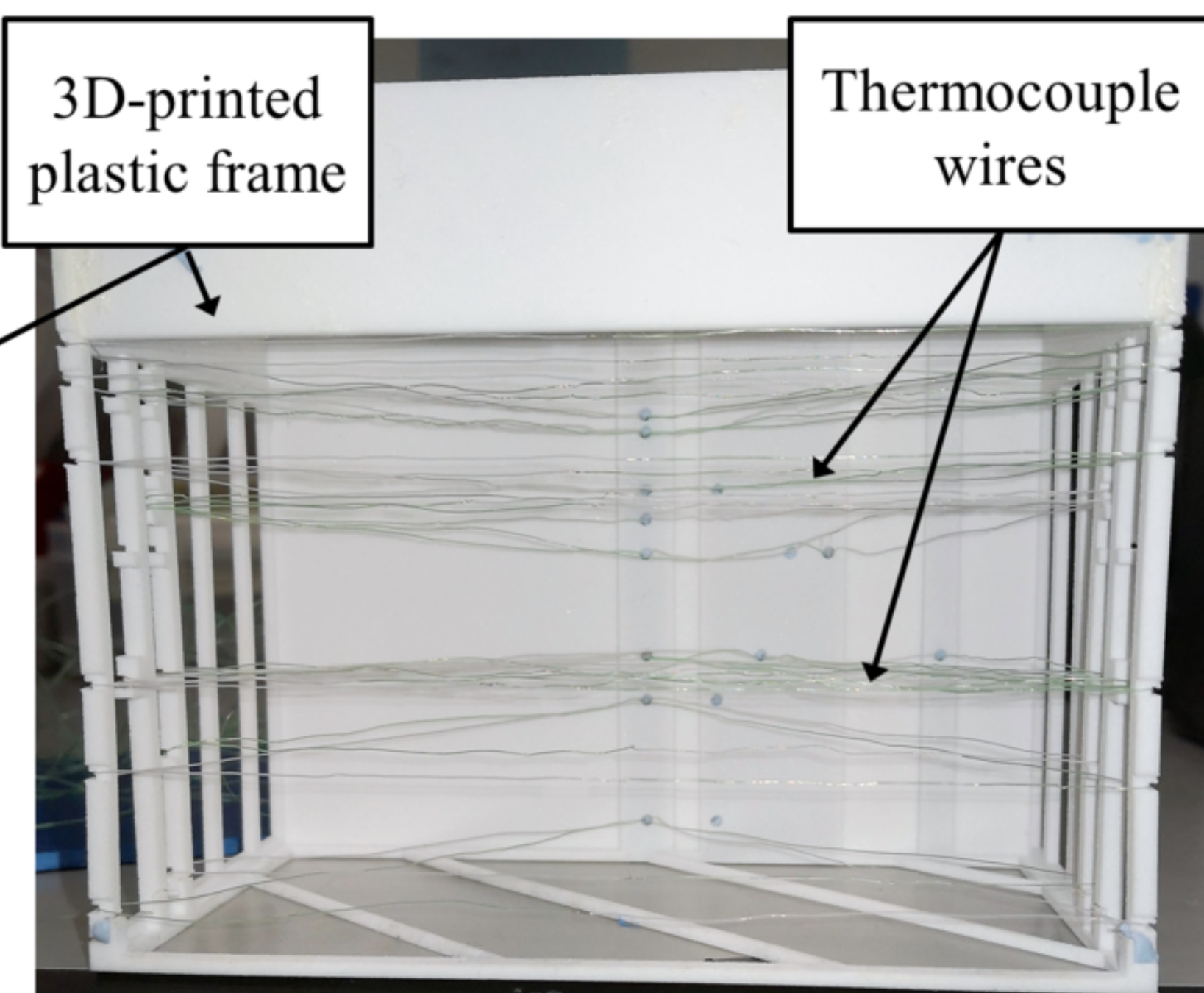
512 **Figure 5.** Comparison of temperature changes for B-mode, PD and SWE imaging exposures  
513 for thermocouple: a) Tc-1, b) Tc-10\*, c) Tc-7.



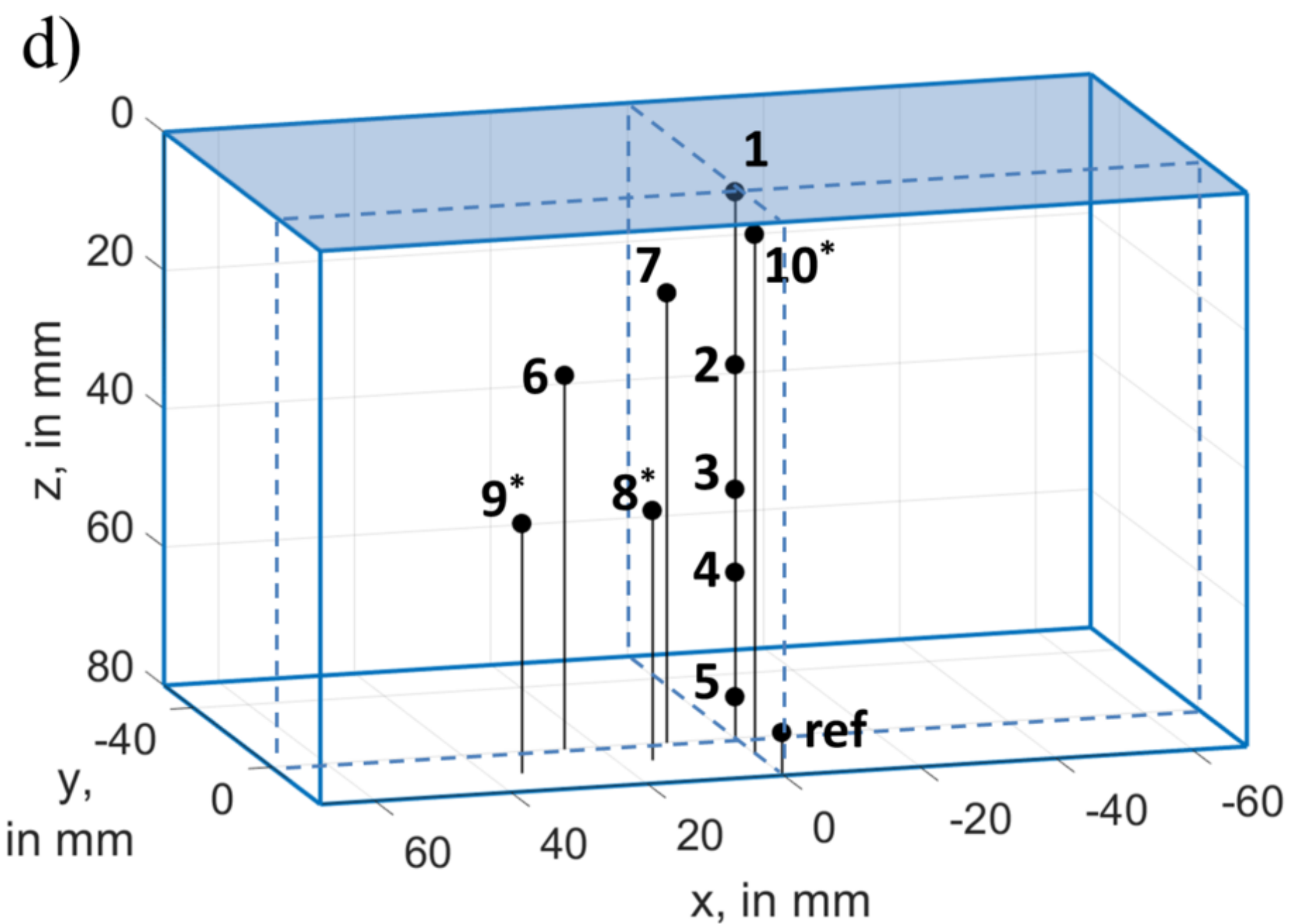
a)



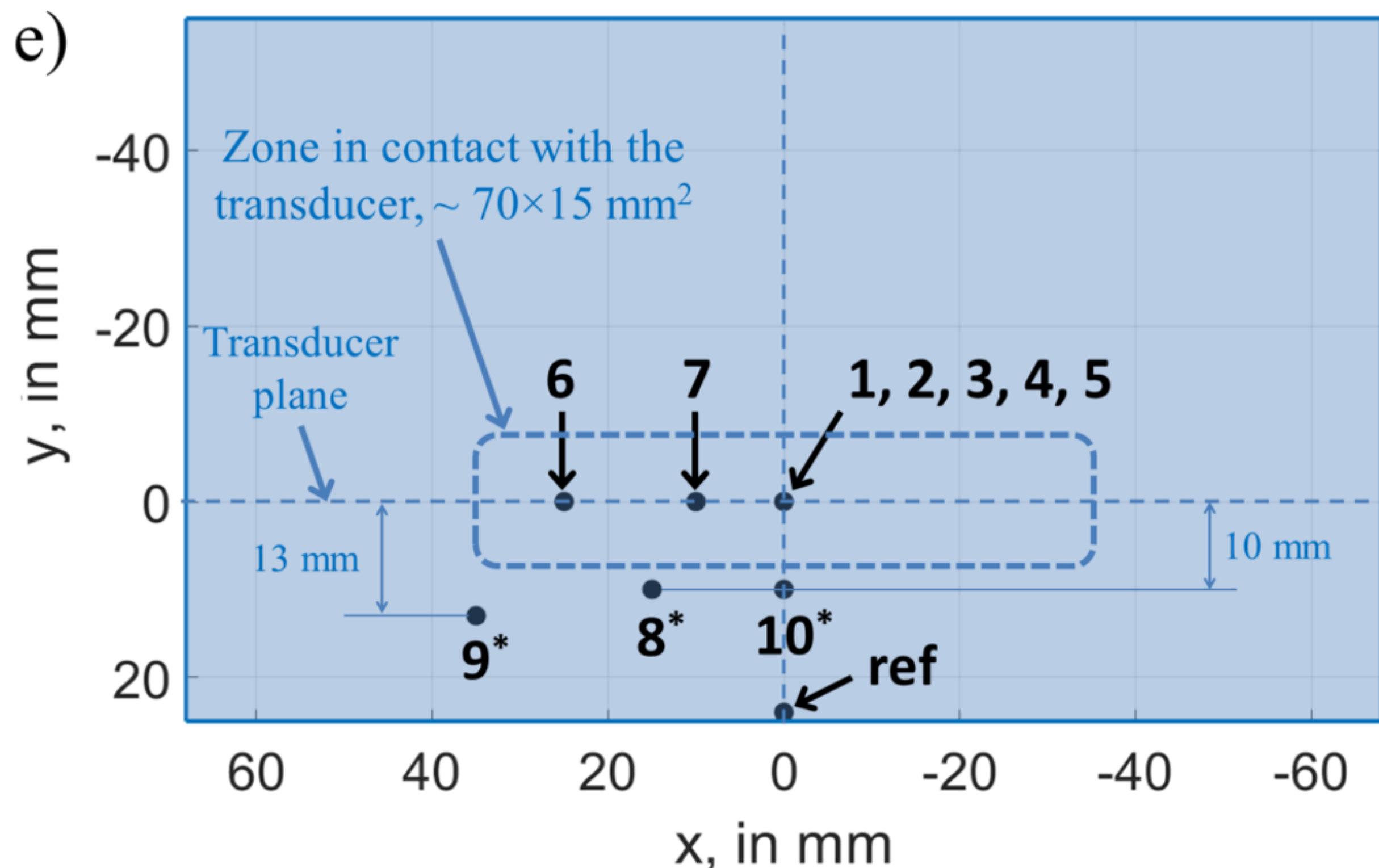
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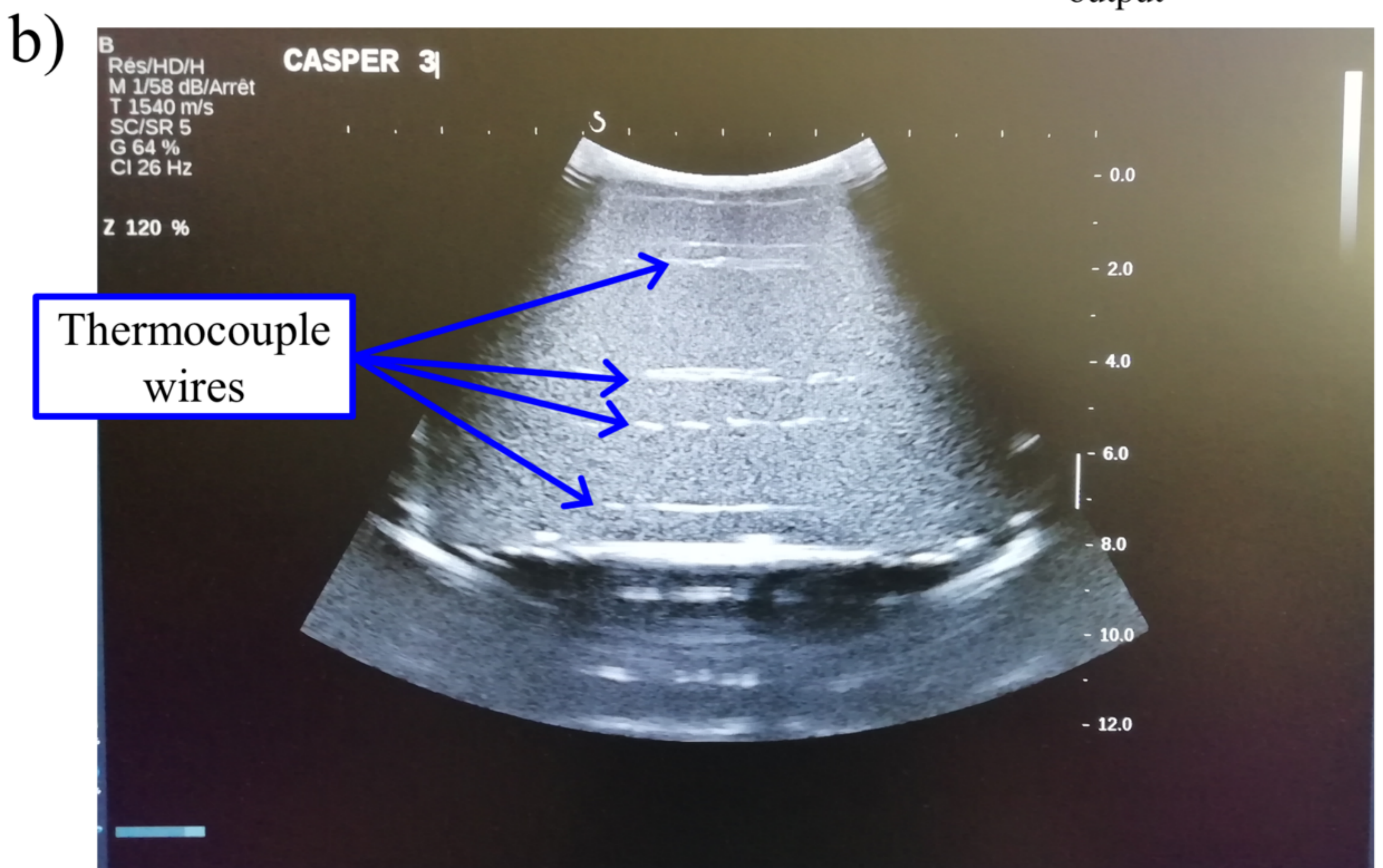
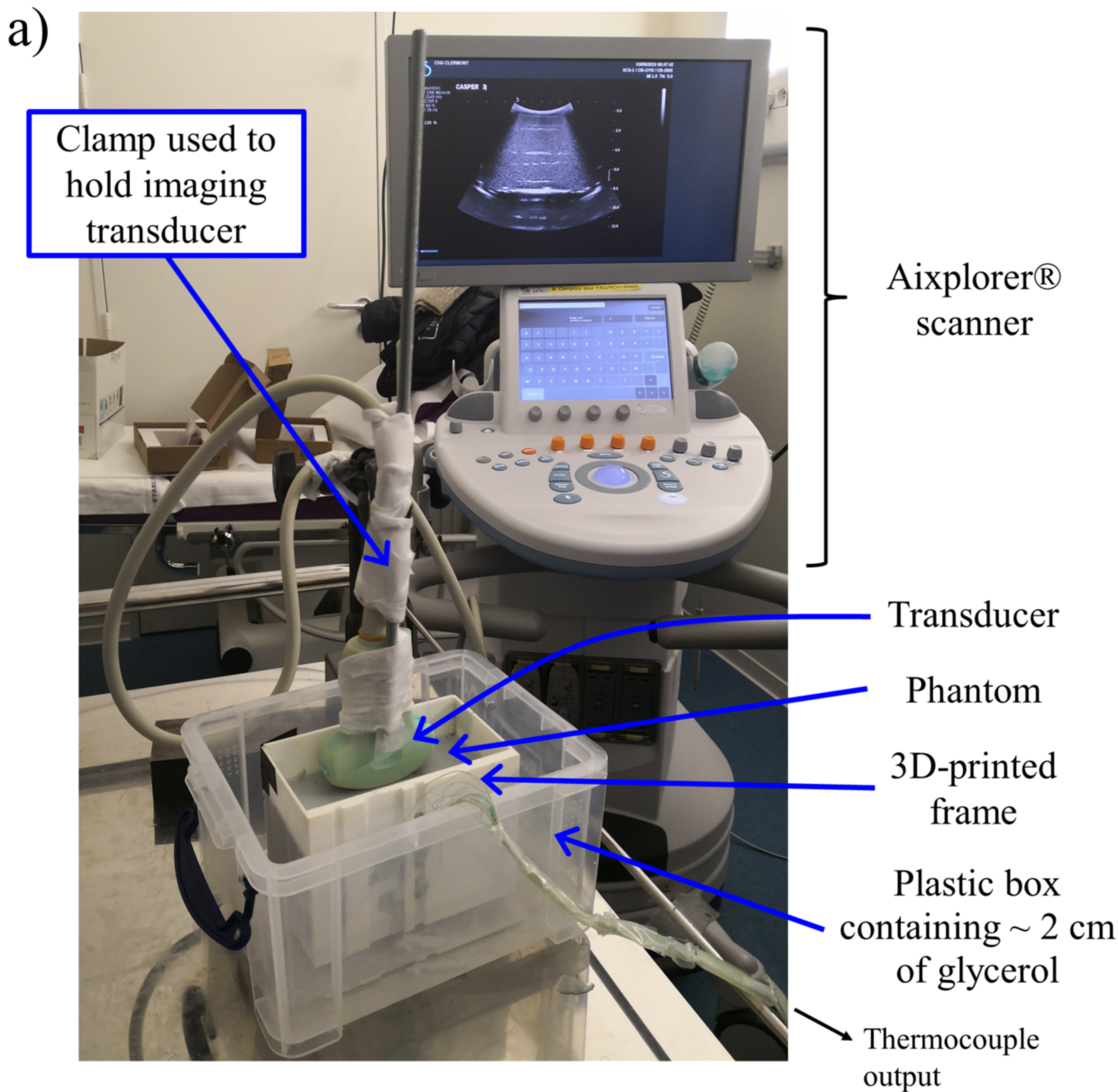


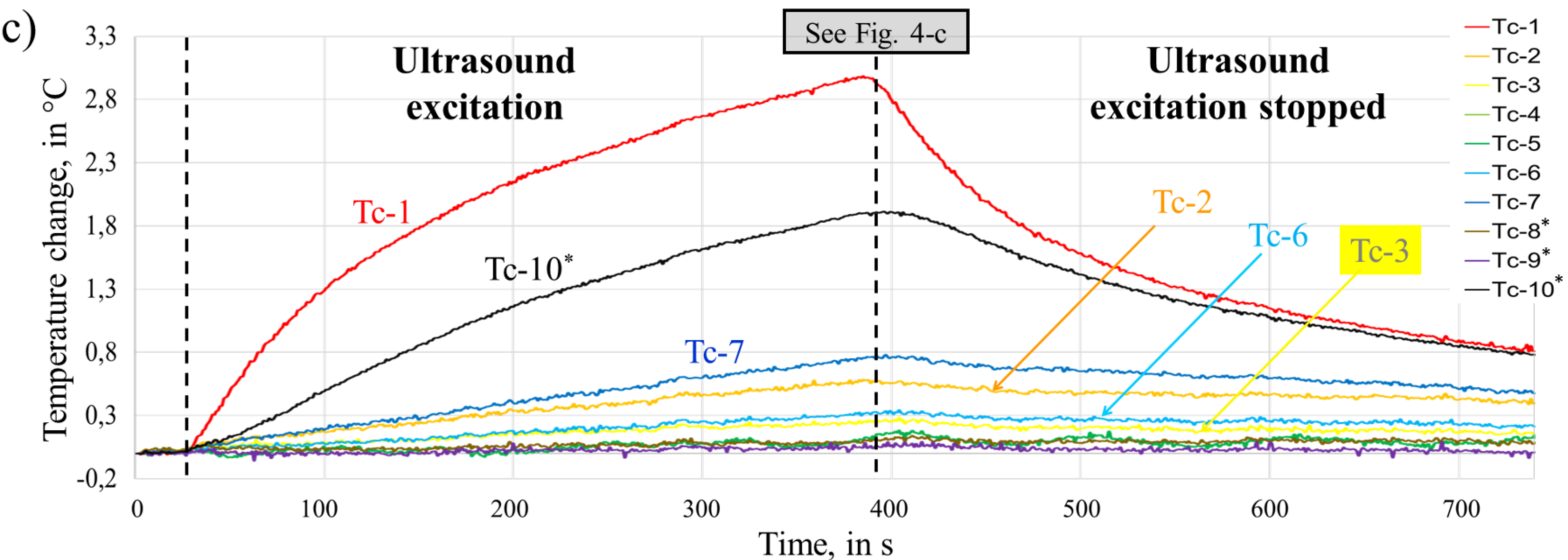
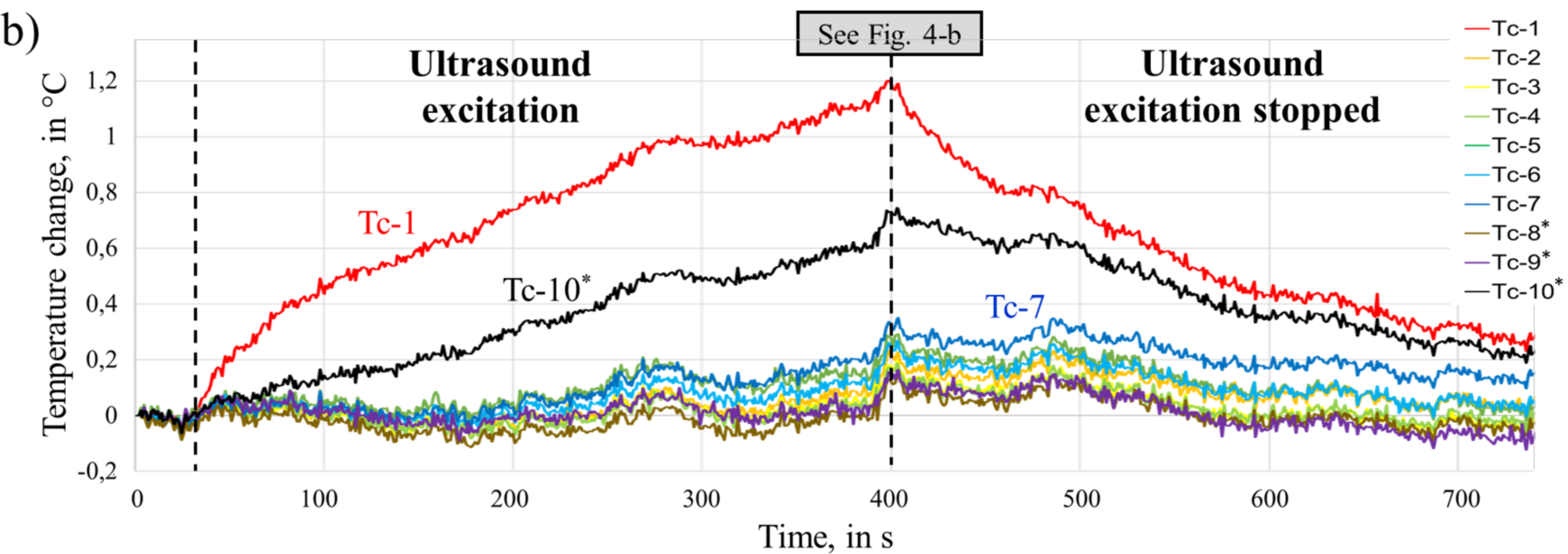
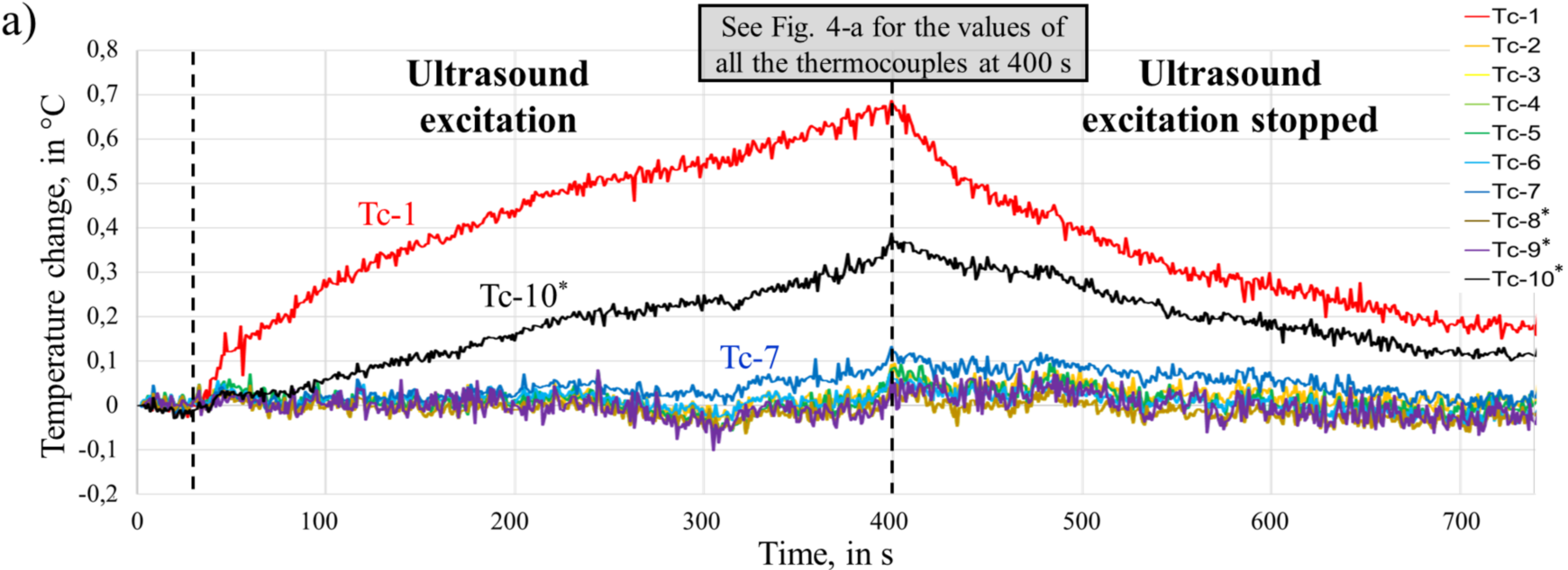
c)



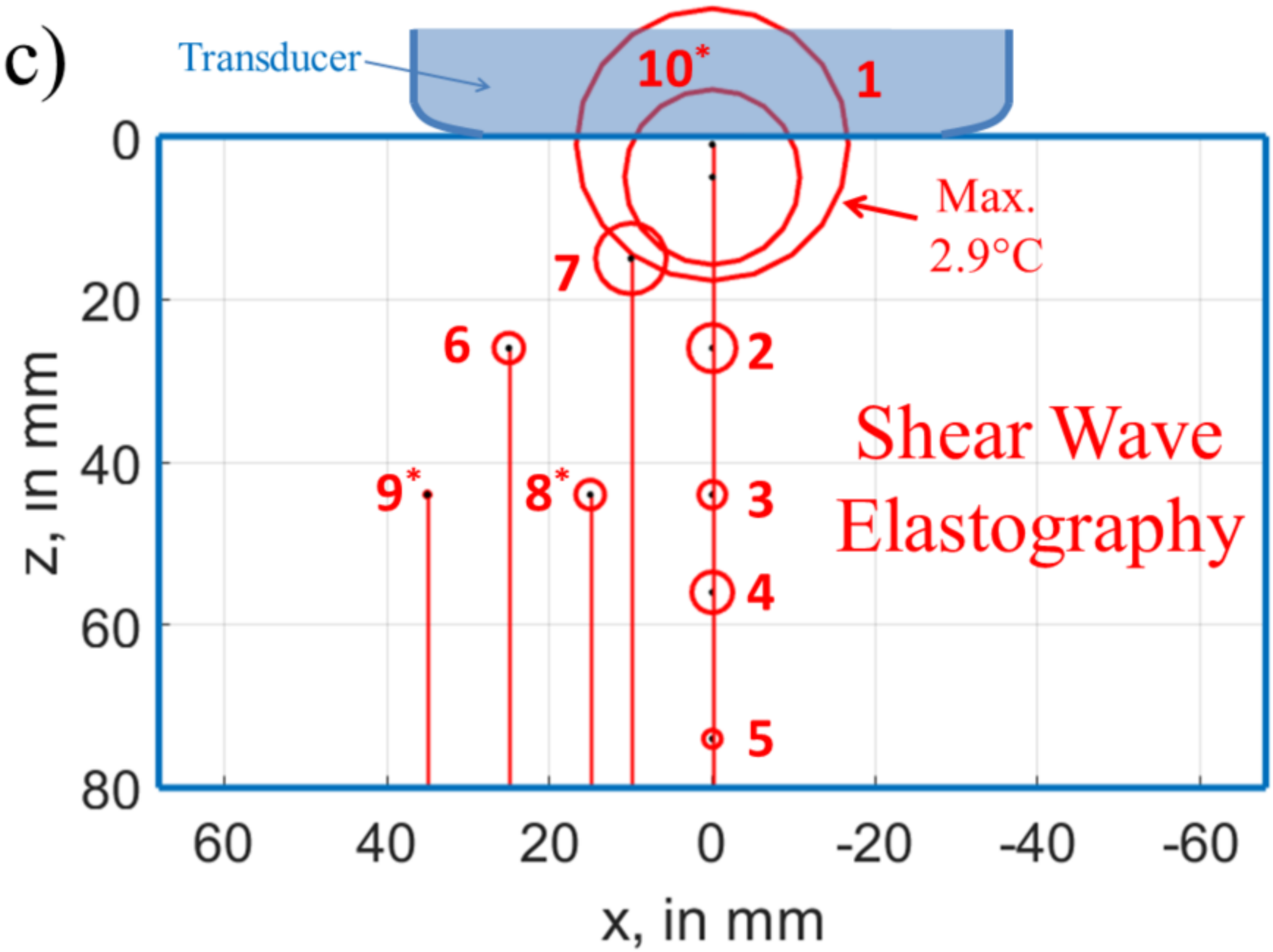
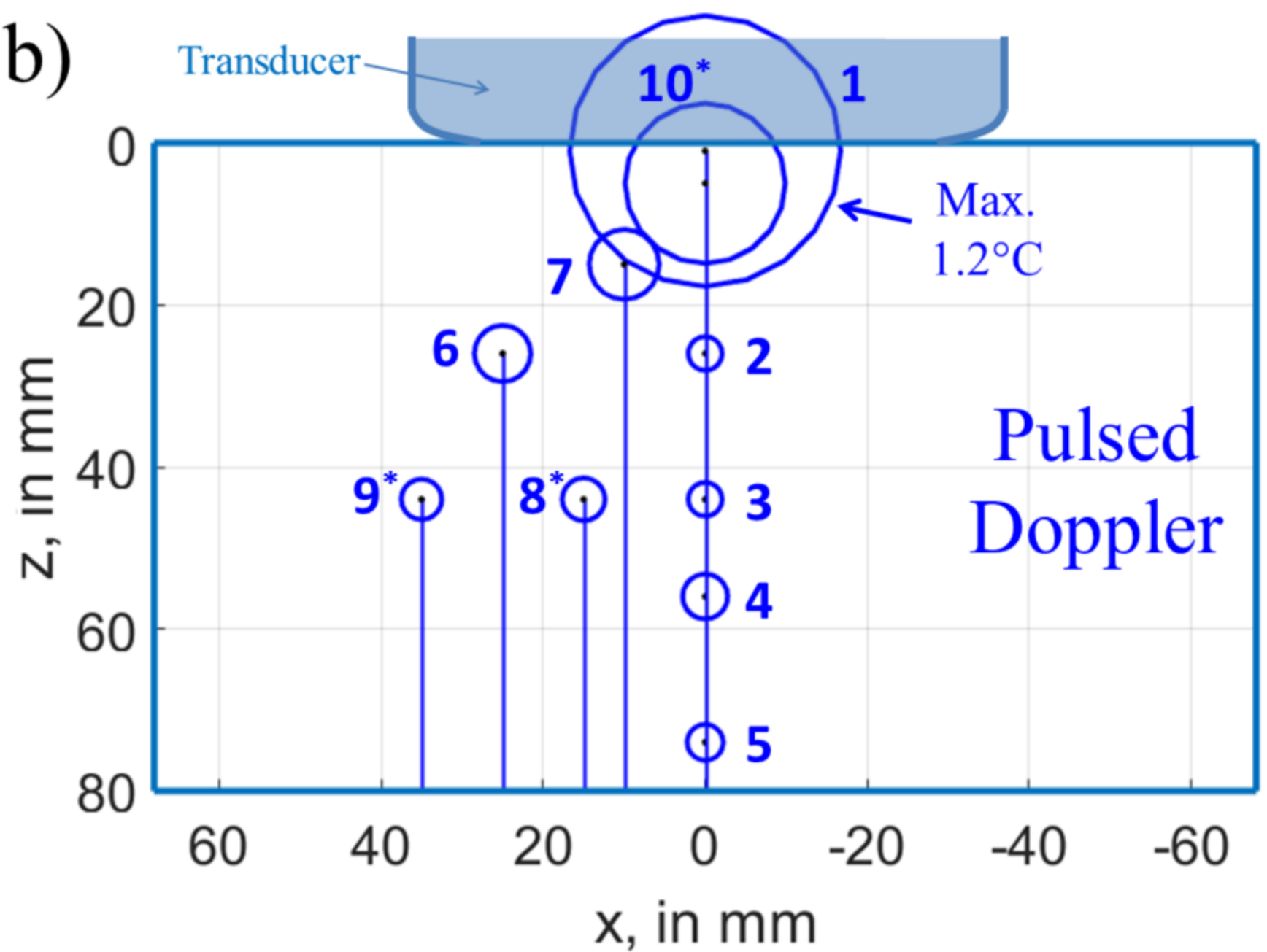
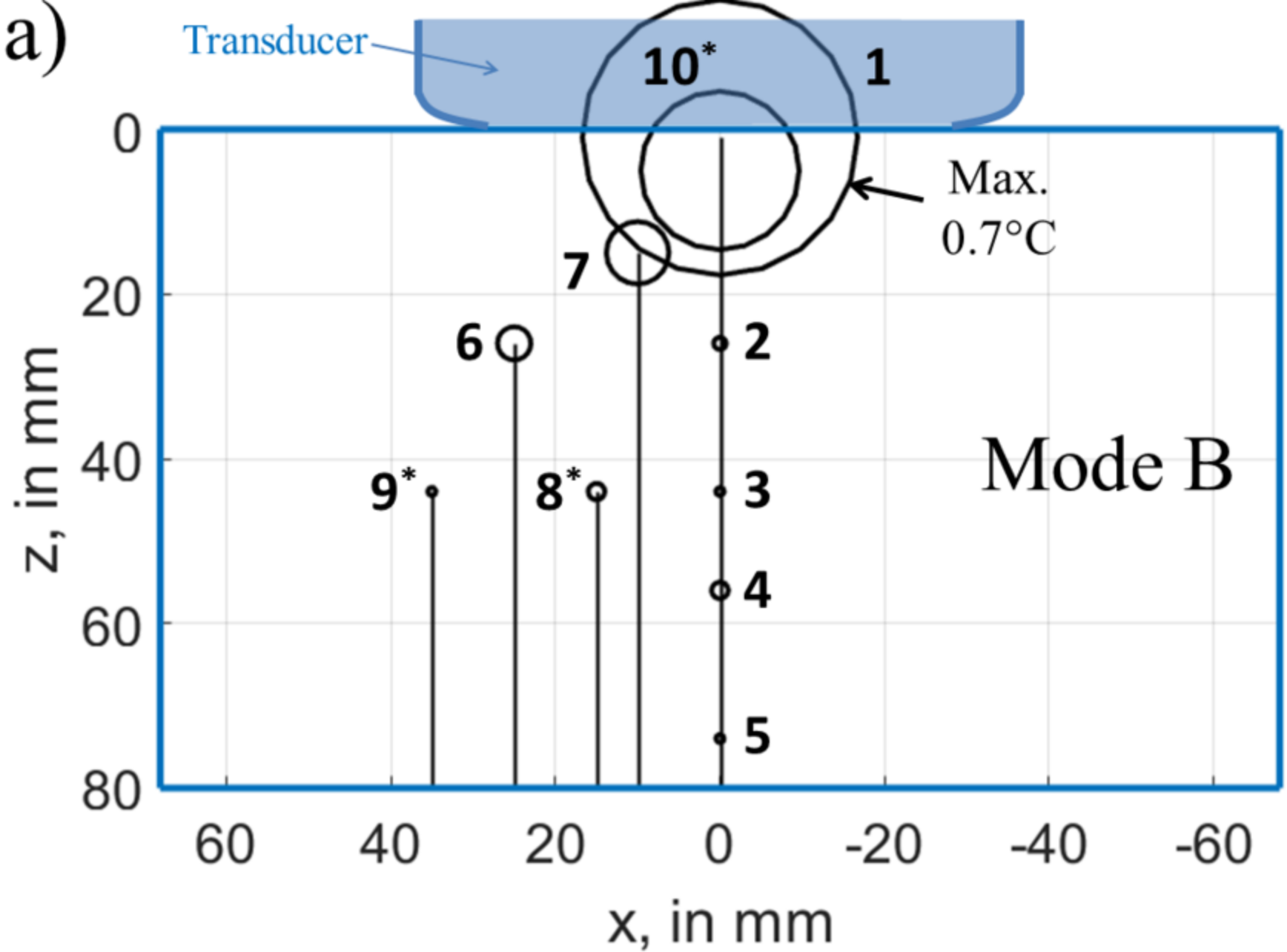
e)

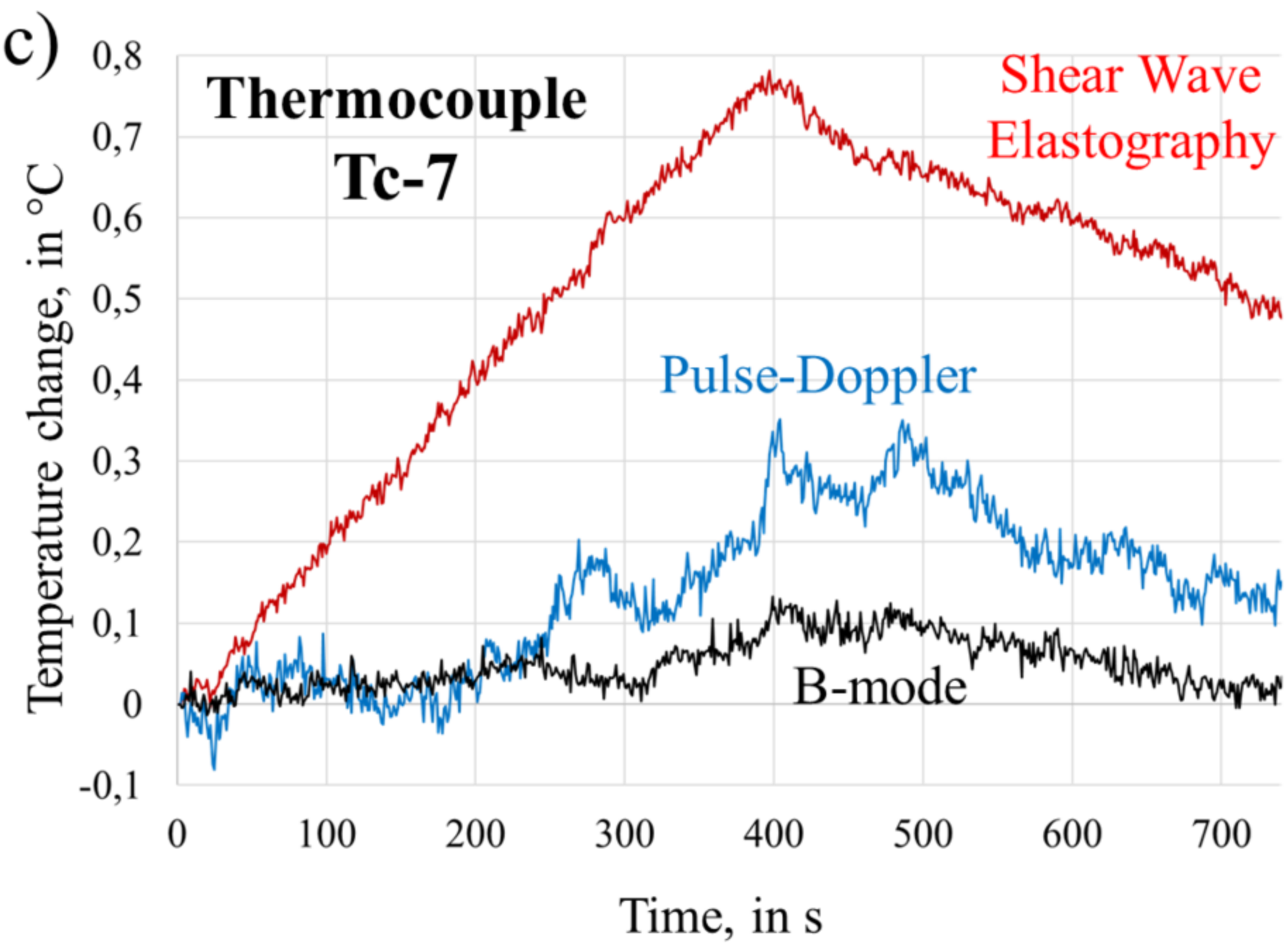
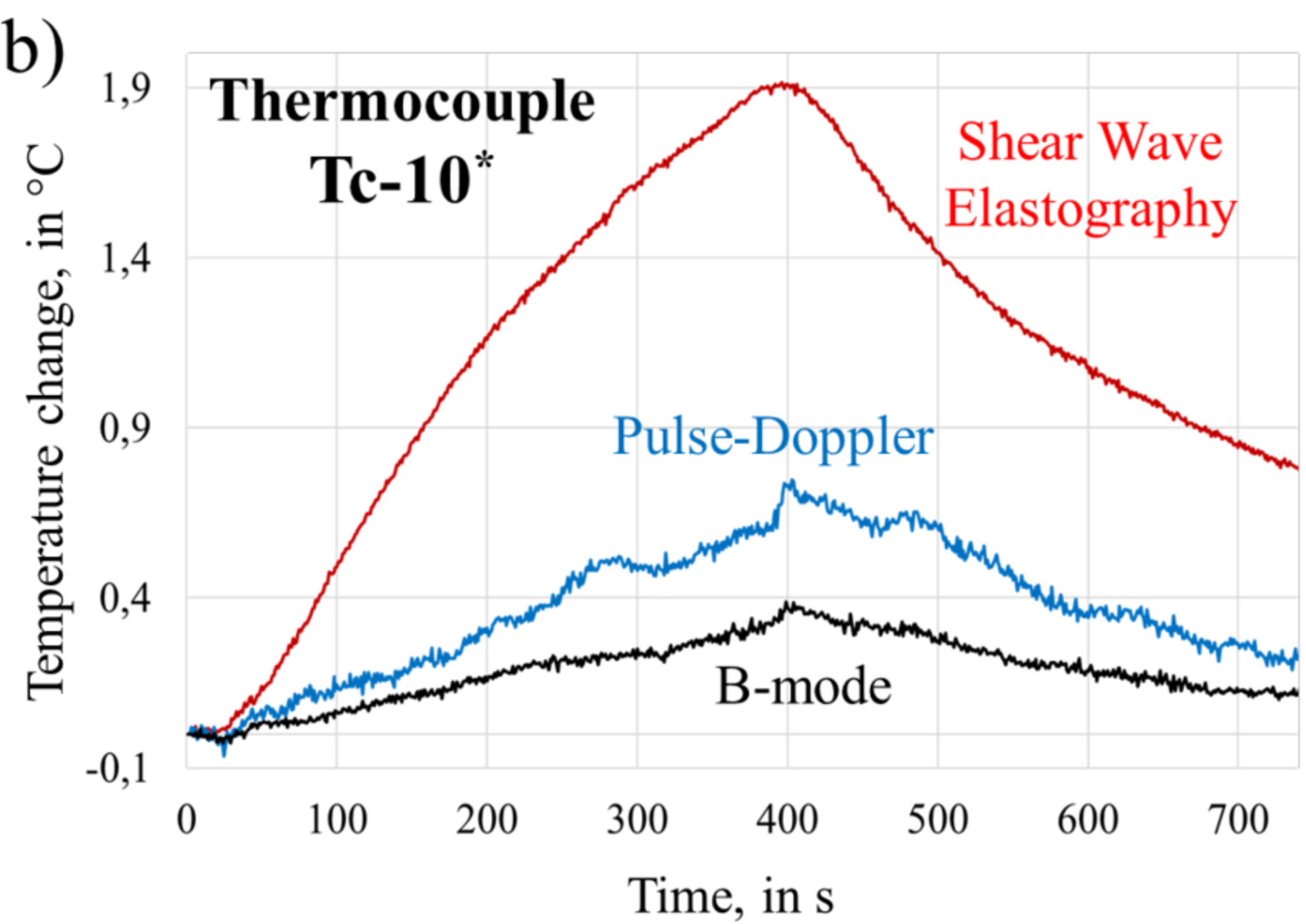
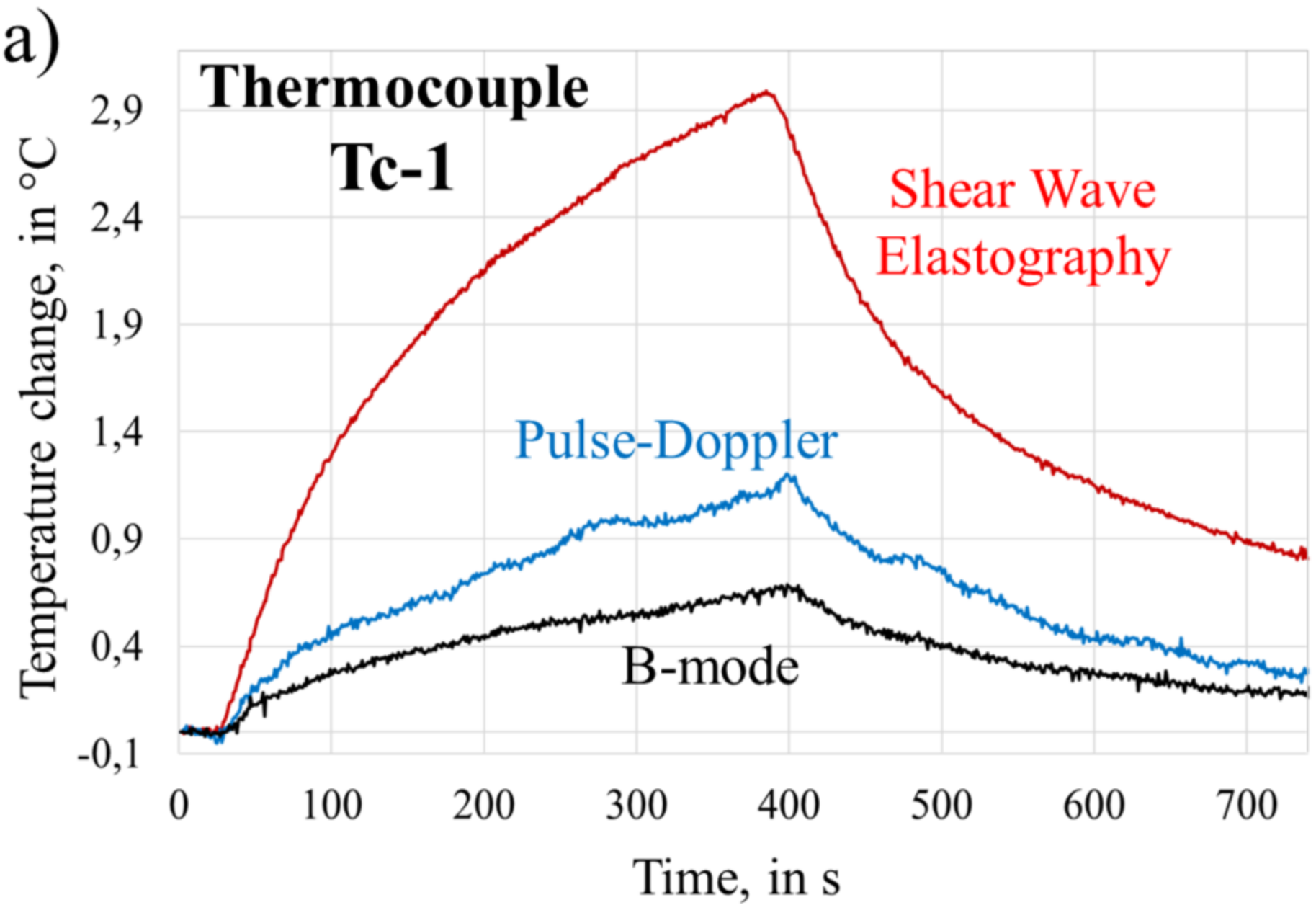












**Table 1.** Coordinates (in mm) of the ten thermocouples used to track the temperature change due to ultrasound excitation. The origin of the coordinates system is shown in Fig. 1-d. An asterisk is used to specify the thermocouples located beyond the imaging plane (which is at  $y = 0$  mm).

	Tc-1	Tc-2	Tc-3	Tc-4	Tc-5	Tc-6	Tc-7	Tc-8*	Tc-9*	Tc-10*
$x$	0	0	0	0	0	25	10	15	35	0
$y$	0	0	0	0	0	0	0	10	13	10
$z$	1	26	44	56	74	26	15	44	44	5

**Table 2.** Scanner settings for the three ultrasound modes used: B-mode, Pulse-Doppler (PD) and Shear Wave Elastography (SWE).

<b>Parameters</b> (OB-GYN GenOB preset)	<b>B-mode</b>	<b>PD</b>	<b>SWE</b>
<b>Total depth</b>	80 mm	22 mm	80 mm
<b>B-mode focal zone</b>	10 – 40 mm	22 mm	25 – 40 mm
<b>Tissuetuner</b> (Speed of sound used to transmit and receive beamforming)	1540 m/s	1540 m/s	1540 m/s
<b>SWE Opt</b> (Res, Std, Pen) for the optimization of elastography resolution and penetration	N/A	N/A	Standard
<b>SWE box geometry</b>	N/A	N/A	Top width: 43.9 mm Bottom width: 63.2 mm Height: 30.8 mm Top depth: 6.7 mm
<b>MI</b> (Mechanical Index)	1.2	1	1.5
<b>T<b>ib</b></b> (Thermal Index bone)	0	0	1.6
<b>T<b>Is</b></b> (Thermal Index soft tissue)	0	0	1.4