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Testing of a HIFU probe for the treatment of superficial venous insufficiency by using MRI

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Abstract. **A new High Intensity Focused Ultrasound (HIFU) probe has been designed and tested by using MRI. The probe is intended to be used by physicians to correct valvular dysfunction in the saphenous vein, which is known to be the cause of superficial venous insufficiency (SVI) and varicose veins. Treating SVI with HIFU is possible, since venous tissue undergoes localized partial shrinkage when subjected to HIFU. In vitro experiments have demonstrated that diameter shrinkage should be sufficient to restore valvular function, as is done in the more aggressive approach known as external valvuloplasty. Numerical simulations and optimization have led to a probe design with two HIFU elements that focus sound uniformly over a line of length 7 mm, at a depth of 15 mm from the skin. A prototype of the probe has been constructed, with a holder that provides space for an MRI-imaging antenna. The probe has been tested by measuring pressure and temperature fields. Results are in good agreement with those predicted by an analytical approach and numerical simulations.**

I. Introduction

Superficial venous insufficiency (SVI) is the most widespread form of venous disease. In most cases, SVI is caused by high pressure in the venous trunk of the grand saphenous vein (GSV). Varicose veins in the lower limbs become a visible consequence of SVI, when normal superficial veins dilate so widely that the thin flaps of venous valves no longer meet in the midline. Modern techniques of correction of the SVI include definitive endovenous occlusion of the GSV by radiofrequency or laser [1], where the collagenous structure of the vein tissue is shrunk by raising the temperature of the vein wall up to 85°C. Less aggressive techniques, such as external valvuloplasty, attempt instead to correct the dysfunctional valves of the GSV by stretching the vein wall and allowing valve flaps to meet again in the middle with the insertion of a plastic ring [2].

In a previous study [3, 4], we proposed an extracorporeal HIFU device to correct valvular dysfunction on the GSV. We showed that localized heating on the perimeter of the valve zone induced a limited contraction of the venous tissue, and we hypothesized that this would correct the dilatation causing valvular dysfunction. Our hypothesis was formulated based on the conclusions reached by endovenous approaches, which have shown that venous tissue responds to heat by a contraction. It is also based on clinical evidence, provided by external valvuloplasty, that a compression of the venous wall can restore the valvular function.

We propose to induce therapeutic effects, as in external valvuloplasty, with an extracorporeal probe. We have named the technique External Ultrasonic Valvuloplasty (EUV). With this probe, it will be possible to treat patients non-invasively in a physician's office.

In the present study, a new HIFU probe is presented and tested. Pressure and temperature fields obtained experimentally are compared with those predicted by numerical simulations.

I. Feasibility Study

An in vitro feasibility study was performed on twenty segments of human saphenous vein [4]. In this study, a spherical probe was used to create two 9 mm-long exposure regions on the vein wall in each segment. The focal point of the sound field was moved mechanically along the vein. Different combinations of in situ acoustic intensity and sound source speeds were tested. Histological analysis verified the absence of vein rupture, vein perforation and tissue carbonization after ultrasound exposure.

The results of this work show that HIFU causes not only limited contraction of the vein but also a hardening effect on the venous wall. The hardening recreates the therapeutic effect of external valvuloplasty, our reference method.

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I. Probe Design

A new HIFU probe, suitable for EUV, has been designed [5]. The probe is MRI-compatible, for testing purposes only. In the actual clinical configuration of the probe, the imaging device will be ultrasound based, not MRI based. Figure 1 shows the principle of the probe. It is composed of two HIFU elements with an open space between them. Sound is focused on a line between the two elements. The open space can be used to place either a US high-resolution device, or an MRI-imaging antenna, to visualize in real time the transverse plane at the center of the focusing line.

The surface of the HIFU elements was calculated to ensure a homogenous pressure level on the focusing line, of sufficient intensity to produce localized heating of the venous wall. Figure 2 shows a diagram of the target zones.

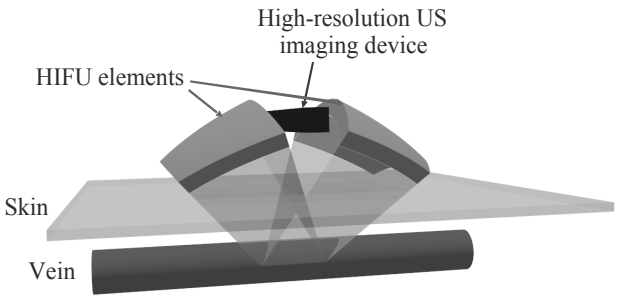

FIGURE 1. Diagram of HIFU probe for the EUV.

We assume that two heated regions on the venous wall will shrink the tissue sufficiently to compensate for the vein dilatation. The two regions are located on the wall at opposite ends of a diameter in a plane parallel to the skin surface. From Figure 2, these regions can be described as follows: length of 7 mm, height of 3 mm, and width of 1 mm. The depth from the skin surface to the center of the target regions is between 10 and 15 mm.

The shape of the active surface was calculated based on an optimization procedure. Constraints were the specifications of the target zone and the positioning of the imaging device.

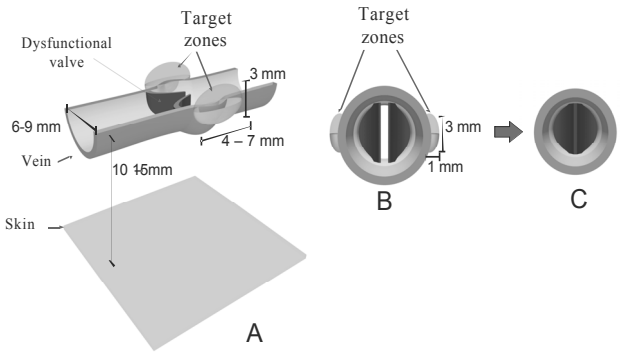

FIGURE 2. Diagram of the target zones for the EUV. The target zones cover the insertion length of valves in the GSV, which is known to be between 4 and 7 mm (A). Two target zones, of 3-mm height and 1-mm width (A and B), are proposed to correct valvular dysfunction (C).

The operating frequency of the probe was set at 3 MHz. Convergence of sound at the focal line was validated by calculating the pressure distribution with the Rayleigh integral, where tissue was considered to be fat (attenuation of 9 $Np \cdot m^{-1} \cdot MHz^{-1}$) [6]. The propagation medium between the probe and the skin was assumed to be water. The optimization approach was repeated until a focusing line at –3dB was obtained, and the specifications of the target zone were met.

A final theoretical validation was performed by calculating the temperature field induced by the probe. The Bio-Heat Transfer Equation was solved [7, 8] with a HIFU shot of 3-s duration and a spatial-average acoustical intensity (I_{SA}) at the focal line of 870 W/cm^2.

Figure 3 shows a representation of the HIFU surface, which is described by a third-order equation. This geometry allows us to meet the required specifications of the target zone. The probe is compact, and leaves space for a 16-mm width imaging device at a distance of 10-mm from the skin surface. The total surface of the HIFU elements is 37.2 cm^2.

A model of the HIFU probe, including its holder, was made by stereo-lithography. The model was

used to perform a compatibility test with a commercially available imaging device (HDI 5000 with a 12-MHz linear array, Philips, Sweden).

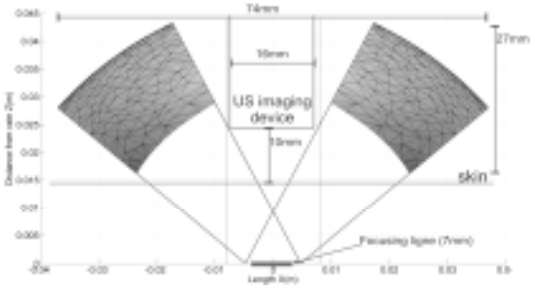

FIGURE 3. Representation of the HIFU surface for the EUV. The HIFU probe has a maximum length of 74 mm, a height of 27 mm and a maximum width (not shown) of 72 mm.

The probe was designed in collaboration with Theraclion (Paris, France), a sound therapy company, and Imasonic (Besançon, France), a transducer company. The probe holder and imaging device are shown in Figure 4. The lower part receives the HIFU elements. The upper part is made of two symmetrical shells that can be fastened to each other by clipping. The figure shows only the back shell. Inside the two shells, the imaging device is inserted. Figure 4 shows in the upper left the connection with the cooling system. Power adaptation is located in the rectangular slot at the front of the figure.

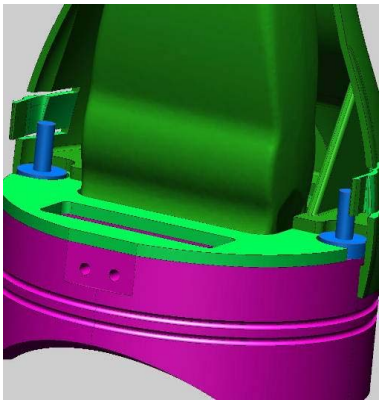

FIGURE 4. 3D prototype of the HIFU probe for the EUV for future clinical applications. It includes a commercially available imaging device (HDI 5000 with a 12-MHz linear array , Philips, Sweden).

I. Pressure And Temperature Fields

Figure 5 shows the pressure field distribution produced by the probe and the tissue temperature after a 3-s HIFU shot. The constraints on the target zones (Figure 2) are well satisfied.

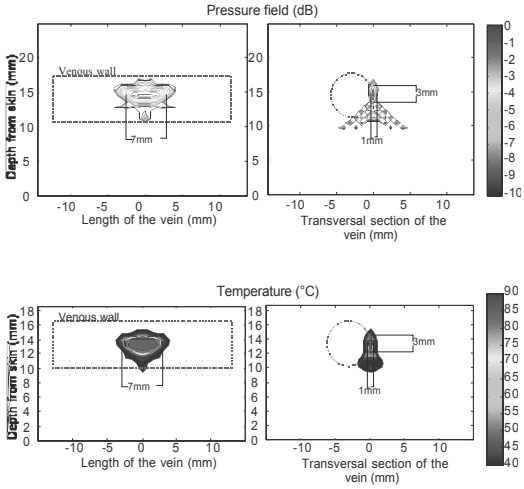

FIGURE 5. Pressure distribution in tissue produced with the HIFU probe (above) and temperature rise (below) after a 3-s HIFU shot. Operating frequency was 3 MHz. Intensity I_{SA} at the surface of the HIFU probe was 0.64 W/cm^2. Tissue was modeled as fat (attenuation of 9 Np·m^{-1}·MHz^{-1} and perfusion of 0.55 kg·m^{-3}·s^{-1}) [5]. Additional heat dissipation due to perfusion in the vein is not taken into account, since blood flow in the vein is not allowed during shooting.

The probe can thus be characterized by measuring the temperature field by MRI, and the firing parameters (duration, power level) can be optimized. To this effect, we use proton resonance frequency (PRF)-based fast magnetic resonance thermometry. This allows us to characterize experimentally the acoustic field profile by means of the temperature map.

Resolution in temperature is 0.5 C. Temporal resolution is approximately 2 s, and spatial resolution is 0.5 mm. Short sonication is necessary in order to avoid thermal diffusion effects on the temperature map.

An MRI image of the active elements of the probe are shown in Figure 6. The two diagrams in Figure 7 show the pressure distribution in two

perpendicular planes, respectively. There is good agreement with the predictions of Figure 5. The interference pattern can be explained by a slight misalignment between the two active surfaces of the probe. These spatial fluctuations of the pressure field will be smoothed out by thermal diffusion in tissue. An example of relative temperature monitoring is shown in Figure 8. The temperature at the focus increases by 50°C after approximately 100 seconds.

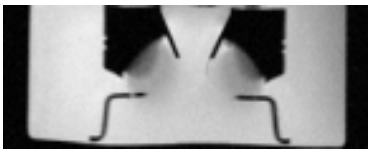

FIGURE 6. MRI image of the active elements of the probe showing passive MRI compatibility.

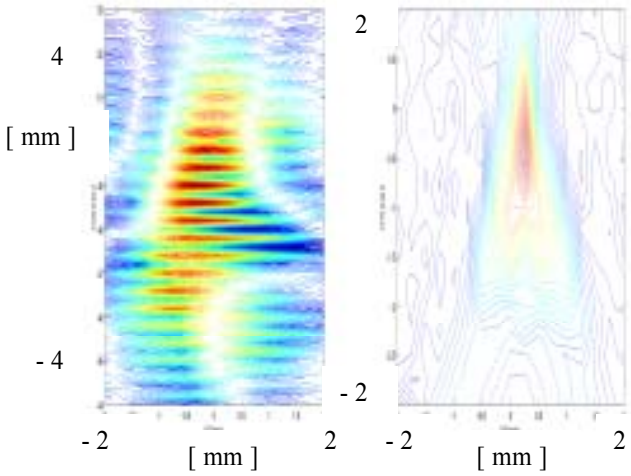

FIGURE 7. Experimental pressure distribution in water measured with a hydrophone. Operating frequency was 3 MHz.

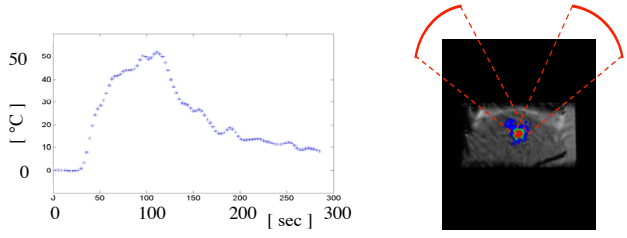

FIGURE 8. Relative temperature distribution in a fresh meat sample after a 60-s HIFU shot. Intensity I_{SA} at the surface of the probe was 0.64 W/cm^2. Blue, green, and red levels indicate, respectively, relative increases of 10, 20, 30 °C.

II. Conclusions

A new real-time imaging HIFU probe has been presented. This probe, which consists of two HIFU elements, is MRI-compatible and has been tested using MRI instrumentation. It is intended to be used in External Ultrasonic Valvuloplasty. The probe holder allows us to insert either a commercially available US-imaging device or an MRI-imaging antenna.

Pressure fields in water have been measured by using a hydrophone. The results confirm the validity of the analytical model. Temperature fields in fresh meat samples have been measured by using PRF-based fast magnetic resonance thermometry. The temperature increase at the focus has been found to be 50°C. Clinical applications of External Ultrasound Valvuloplasty are envisioned in the near future, with a probe guided electronically by an ultrasound imaging device.

Acknowledgements

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III. References

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