Simulation-Led Design to Optimize Innovative Acoustic Phantom and Ice Catheter Calibration Method

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Abstract

Intracardiac Echocardiography (ICE) ultrasound imaging of cardiac cavities is a known diagnostic and monitoring technique, used during interventional cardiology and electrophysiology procedures.
The SOUNDSTAR® Catheter, manufactured by Biosense Webster, Inc., enables locating the position and registration between ultrasound images and magnetic maps of cardiac cavities. This catheter comprises both an acoustic imaging device, and a magnetic tracking sensor, each with its own coordinate system. To correlate locations measured using both sensors, a registration (calibration) procedure is required to produce reliable images and anatomical structure locations.
Most ultrasound calibration techniques known today are intended for external probes, and are not adapted to the characteristics of catheters. The required high-level operator skills and time-consuming procedures are the main disadvantages of such techniques.
Acoustic simulations, created with COMSOL Multiphysics® modeling software, were performed to optimize innovative phantom design and calibration method, by adapting them to catheter characteristics. Both transient and frequency domain interfaces of the Pressure-Acoustic module were used to analyze pressure field variation for propagation of acoustic plane waves in the medium, and their reflections from an acoustic target back into the transmission transducer.
The analysis was intended for understanding the performance and "acoustic signature" (also known as echo) of multiple tested targets, with the aim of improving target ultrasound imaging, by developing an optimal "diffuse reflector" — causing incident waves to scatter in all directions, providing sufficient echo, and making it automatically identified in ultrasound images.
Target comparisons were made between various parameters, such as geometrical shape, size, distance from the transducer, spatial distribution, and intersection with the ultrasound fan. The study included analysis of wave propagation and interference in the near and far fields, by means of reflectivity (or echo strength), RADAR cross-section, and reflection directivity — depending on in-plane transmitted wave orientation.
The study shows that diffuse targets demonstrate better performance than specular targets for the intended purpose, because rounded surfaces always have some point of the surface normal to the wave source. The study also shows that the smaller the target size; the lower the echo, and the better the image resolution (as assessed by point-spread function).
Trade-off relations have been shown between target size, orientation dependency, and image resolution: large targets (>10λ, where λ is the wavelength) provide higher echo, and

demonstrate less orientation dependency than small targets (in the order of λ). On the other hand, the smaller the target; the better the image resolution.
In conclusion, a diffuse target with a rounded surface and a small enough diameter (with respect to λ), made of a hard-acoustic material with a rough surface and perpendicular (relative to the ultrasound fan) was found to be optimal. Each selected target is designed to appear as a dot in ultrasound images, enabling automatic target identification, simplifying the calibration procedure, and eliminating user dependency.
A few validation prototypes with different parameters were produced that were based on the study results, and through which the conclusions were proven.
This study led to the development of an innovative calibration technique that yields significant improvements in the calibration process of ICE catheters, in addition to a new patent application.

Figures used in the abstract

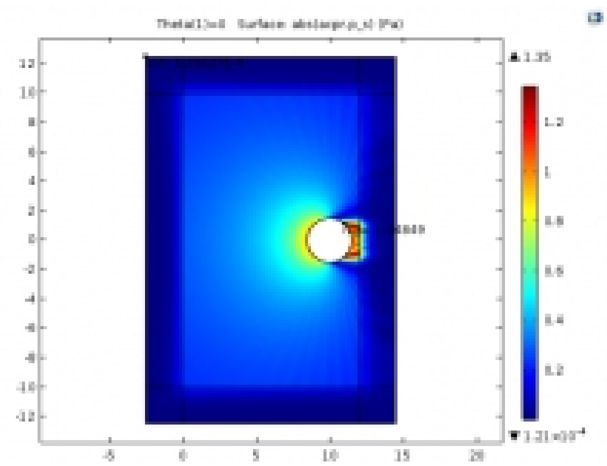

Figure 1: Absolute pressure field of rounded surface target