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Combining 3D SONAR with High Resolution Imaging to Improve Vision in Atrial Fibrillation Ablation

Stephanie Chang

TMS School

ABSTRACT

Real-time, accurate imaging of improperly functioning tissue that causes atrial fibrillation (AF) is essential for successful catheter ablation procedures. Ablation procedures and success rates may be improved by overlaying intracardiac echocardiography with high resolution cardiac imaging. Data extracted from previous research reports that current pharmacological agents do not address the principal cause of AF. Unlike medication, catheter ablation resolves the issue by treating AF's source. Therefore, catheter ablation is the better alternative. However, while catheter ablation is preferable to medication, the detail and accuracy of anatomical visualizations used to guide the catheter can be inconsistent. While real time guidance technology updates, the visibility quality is limited. However, detailed preliminary imaging does not accurately reflect the latest changes. This paper discusses the current limitations of catheter ablation and proposes real-time three-dimensional Sound Navigation and Ranging (SONAR) imaging paired with high-resolution cardiac Magnetic Resonance Imaging (MRI) as a novel tool to improve live-imaging localizations and resolution for cardiac ablation procedures.

Atrial Fibrillation

Atrial fibrillation (AF) is a type of heart arrhythmia commonly found in clinical practice. It has a prevalence of 2.7-6.1 million cases in the USA and is expected to rise to 5.6-12 million by 2050.[1] AF is the rapid, irregular, and unpredictable electrical activation of the atrial tissue resulting in highly variable ventricular rates. Typically, the sinoatrial node (located in the right atrium) generates electrical signals that cause the right and left atriums to contract. When the heart's tissue or electrical signaling is damaged, the atria quivers, or fibrillates. The disorganized signals reduce contraction efficiency as the atria are uncoordinated with the ventricles, reducing blood flow to the rest of the body.[2] Some patients do not experience symptoms while others may experience heart palpitations, lightheadedness, and extreme fatigue. In addition to the severe effect on a patient's quality of life, people with AF have a higher risk of stroke and mortality. The weakened contraction of the atria due to AF causes slowed blood movement, which can lead to blood clot formation within the heart; therefore, the risk of stroke is higher in patients with AF. These blood clots can potentially travel to the brain and cause stroke - resulting in disability or death.[14]

Once the contraction of the atria becomes irregular, blood does not flow properly from the atria to the ventricles. AF may occur in brief episodes or as a chronic condition[2] and can be categorized as paroxysmal, reverts to sinus rhythm within 7 days; persistent, lasts more than 7 days; long-standing persistent, lasts for more than 12 months; or permanent AF.[3] Permanent AF is when a patient decides to not to pursue further action to restore or maintain sinus rhythm.[3] Electrical and morphological remodeling occurs when molecular, cellular, and/or interstitial changes alter the size, mass, geometry and function of the heart, which can be associated with AF promotion.[4, 5]

AF is a disease with genetic complexity making it difficult to predict and treat. The Genome-wide association studies identified common genetic variants at nine different chromosomal loci significantly associated with AF. For example, the cardiac sodium (INa) channel, encoded by the SCN5A, generates the upstroke of the atrial action potential and is associated with AF. Mutations in SCN5A have been linked to AF, but also to ventricular arrhythmias, progressive cardiac conduction disease, and overlap syndromes with mixed arrhythmia phenotypes.[2] AF is therefore a complex disease making it difficult to treat.

Evaluation of Current Treatments

Antiarrhythmics are used to control the atrial rate in AF. These medications are classified according to the main mechanism of action, though several agents retain properties from multiple classes.[6] The classes include Class I: Sodium-channel blockers such as Quinidine[7]; Class II: Beta-blockers such as atenolol[8]; Class III: Potassium-channel blockers such as amiodarone[9]; Class IV: Calcium-channel blockers such as amlodipine[10], and miscellaneous antiarrhythmics such as adenosine[11] that can fall into several categories. Despite being widely used, antiarrhythmics have debatable results with class I and IIIA agents only being able to terminate about 50% of AF episodes.[12] Moreover, antiarrhythmics were all also associated with some degree of proarrhythmic potential. While suppressing arrhythmias with the medications, the drugs themselves can lead to other arrhythmias which may be more dangerous. For example, Class IA - such as quinidine, procainamide, and disopyramide - effectively prolong the QT interval, increasing the risk of ventricular tachycardia.[13]

Due to the debatable results of antiarrhythmic medication, there should be alternative lines of treatment such as catheter ablation. Anticoagulants, or blood thinners, are medications that prevent blood clots which lower the risk of stroke. The weakened contraction of the atria due to AF causes slowed blood movement, which can lead to blood clot formation within the heart; therefore the risk of stroke is higher in patients with AF. These blood clots can potentially travel to the brain causing stroke - resulting in disability or death.[14] Therefore, blood thinners are only provided to high stroke risk patients.

Current Catheter Ablation Success Rate

Catheter ablation is an increasingly offered treatment option to restore sinus rhythm and improve long-term clinical outcomes to patients suffering from AF. Catheter ablation uses heat to strategically destroy abnormal tissue to block irregular electrical signals using thin tubes, known as catheters, inserted into veins or arteries[15]. The first multicentre trial to compare catheter ablation and antiarrhythmic drugs as first-line therapy for persistent AF reported that ablation resulted in more effective maintenance of sinus rhythm and better quality of life.[15] However, despite dramatic improvements in techniques over the last two decades, the short and long-term success rate of catheter ablation remains modest.[16] According to a study analyzing catheter ablation success rates treating AF patients with single-procedure outcomes, paroxysmal AF ablation studies showed, unadjusted success rate summary estimates ranged from 73.1% in 2003 to 77.1% in 2016 (increasing 0.9%/year). In non-paroxysmal AF ablation studies, unadjusted success rate summary estimates ranged from 70.0% in 2010 to 64.3% in 2016 (increasing 1.1%/year). Though after controlling for study design and patient demographics, the rate of improvement in success rate summary estimate increased 1.6%/year in paroxysmal studies.[17] Therefore, increased customization depending on individualized patient needs remain crucial for meaningful improvements of catheter ablation.

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Preliminary Cardiac Imaging (CT/MR) Integration with 3-Dimensional Intracardiac Echocardiography

Mapping and visualizing the anatomic relationship of the left atrium and pulmonary veins is vital for efficiently guiding successful AF ablation. Pre-procedure X-ray computed tomography (CT) and magnetic resonance imaging (MRI) angiography are commonly used to visualize the complex construction and relationship of the left atrium, pulmonary veins, and surrounding structures, therefore posing a guide to ablation lesion placement specific to the patient's anatomy and location of the electrophysiological disturbance.[18] Additionally, preprocedural images can also be merged into 3D electroanatomical mapping (EAM) systems to visualize these structures in further detail. However, because of changes in patient position, movement within the chest cavity, and/or cardiac rhythm, the use of CT, MRI, and EAM images obtained pre-procedurally may not accurately reflect the most current cardiac anatomy posing difficulty to guide complex procedures.[19]

Real-time guidance and visualization of cardiac anatomy is critical for procedural efficiency in catheter ablation procedures. Intracardiac echocardiography (ICE), a branch of SONAR technology, is a well-established tool in complex electrophysiological procedures, in particular in AF ablation with a modality that has recently been applied to generate 3D images[20]. Though ICE has the benefit of generating images in real-time, ICE depiction of 3D atrial anatomy is less detailed than images obtained by CT or MRI, has limited visualization range due to the close distance of the ICE catheter, and relative instability of ICE catheter images[21]. Figure 1[19] depicts a grayscale histogram seen in a muscle ultrasound demonstrating the limited contrast, as healthy versus diseased tissue look virtually alike. Even with an experienced user, the histogram proves limited contrast; therefore ICE has a high margin of error which increases with procedure difficulty. The combination of preliminary cardiac imaging with ICE would allow both detailed imaging of an individual's cardiac anatomy and real-time guidance during the ablation procedure. To aid the issue, algorithms, artificial intelligence, and dedicated muscle visualization systems can be used to help with image interpretation to improve usability.

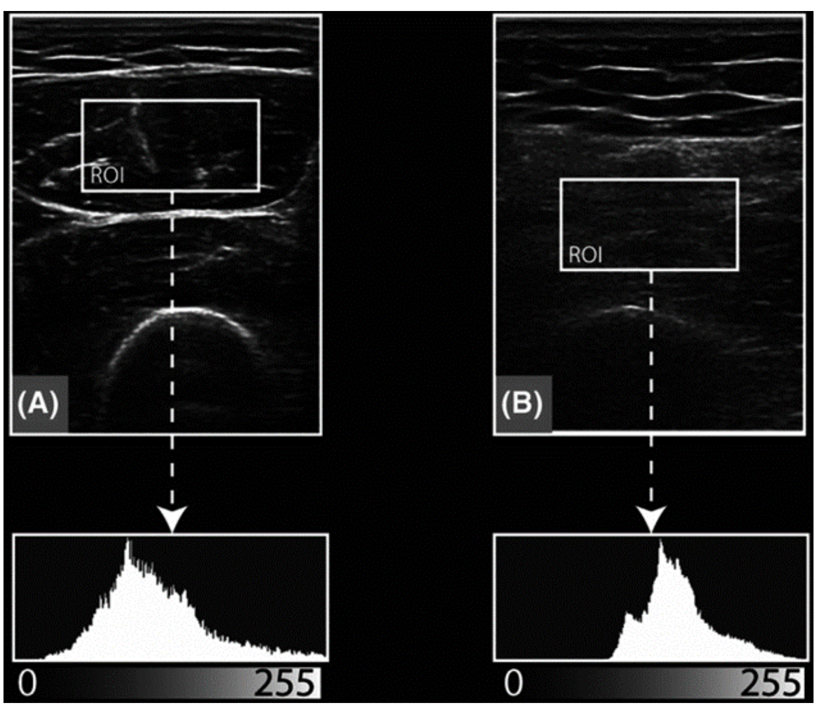

Figure 1. Grayscale histograms (0 = black and 255 = white) in a region of interest (ROI) in a healthy (A) and diseased (B) muscle from a muscle ultrasound (Wijntjes and Van Alfen, 2020[19])

SONAR Technology

SONAR, short for "Sound Navigation and Ranging," is used to explore and map the ocean, as it is able to locate a transducer in relation to surrounding objects. The two types of SONAR are active and passive, with this report focusing on active SONAR to localize the catheter in relation to heart walls.[22] Active SONAR transducers emit an acoustic signal, a "ping," into the water. If an object is in the path of the sound pulse, the sound bounces off the object and returns an "echo" to the SONAR transducer. Moreover, objects can be determined by density: whether they absorb or bounce off said "echo." If the transducer is equipped with the ability to receive signals, it measures the strength of the signal. By determining the time and strength between the emission of the sound pulse and its reception, the transducer can determine the range, orientation, and of the object.[23]

Though it is crucial for an effective ablation procedure, current technologies lack detailed real-time imaging. To overcome these limitations, 3D/360 SONAR technology can provide a 360°, three-dimensional view of surgical tools, surrounding tissue, and organs to provide a more accurate picture. 3D-SONAR is a relatively new SONAR implementation as it has been developing over the past ten years and has only recently become commercially available. Unlike conventional SONAR such as multi-beam and scanning SONAR, which can generate 3D images by scanning and combining data as a post-process, true 3D-SONAR creates 3D data instantaneously and in real-time. A 3D-SONAR image is created by simultaneously forming acoustic beams to fill a 3D volume, as opposed to a narrow fan of beams.[23] SONAR anglers have also been implemented with a 360° range of view. With traditional imaging, anglers have the ability to view SONAR returns directly below and to the side of their boats, but 360 SONAR anglers have an expanded view of the water not only beneath and to the sides but all around.[24] The integration of SONAR into cardiac catheters will allow real-time generation of 3D images and a 360° view range on all axis- expanding the imaging recency, quality, and range. Once paired with preliminary high-resolution imaging, SONAR will allow real-time localization of the catheter in addition to high quality imaging.

Noise Cancellation

Active SONAR has two performance limitations. First, excess noise may occur if the transducer picks up an echo unrelated to the "ping," such as the heartbeat. Second, reverberation may occur when sound persists as a result of repeated reflection or scattering after the sound source has stopped. While an echo is a distinct sound, reverberated sounds are difficult to hear clearly because the reflections repeat. In general, one of these will dominate, enabling their distinction.[25]

Noise canceling monitors the sound around the source preventing the unwanted excess noise or reverberation. Miniature microphones detect outside noise frequencies and emit the exact opposite signal to effectively "cancel out" both sets of sounds once the sound waves collide (Figure 2). If a loudspeaker emits tonal sound, the amplitude and phase of a second speaker can emit pressure directly in front of the first to cancel the pressure in both speakers. The result is that no sound pressure is radiated from a far field but a local sound field exists.[25] Moreover, the heartbeat, even if in fibrillation, is periodic and predictable. Therefore, the recurring fibrillatory sound generated by the heart can be eliminated, reducing error. This strategy would allow the ultrasound to generate images in real time with increased reliability.

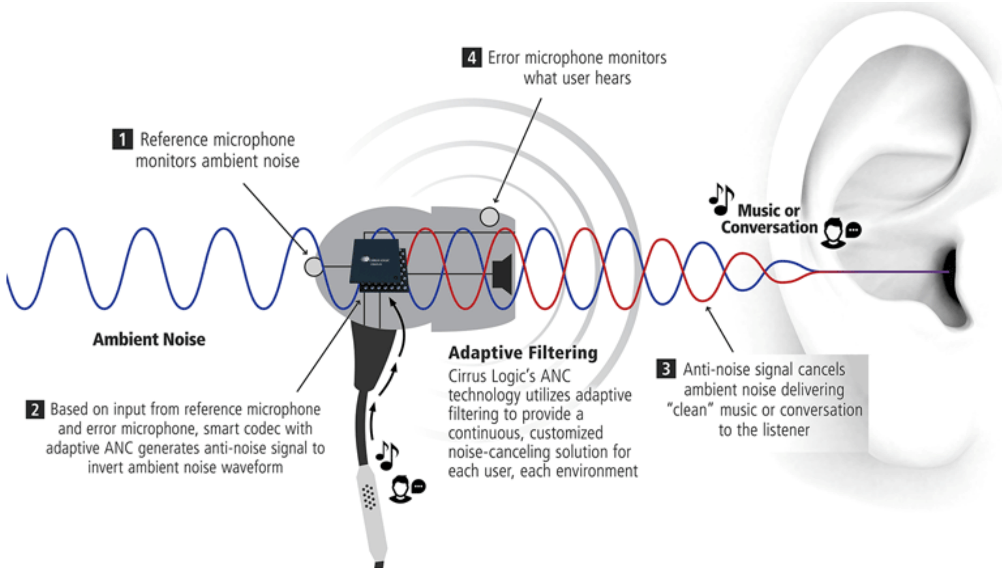

Figure 2. Illustration of Noise Cancellation (Schweber, 2018)[25]

The Current Use of Intraoperative 360°/3D SONAR in Medicine

Real-time 3D image guided visualization has already been used in radiation therapy. For instance, a 360°/3D transvaginal ultrasound system has been used to guide an intraoperative needle during interstitial gynecologic brachytherapy.[26] In cases of radiation therapy, a precise patient-positioning system has been developed through alignment of real-time 3D surface images, captured using a state-of-the-art 3D stereovision system. A surface image is also used as reference, obtained from preliminary treatment planning data. Results from phantom experiments and clinical applications demonstrated the excellent efficacy of <2 minutes as well as the desired accuracy and precision of <1 mm in isocenter shifts and of <1 degree in rotations.[28] The proposal of this paper and this radiation therapy case align with the idea of real-time 360°/3D SONAR paired with preliminary imaging which can improve surgery success and thus improve patient care and outcome. Hence, similar principles can be incorporated into catheters.

The Potential Technology: MRI/CT Overlay onto 360°/3D SONAR Generated Images

A potential combination to increase visualization is to overlay a patient's preliminary medical imaging overlayed onto real-time 3D SONAR during the procedure. First the detailed CT or MRI would be taken as close to the procedure time as possible. Then, during the procedure, the patient's anatomical data can be processed as a simple 2D slice like during an echocardiogram. In Figure 3A, color is mapped to signal strength relative to the transducer.[29] In a potential medical case, loud echos, such as thin tissue, can be mapped as red and quiet echos, such as more sound-absorbing muscle, can be blue. After, depth surrounding the transducer can be mapped. Figure 3B shows a look-down orthographic projection with targets plotted in a 3D space.[29] This can be applicable to find the distance between structures, such as heart walls or valve location, above and below the transducer.

Finally, these data points can be visualized in a 3D space. In Figure 3C, the same data is plotted in 3D, allowing clear navigation in an improved perspective.[29] Again, preliminary imaging can enhance this by linking the data points to the patient's anatomy.

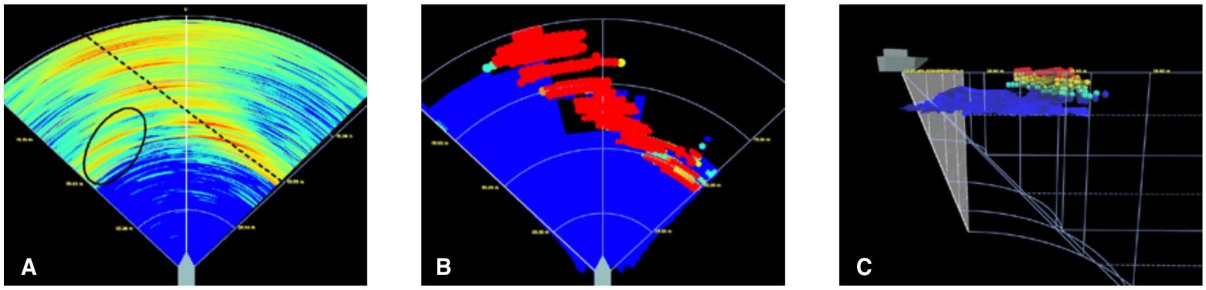

Figure 3. 3D SONAR Development. As shown in Figure 3A, color is mapped to signal strength where red is "loud" and blue is "quiet". There is clearly a feature crossing the field of view at about 45° (noted with the dotted line) as well as another feature or "bright" spot (noted by the oval) (FarSounder, 2014)[29]. Figure 3B: Color is mapped to depth. As noted by the red and blue data points, there is a presence of shallow and deep objects, respectively (FarSounder, 2014)[29]. Figure 3C: The rotated "third person" view, signal strength, and depth combined with this technique allow 3D navigation (FarSounder, 2014)[29].

Conclusion: Paired MRI and SONAR Imaging

Increasing knowledge of the anatomic basis for cardiac arrhythmias and improved catheter ablation tools have increased our ability to cure complex rhythms such as AF. By overlaying a patient's MRI or CT scans onto their 360°/3D SONAR generated images, detailed and real-time images can be created. Preliminary MRI or CT generate highly detailed images of the cardiac anatomy, but have the limitation of not providing the most current structure and rhythms. On the other hand, SONAR technology is able to produce real-time images. With 3D SONAR in addition to MRI or CT, this innovation can provide a 360°, 3D view of anatomy as well as surgical tools for an even more detailed picture. With the current usage of a similar procedure in intraoperative radiation therapy posing desirable results, this method shows promise in improving accuracy and patient outcomes following ablation procedures. By having real-time, detailed imaging during the procedure, the combination of MRI/CT imaging with 360°, 3D SONAR can significantly improve how current ablation is performed to treat AF.

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References

1. Go, A. S., Mozaffarian, D., Roger, V. L., Benjamin, E. J., Berry, J. D., Blaha, M. J., Dai, S., Ford, E. S., Fox, C. S., Franco, S., Fullerton, H. J., Gillespie, C., Hailpern, S. M., Heit, J. A., Howard, V. J., Huffman, M. D., Judd, S. E., Kissela, B. M., Kittner, S. J., & Lackland, D. T. (2014). Heart Disease and Stroke Statistics—2014 Update. Circulation, 129(3). https://doi.org/10.1161/01.cir.0000441139.02102.80
2. Savio-Galimberti, E., & Dawood Darbar. (2014). Atrial Fibrillation and SCN5A Variants. 6(4), 741–748. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4254730/#R13
3. Al-Makhamreh, H. K., Nasr Alrabadi, Haikal, L., Krishan, M., Noor Al-Badaineh, Osama Faleh Odeh, Tawfiq Barqawi, Nawaiseh, M., Shaban, A., Bin, Lama Khamies, & Hammoudeh, A. J. (2022). Paroxysmal and Non-Paroxysmal Atrial Fibrillation in Middle Eastern Patients: Clinical Features and the Use of Medications. Analysis of the Jordan Atrial Fibrillation (JoFib) Study. 19(10), 6173–6173. https://doi.org/10.3390/ijerph19106173
4. CDC. (2022, October 14). Atrial Fibrillation. Centers for Disease Control and Prevention. https://www.cdc.gov/heartdisease/atrial_fibrillation.html
5. Corradi, D., Callegari, S., Maestri, R., Stefano Benussi, & Alfieri, O. (2008). Structural remodeling in atrial fibrillation. 5(12), 782–796. https://doi.org/10.1038/ncpcardio1370
6. King, G. S., Goyal, A., Yulia Grigorova, & Hashmi, M. F. (2023, February 19). Antiarrhythmic Medications. Nih.gov; StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK482322/
7. Sodium Channel Blockers | DrugBank Online. (2023). Drugbank.com; DrugBank. https://go.drugbank.com/categories/DBCAT000600
8. NHS Choices. (2023). Beta blockers. https://www.nhs.uk/conditions/beta-blockers/
9. Roden, D. M. (2016). Pharmacogenetics of Potassium Channel Blockers. 8(2), 385–393. https://doi.org/10.1016/j.ccep.2016.02.003
10. Calcium channel blockers. (2017). Heart and Stroke Foundation of Canada. https://www.heartandstroke.ca/heart-disease/treatments/medications/calcium-channel-blockers

11. Amiodarone: MedlinePlus Drug Information. (2017). Medlineplus.gov. https://medlineplus.gov/druginfo/meds/a687009.html#:~:text=Amiodarone%20is%20used%20to%20treat,class%20of%20medications%20called%20antiarrhythmics
12. Roy, D., Talajic, M., Dorian, P., Connolly, S. J., Eisenberg, M. J., Green, M. A., Kus, T., Lambert, J., Dubuc, M., Gagné, P., Nattel, S., & Thibault, B. (2000). Amiodarone to Prevent Recurrence of Atrial Fibrillation. 342(13), 913–920. https://doi.org/10.1056/nejm200003303421302
13. Belardinelli, L., Giles, W. H., Rajamani, S., Karagueuzian, H. S., & Shryock, J. C. (2015). Cardiac late Na+ current: Proarrhythmic effects, roles in long QT syndromes, and pathological relationship to CaMKII and oxidative stress. 12(2), 440–448. https://doi.org/10.1016/j.hrthm.2014.11.009
14. Pundi, K., Baykaner, T., Mellanie True Hills, Lin, B., Morin, D. P., Sears, S. F., Wang, P. J., & Stafford, R. S. (2021). Blood Thinners for Atrial Fibrillation Stroke Prevention. 14(6). https://doi.org/10.1161/circep.120.009389
15. Mont, L., Bisbal, F., Hernández-Madrid, A., Nicasio Pérez-Castellano, Viñolas, X., Arenal, A., Arribas, F., Fernández-Lozano, I., Andrés Bodegas, Cobos, A., Matía, R., Julián Pérez-Villacastín, Guerra, J. M., Ávila, P., María López-Gil, Castro, V. M., Arana, J. M., & Josep Brugada. (2014). Catheter ablation vs. antiarrhythmic drug treatment of persistent atrial fibrillation: a multicentre, randomized, controlled trial (SARA study). 35(8), 501–507. https://doi.org/10.1093/eurheartj/eht457
16. Kirchhof, P., & Calkins, H. (2017). Catheter ablation in patients with persistent atrial fibrillation. 38(1), 20–26. https://doi.org/10.1093/eurheartj/ehw260
17. Perino, A. C., Leef, G., Cluckey, A., Yunus, F. N., Askari, M., Heidenreich, P. A., Narayan, S. M., Wang, P. J., & Turakhia, M. P. (2019). Secular trends in success rate of catheter ablation for atrial fibrillation: The SMASH-AF cohort. 208, 110–119. https://pubmed.ncbi.nlm.nih.gov/30502925/
18. Aravindan Kolandaivelu. (2012). Role of Cardiac Imaging (CT/MR) Before and After RF Catheter Ablation in Patients with Atrial Fibrillation. 5(2), 523–523. https://doi.org/10.4022/jafib.523
19. Juerd Wijntjes, & Nens van Alfen. (2020). Muscle ultrasound: Present state and future opportunities. 63(4), 455–466. https://doi.org/10.1002/mus.27081
20. Russo, A., Russo, E., Gaetano Fassini, Casella, M., Innocenti, E., Zucchetti, M., Cefalù, C., Solimene, F., Mottola, G., Colombo, D., Bologna, F., Benedetta Majocchi, Santangeli, P., Riva, S., Luigi Di Biase, Fiorentini, C., & Tondo, C. (2013). Role of Intracardiac echocardiography in Atrial Fibrillation Ablation. 5(6), 786–786. https://doi.org/10.4022/jafib.786
21. Hijazi, Z. M., Kalyanam Shivkumar, & Sahn, D. J. (2009). Intracardiac Echocardiography During Interventional and Electrophysiological Cardiac Catheterization. 119(4), 587–596. https://doi.org/10.1161/circulationaha.107.753046
22. US. (2023). What is sonar? Noaa.gov. https://oceanservice.noaa.gov/facts/sonar.html#:~:text=Active%20sonar%20transducers%20emit%20an,the%20strength%20of%20the%20signal.
23. 3D Sonar in Object Detection. (2008). Hydro-International.com. https://www.hydro-international.com/content/article/3d-sonar-in-object-detection
24. MEGA 360 Imaging®. (2022, October 17). Johnsonoutdoors.com. https://humminbird.johnsonoutdoors.com/us/learn/imaging/mega-360-imaging
25. Schweber, B. (2018, August 13). Active noise cancellation, Analog IC Tips. https://www.analogictips.com/active-noise-cancellation-part-2-implementation-faq/
26. Advantages of SONAR | Disadvantages of SONAR. (2023). Rfwireless-World.com. https://www.rfwireless-world.com/Terminology/Advantages-and-Disadvantages-of-SONAR.html#:~:text=Drawbacks%20or%20disadvantages%20of%20SONAR&text=%E2%9E%A8SONAR%20system%20generates%20lot,causes%20refraction%20of%20acoustic%20energy.

27. Rodgers, J. R., Bax, J., Surry, K., Velker, V., Leung, E., D'Souza, D., & Fenster, A. (2019). Intraoperative 360-deg three-dimensional transvaginal ultrasound during needle insertions for high-dose-rate transperineal interstitial gynecologic brachytherapy of vaginal tumors. 6(02), 1–1. https://doi.org/10.1117/1.jmi.6.2.025001
28. Liu, D., Yin, G., & Li, S. (2006). Real-time 3D image guided patient positioning in radiation therapy. https://doi.org/10.1117/12.651361
29. FarSounder. (2014). FarSounder 3D Forward Looking Sonar for Navigation. FarSounder 3D Forward Looking Sonar for Navigation. https://www.farsounder.com/3d-sonar-explained