International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Ablation Medical Devices with Chemical Technologies: Engineering aspects, System, Mechanism, and Future Directions

Somashekharayya Hiremath

Lead Engineer
Medical Devices, Ablation Technologies.
United States of America

Abstract

Chemical ablation technology has emerged as a new method in minimally invasive medicine, providing specific and optimal treatment solutions for various diseases, including malignant tumors, cardiovascular diseases, renal denervation, and cardiac arrhythmia, by leveraging specially formulated cytotoxic agents delivered through precisely engineered devices. Chemical ablation minimizes collateral tissue damage while maximizing therapeutic outcomes. This paper offers a comprehensive overview of Ablation Medical Devices with Chemical Technologies, principles, critical system engineering considerations, applications, and the emerging role of computational modeling, notably finite element analysis (FEA) and fluid-structure interaction (FSI) in refining device design, optimizing, and enhancing procedure accuracy through engineering methods. Additionally, it addresses current challenges and outlines future directions, signaling an evolving, patient-centric era where the Ablation Medical Devices with Chemical Technologies stands to broaden its scope and impact significantly.

Keywords: Ablation Technologies, Chemical Technologies, Ablation Medical Devices, Chemical Ablation Systems, Medical Devices.

1. Introduction

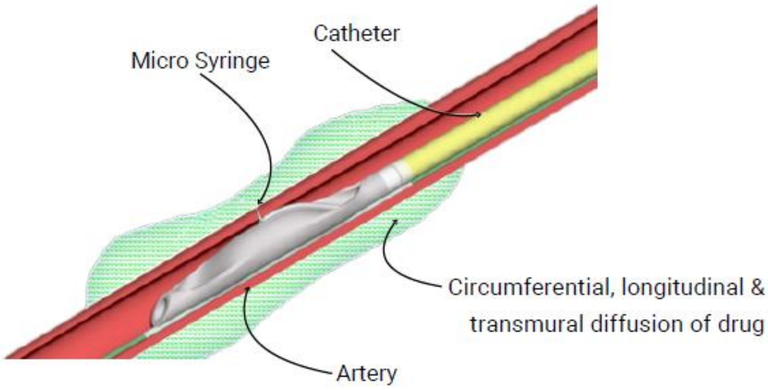
Ablation therapy constitutes a cornerstone of modern interventional medicine, typically relying on physical methods, thermal, electrical, or mechanical, to destroy pathological tissues such as tumors or ectopic conduction foci in cardiac arrhythmias [4, 12, 14, 25]. However, chemical ablation has recently been found to have the potential to selectively induce necrosis with minimal invasiveness, thereby lowering the risks of infection, excessive bleeding, and prolonged convalescence [12, 15, 16]. Whether in renal denervation or oncological practice, for instance, to treat liver lesions using ethanol injections [9, 12, 16] or in cardiology, chemical ablation can specifically target diseased areas, limiting damage to adjacent healthy structures [14, 15, 17].

As technology matures, efforts to optimize safety and improve efficacy are being bolstered by engineering breakthroughs [6, 19]. These include advanced catheter systems, image-guided injection protocols, and integrative computational tools that model agent diffusion and predict lesion geometry [17, 18]. This paper focuses on a comprehensive overview of Ablation Medical Devices with Chemical Technologies, critical system engineering considerations, applications, and computational modeling, notably finite element analysis (FEA), fluid-structure interaction (FSI) in refining device design, optimizing, and enhancing procedure accuracy through engineering methods and application to provide solutions to evolving healthcare needs.

2. Main Body

Traditional surgical interventions for conditions such as tumors and cardiovascular diseases carry substantial risks, including infection, prolonged convalescence, and inadvertent harm to healthy tissues [5, 7]. These limitations underscore the importance of developing minimally invasive methods that can accurately pinpoint and remove pathological tissue with the least amount of collateral damage possible. Chemical ablation has emerged as a potential solution, which offers a targeted and less invasive method that may have lower risks of many of the complications seen with open surgical procedures. However, it is essential to continue research in this field to improve the safety and effectiveness of the technique, chemical ablation technology and increase the range of clinical applications so that chemical ablation can be used routinely in medical practice.

Chemical ablation presents a minimally invasive solution by introducing cytotoxic agents directly into abnormal tissues through chemical ablation while minimizing harm to surrounding healthy structures, leading to localized cell destruction [4, 16, 18]. This targeted approach reduces the need for extensive surgical procedures, which in turn reduces the risk of complications and shortens recovery times [12, 14]. The clinical efficacy of chemical ablation has been demonstrated through techniques such as percutaneous ethanol injection for treating liver tumors and renal denervation [1-3, 9, 14, 15]. With ongoing advancements in chemical formulations and delivery methods, this technique and technology does have significant potential for broader medical applications and is a precise and effective alternative to traditional surgical interventions [2, 3, 14-16].



Source: https://www.dicardiology.com/

Figure 1. Ablation Device Delivering Chemical Agent in the Artery.

Figure 1 depicts a mechanical ablation device delivering a chemical agent comprising a catheter and a micro-syringe positioned within an artery. The catheter enters the artery and delivers a specialized chemical agent, thereby forming a circumferential, longitudinal, and transmural zone of agent diffusion around the lesion. Such localized delivery ensures targeted tissue necrosis while preserving healthy structures, highlighting the minimally invasive nature and precision of chemical ablation.

Technology

Chemical ablation is a minimally invasive therapeutic technique that involves the percutaneous injection of cytotoxic chemical agents such as ethanol or acetic acid into targeted tissues under precise imaging guidance [4, 14, 15, 17]. These agents induce coagulative necrosis, effectively destroying abnormal cells while minimizing damage to surrounding healthy structures [11, 12, 19]. The procedure is commonly guided by ultrasound or computed tomography (CT) to ensure accurate delivery of the chemical agents, improving treatment efficacy and patient safety [15, 19]. Chemical ablation has been widely utilized in the management of conditions such as liver tumors and cardiac arrhythmias, demonstrating its effectiveness in reducing tumor burden and restoring normal cardiac function [13, 25].

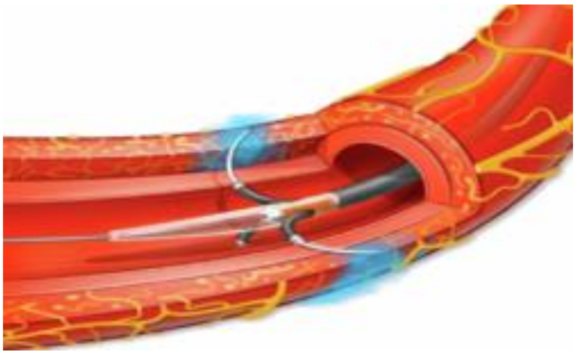


Figure 2: Chemical Ablation Device Injecting Chemical Agent into the Target Region [10].

As shown in Figure 2, a chemical ablation device delivers a blue-colored chemical agent into the patient’s artery at a target zone. The chemical agent is diffused into the surrounding tissue and induces a controlled necrosis at the location of the diseased cells.

3. System Design and Engineering Aspects

The delivery mechanism of chemical ablation technology is dependent on specialized needle or catheter-based platforms, which are engineered to navigate complex anatomical pathways and are a critical element of this technology [1, 6,9]. These delivery tools are engineered from advanced materials that do not corrode or degrade in response to cytotoxic agents and, hence, are able to perform reliably over the duration of an ablation course [10, 14, 17]. Their architecture can incorporate microlumens or adjustable tip configurations, allowing clinicians to deposit the chemical solution at precisely targeted sites [1, 12, 18]. Through precise control of the injection depth and angle, the device improves the tissue reach and optimizes the therapeutic outcome of the treatment [16, 19].

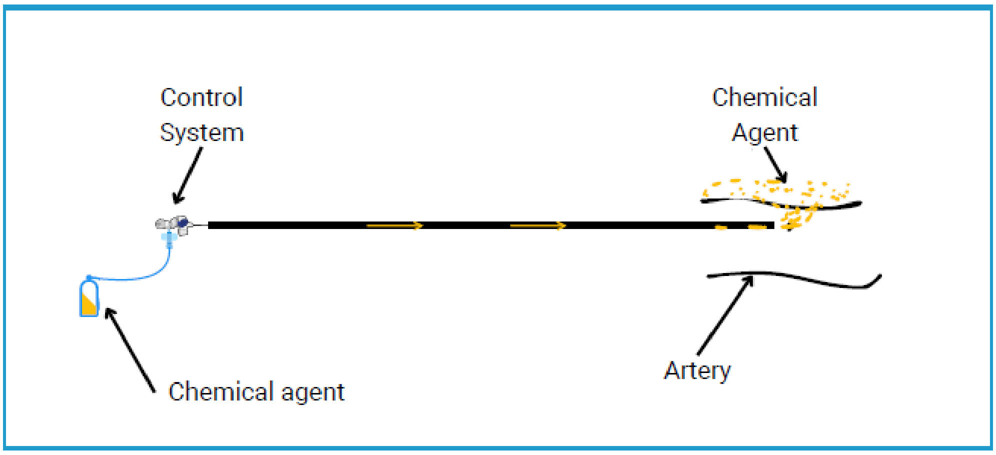


Figure 3. Ablation Medical Device System with Chemical Technology.

Figure 3 schematic outlines a complete ablation system that integrates chemical technology. The illustration displays the chemical agent system (housing or reservoir), a control module for infusion rate and safety features, and the catheter body connecting to the artery. At the tip, a specialized mechanism delivers chemical agents directly to the pathological region. This design ensures optimized therapy by controlling the dosage, flow rate, and contact parameters of the treatment in real time, leading to proper lesion treatment with minimal collateral damage.

Imaging Integration

Imaging integration plays an indispensable role in chemical ablation. Real-time visualization using ultrasound, CT, or fluoroscopic guidance enables operators to accurately place catheters or needles, track the spread of chemical agents, and assess the evolving ablation zone [7, 11]. Visual feedback regarding agent diffusion or lesion necrosis boundaries allows for immediate procedural adjustments, thus reducing complications like off-target necrosis or incomplete ablation [12, 14, 15]. The synergetic interplay between refined delivery mechanisms and high-resolution imaging has significantly elevated procedural accuracy and outcomes [5, 13, 15].

Automated Flow Regulation

To further improve safety and controllability, modern chemical ablation systems employ automated flow regulators, pressure sensors, and dose-control modules that precisely modulate the volume, concentration, and infusion rate of the chemical agent [8, 12]. Such features curtail the risk of overshooting the lesion or harming adjacent healthy tissue [6, 17]. In addition, controlled infusion profiles also conserve the agent's cytotoxic effectiveness and avoid local accumulation of the agent, which, if not checked, could endanger the surrounding structures [14, 18, 19]. To this end, device manufacturers include these features to enable clinicians to apply ablative agents with minimal chances of severe complications.

Human-machine interface (HMI)

A clear and intuitive human-machine interface (HMI) tie together these various engineering elements. User-friendly dashboards combine anatomical images and real-time lesion coverage with essential procedure data such as chemical agent flow rates or tissue impedance values [6]. In some cutting-edge setups, simulation outputs are displayed on the screen to give a preview of the predicted lesion formation or to guide the operator on the dosage adjustments that may be needed [19]. It can be a real asset for both novice and expert users, and it can help improve decision-making and lead to a safer, more standardized ablation context [6]. With continued advancements in material science, imaging capabilities, and robotic-assisted delivery systems, chemical ablation technology is evolving toward more efficient, safe, and highly targeted treatments, further expanding its applications across various medical fields [16].

Computational Modeling

Dependency on research and development activities and prototyping in ablation device development increases research costs and prolongs the time to clinical deployment. Conventional ablation tools often emerge from iterative bench experiments and animal studies, which entail multiple design revisions and extensive validation. Without strong computational systems to aid in these modifications, even small alterations in the geometry or the means of delivering the chemicals necessitate another round of preclinical studies, which only slows down the process. The other source of uncertainty is tissue heterogeneity and patient-specific anatomical variability, which makes the prediction of lesion size and depth a challenging task. Such inconsistencies may lead to ineffective ablation or collateral tissue damage, which is unsafe and ineffectual [10, 11]. However, experienced clinicians must remain vigilant to the energy levels, the duration of exposure to the chemical agent, and the navigational aspects of the procedure, indeed, small errors at this stage may result in a poor lesion or even complications [13, 15].

Computational modeling addresses these challenges by systematically dissecting energy transfer and tissue interactions through numerical simulations such as finite element analysis (FEA) and fluid-structure interaction (FSI) [20, 22]. By virtually testing device parameters ranging from thermal ablation electrode designs to chemical ablation and chemical agent diffusion patterns, engineers can observe how energy fields evolve under diverse boundary conditions without relying on repeated animal laboratories during the development cycle [20, 21]. This approach opens up new opportunities for the design of experiments and simplifies prototyping, shortens development cycles, and clarifies how different tissues respond under varying ablation conditions, delivering near-real-time or real-time insights that help clinicians fine-tune power settings, contact force, and spatial targeting. Ultimately, computational modeling reduces guesswork in predicting final lesion outcomes, fosters more precise device engineering, and paves the way for a more user-friendly, error-resistant clinical workflow.

Chemical Ablation and Mass Transfer

Chemical ablation employs cytotoxic agents such as ethanol or sclerosing solutions to induce targeted tissue necrosis. Extending FEA with mass transfer equations further refines the ability to model chemical diffusion and subsequent tissue reactions. These simulations however help confirm whether a chosen injection site, dosage or infusion rate suffices to saturate diseased tissue while preserving healthy structures depending on key variables like agent concentration, diffusion coefficients and flow rates in vascular regions determine the ultimate lesion volume [23, 24].

4. Applications

Chemical ablation technology has demonstrated considerable success in several medical fields, primarily because of its capacity to destroy pathological tissue with minimal damage to healthy structures [12]. In oncology, one of its most established applications is the treatment of liver tumors, particularly hepatocellular carcinoma (HCC) [9, 12, 16]. A cytotoxic agent is introduced directly into the tumor mass under imaging guidance; this has become a widely used technique, and it is called percutaneous ethanol injection (PEI). Localized necrosis is induced, and PEI offers a feasible solution for patients who cannot undergo surgical resection or tolerate thermal ablation [12]. The minimally invasive nature of the approach simplifies recovery and avoids many of the risks typically associated with open surgical approaches. Similar to RFA, PEI can provide results similar to those of more invasive interventions, thus cementing its place as a first-line management option for liver cancer [3, 7, 9].

Beyond oncological treatments, chemical ablation has also been investigated in the realm of cardiology, renal denervation for treating hypertension, and especially for managing certain arrhythmias [1-3, 13-14, 25]. While radiofrequency cryoablation and thermal ablations remain the dominant modalities for addressing aberrant electrical pathways in the heart and renal denervation, there are clinical scenarios in which chemical ablation could offer unique benefits [7]. For instance, localized chemical injections that selectively dismantle arrhythmogenic tissue without inducing excessive thermal or mechanical injury could reduce complications in complex anatomical regions [14]. Although research in this area is still evolving, initial findings suggest that properly formulated chemical agents, when delivered through precise catheter systems under high-resolution imaging, may improve treatment outcomes for specific arrhythmic conditions [2]. With accumulating data, chemical ablation may become a desirable addition to current methods and thus increase the options for minimally invasive management of arrhythmia [5, 25].

5. Impact

The use of chemical ablation technology is increasing and has changed the landscape of minimally invasive medicine because they are less invasive [4]. In contrast to open surgical procedures, which can require extensive incisions and longer hospital stays, chemical ablation often necessitates only a small puncture site for needle or catheter entry [12]. This more conservative approach helps patients return home sooner, shortens convalescence periods and diminishes the risk of postoperative complications such as infection or severe scarring [16]. Hence the overall healthcare burden is lowered because there are fewer inpatient resources required, and more patients can return to normal life sooner [19]. Another pivotal advantage lies in targeted treatment, wherein physicians can deliver cytotoxic agents directly to diseased tissue under accurate imaging guidance [4]. Because chemical ablation does not rely on heat, the procedure spares nearby healthy cells from injury [12]. This precision is particularly valuable in anatomically sensitive areas, such as the liver or cardiac chambers, where uncontrolled thermal spread or mechanical disruption could induce serious damage [13]. The option to localize agent diffusion in small or irregularly shaped lesions can open new horizons in cancer treatment and beyond, improving therapeutic efficacy while safeguarding patient well-being [16]. The expanded treatment options afforded by chemical ablation have brought advanced care to patient populations who would otherwise be ineligible for traditional surgery or standard ablation modalities [12]. Individuals with comorbidities, poor baseline health, or anatomies unsuitable for radical surgery can now receive effective interventions that significantly reduce tumor burden or stabilize arrhythmic foci [14, 25]. Thus, clinical gaps are closed, and a more equitable healthcare model can be built so that a more diverse population of patients can get complex care, which will improve overall public health [19].

6. Future Directions

The future scope of chemical ablation is underscored by the continuous innovation in imaging, agent formulations and procedural integration. Advanced imaging technologies including real time MRI or CT based navigation systems may be used to enhance the accuracy of injection thus enabling the clinicians to visualize and adjust the chemical delivery on the fly with exquisite precision. Such synergy between imaging and ablative procedures could expedite diagnosis-to-therapy workflows and lead to more consistent patient outcomes, particularly in anatomically challenging sites. Simultaneously, novel ablative agents designed for superior tissue selectivity and minimal toxicity are poised to expand the therapeutic reach of chemical ablation. Researchers are developing cytotoxic solutions that are more effective in breaking down tumor cells or remaining active in complex microenvironments [6]. These formulations may be useful in situations where conventional agents have been only partially effective and thus may help patients who need more intense or unusual ablation therapies [19]. Another promising dimension is multimodal synergy, in which chemical ablation is combined with therapies like immunotherapy or systemic chemotherapy [16]. Using cytotoxic agents that can kill not only pathological tissues but also potentially antigenic tumors, clinicians may be able to trigger a patient's immune response and improve cancer control overall [6]. This integration could transform localized ablation into a more holistic strategy for managing advanced malignancies or resistant tumors [19].

Finally, advanced robotics and AI herald a new chapter of partially or fully automated chemical ablation procedures. Automated catheters guided by real-time computational modeling may significantly reduce operator workload and limit variability in technique. For instance, such systems coupled with sensor feedback to synchronize simulations could guarantee that the dosage and delivery are precisely on target for the patient’s anatomy which would lead to reproducible and standardized outcomes across different settings.

7. Conclusion

Medical devices with Chemical ablation technologies have emerged as a transformative advancement in minimally invasive medical treatments, providing effective, targeted, and less invasive alternatives for managing various conditions, particularly in oncology and cardiology. As ongoing research, engineering and technological innovations continue to refine chemical ablation technology, chemical formulations, delivery mechanisms, and imaging-guided precision, the potential for broader applications across additional medical specialties is rapidly expanding.

Future advancements, including improved imaging, new ablative agents, and integration with multimodal therapies, should improve treatment efficacy and safety and improve patient outcomes. Innovation and clinical validation are both continuously evolving, and chemical ablation is set to become a vital asset in today's medical practice, offering more precision, better therapeutic outcomes, and better patient access to minimally invasive treatment solutions.

References

1. Fischell TA, Fischell DR, Ghazarossian VE et al. Next generation renal denervation: chemical “perivascular” renal denervation with alcohol using a novel drug infusion catheter. Cardiovasc Revasc Med 2015. doi:10.1016/j.carrev.2015.04.008
2. Freyhardt, P., Haage, P., Walter, A., Aufmesser-Freyhardt, B., Guenther, R. W., & Streitparth, F. (2020, June). Renal Sympathetic Denervation by Image-Guided Percutaneous Ethanol Injection–Histopathologic Characteristics, Efficacy and Safety. In RöFo-Fortschritte auf dem Gebiet der

Röntgenstrahlen und der bildgebenden Verfahren (Vol. 192, No. 06, pp. 549-560). © Georg Thieme Verlag KG.

3. Kapil, V., Jain, A. K., & Lobo, M. D. (2014). Renal Sympathetic Denervation - A Review of Applications in Current Practice. Interventional cardiology (London, England), 9(1), 54–61.
4. Ahmed, M., Brace, C. L., Lee Jr, F. T., & Goldberg, S. N. (2011). Principles of and advances in percutaneous ablation. Radiology, 258(2), 351-369
5. Bertog, S., Vega, F., Ghazarossian, V., Pathak, A., Vaskelyte, L., Sievert, H., ... & Virmani, R. (2017). Chemical sympathetic denervation: promising, but important distinctions between agents and methods. Eurointervention: Journal of Europcr in Collaboration with the Working Group on Interventional Cardiology of the European Society of Cardiology, 13(9), e1131-e1132.
6. Keum, H., Cevik, E., Kim, J., Demirlenk, Y. M., Atar, D., Saini, G., ... & Oklu, R. (2024). Tissue Ablation: Applications and Perspectives. Advanced Materials, 36(32), 2310856.
7. Toutouzas, K., Synetos, A., Pietri, P., & Stefanadis, C. (2017). Chemical renal denervation: an effective method to treat resistant hypertension?. Eurointervention: Journal of Europcr in Collaboration with the Working Group on Interventional Cardiology of the European Society of Cardiology, 13(9), e1129-e1130.
8. Singal, A., Ballard, J. R., Rudie, E. N., Cressman, E. N., & Iaizzo, P. A. (2016). A review of therapeutic ablation modalities. Journal of Medical Devices, 10(4), 040801.
9. Li, Z., Zhang, K., Lin, S. M., Mi, D. H., Cao, N., Wen, Z. Z., & Li, Z. X. (2017). Radiofrequency ablation combined with percutaneous ethanol injection for hepatocellular carcinoma: a systematic review and meta-analysis. International Journal of Hyperthermia, 33(3), 237-246.
10. Ogoyama, Y., & Kario, K. (2024). Differences in the effectiveness and safety of different renal denervation devices. Hypertension Research, 47(10), 2678-2684.
11. Goldberg, S. N., & Gazelle, G. S. (2001). Radiofrequency tissue ablation: physical principles and techniques for increasing coagulation necrosis. Hepato-gastroenterology, 48(38), 359-367.
12. Shiina, S., Tateishi, R., Imamura, M., Teratani, T., Koike, Y., Sato, S., ... & Koike, K. (2012). Percutaneous ethanol injection for hepatocellular carcinoma: 20-year outcome and prognostic factors. Liver International, 32(9), 1434-1442.
13. Calkins, H., Hindricks, G., Cappato, R., Kim, Y. H., Saad, E. B., Aguinaga, L., Akar, J. G., Badhwar, V., Brugada, J., Camm, J., Chen, P. S., Chen, S. A., Chung, M. K., Nielsen, J. C., Curtis, A. B., Davies, D. W., Day, J. D., d'Avila, A., de Groot, N. M. S. N., Di Biase, L., … Yamane, T. (2017). 2017 HRS/EHRA/ECAS/APHRS/SOLAECE expert consensus statement on catheter and surgical ablation of atrial fibrillation. Heart rhythm, 14(10), e275–e444.
14. Mahfoud, F., Renkin, J., Sievert, H., Bertog, S., Ewen, S., Böhm, M., ... & Persu, A. (2020). Alcohol-mediated renal denervation using the peregrine system infusion catheter for treatment of hypertension. Cardiovascular Interventions, 13(4), 471-484.
15. Ansari, D., & Andersson, R. (2012). Radiofrequency ablation or percutaneous ethanol injection for the treatment of liver tumors. World journal of gastroenterology: WJG, 18(10), 1003.
16. Chen, S., Zeng, X., Su, T., Xiao, H., Lin, M., Peng, Z., ... & Kuang, M. (2022). Combinatory local ablation and immunotherapies for hepatocellular carcinoma: Rationale, efficacy, and perspective. Frontiers in Immunology, 13, 1033000.
17. Lee, J. H., Won, J. H., Bae, J. I., Kim, J. H., Lee, H. S., & Jung, S. M. (2009). Chemical ablation of the gallbladder with acetic acid. Journal of Vascular and Interventional Radiology, 20(11), 1471-1476.

18. Bertog S, Fischel TA, Vega F et al. Randomised, blinded and controlled comparative study of chemical and radiofrequency-based renal denervation in a porcine model. EuroIntervention: journal of EuroPCR in collaboration with the Working Group on Interventional Cardiology of the European Society of Cardiology 2017; 12: e1898–e1906
19. Swierz, M. J., Storman, D., Riemsma, R. P., Wolff, R., Mitus, J. W., Pedziwiatr, M., ... & Bala, M. M. (2020). Percutaneous ethanol injection for liver metastases. Cochrane Database of Systematic Reviews, (2).
20. Hogge, M., & Gerrekens, P. (1985). Two-dimensional deforming finite element methods for surface ablation. Aiaa Journal, 23(3), 465-472.
21. Lee, J., Yoo, J., & Lee, K. (2014). Numerical simulation of the nano-second pulsed laser ablation process based on the finite element thermal analysis. Journal of Mechanical Science and Technology, 28, 1797-1802.
22. Hirschhorn, M., Tchantchaleishvili, V., Stevens, R., Rossano, J., & Throckmorton, A. (2020). Fluid-structure interaction modeling in cardiovascular medicine - A systematic review 2017-2019. Medical engineering & physics, 78, 1–1
23. Granot, Y., & Rubinsky, B. (2008). Mass transfer model for drug delivery in tissue cells with reversible electroporation. International journal of heat and mass transfer, 51(23-24), 5610-5616.
24. Tucci, C. (2021). Modelling heat transfer in tissues treated with thermal ablation.
25. Brugada, P., de Swart, H., Smeets, J. L., & Wellens, H. J. (1989). Transcoronary chemical ablation of ventricular tachycardia. Circulation, 79(3), 475-482.