Results from the Study of Lesions Created by Robot-Assisted Radiofrequency Ablation

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Abstract: The integration of robotic systems in radiofrequency (RF) catheter ablation, has the potential to enhance both the efficiency and safety of the procedure. The objective of our research was to develop and implement a proprietary measurement platform, designed to optimize a robot-assisted ablation process through in vitro experimentation, with the goal of achieving fully stable catheter positioning. In our experiments, we focused on maintaining two key parameters: Constant contact force and Stable catheter positioning. To achieve this, we designed and manufactured a specialized contact force limiting device. The stability of catheter positioning was ensured through the utilization of a robotic arm. In addition to maintaining constant contact force, we examined the parameters influencing the volume of lesions formed at varying temperatures and ablation durations. Our experiments were conducted using custom-developed equipment, designed for this study. The study investigated lesion sizes generated by RF ablation at 30 Watts, examining the effects of varying temperatures (60°C, 65°C, 70°C) and ablation durations (10, 20, 30 seconds). Porcine heart tissue samples were subjected to ablation, resulting in the creation of a total of 186 lesions. Following the ablation procedures, the depth, width, and volume of the lesions were systematically measured. A multivariate linear regression model was employed to analyze the impact of temperature and ablation duration on the volume of the lesions. To ensure stability in catheter positioning, a robotic arm was utilized in conjunction with a custom-developed and manufactured contact force limiter. Subsequently, we employed the

assembled in vitro equipment to facilitate the preparation of the lesions. Our experiments successfully produced accurate and reproducible ablation patterns, yielding consistent and reliable results. Increasing the temperature from 60°C to 65°C and 70°C resulted in a significant increase in lesion volume, with measurements of 23.57±12.81 mm³, 38.42±16.86 mm³ and 46.88±15.62 mm³, respectively ($p<0.001$). Similarly, extending the ablation time from 10 seconds to 20 seconds and 30 seconds also led to a significant increase in lesion volume, with volumes of 23.57±12.81 mm³, 28.52±12.50 mm³ and 33.09±18.88 mm³, respectively ($p=0.0035$). Our research enhances the understanding of how lesion geometry evolves, over different ablation parameters.

Keywords: Radiofrequency ablation, Lesion formation, Atrial fibrillation ablation, Robot-assisted intervention

1 Introduction

Radiofrequency ablation (RFA) is a well-established and effective therapeutic modality for treating atrial fibrillation (AF) and various other arrhythmias, aiding in the restoration of normal cardiac rhythm while minimizing potential complications [1-6]. Advances in technology, including robotics and artificial intelligence, have the potential to markedly enhance the efficiency of medical procedures and decrease the risk of adverse outcomes. The advancement and incorporation of these technologies are pivotal in the ongoing evolution of contemporary medical practice [7-8].

The objective of ablation is to induce transmural, continuous, and sustained cellular damage, resulting in lesion formation [9]. During this procedure, the catheter tip is positioned against the myocardium to deliver radiofrequency (RF) energy, which is converted into thermal energy and subsequently induces tissue necrosis. Effective energy transfer is highly dependent on the quality of contact between the catheter and the myocardial tissue [10][11].

The biophysics underlying lesion formation during RFA results from a complex interplay of multiple factors, including application time, catheter contact force, power delivered, and tissue impedance [12]. Point-by-point ablation is a commonly employed technique in the treatment of arrhythmias [11]. Enhancing the efficiency of RFA often involves adjustments to the ablation power and/or duration. Current research is focused on characterizing the properties of ablation lesions, such as their size, shape, and depth [13-17].

Although RFA is typically performed by skilled electrophysiologists, there are ongoing efforts to enhance procedural precision through innovations such as catheter positioning systems (CPS) and robotic control. However, increasing precision can also introduce risks, including extended procedure times and potential complications. Current literature indicates that while catheter robots are

commercially available, the prevailing standard of care continues to emphasize minimally invasive techniques performed under human oversight [18-20].

Robotic-assisted systems offer enhanced targeting and precise positioning of the catheter tip, thereby improving the consistency of RFA procedures. These systems facilitate accurate and stable catheter guidance, which can enhance both the efficiency and safety of the intervention. Robotic platforms are adept at fine-tuning movements and maintaining continuous contact with cardiac tissue, crucial for effective RF energy delivery and optimal lesion formation [21]. Additionally, robotic-assisted systems allow for precise control of contact force and catheter direction, which are critical factors in achieving transmural lesions [22][23]. These automated systems also contribute to reduced procedure duration, minimized radiation exposure for both patients and physicians, and improved intervention success rates [24].

The objective of our research was to utilize a proprietary measurement platform to standardize a robot-assisted ablation process in in-vitro experiments, ensuring constant contact force and stable catheter positioning. Utilizing this platform, we conducted experiments to examine lesion size formation under constant contact force across varying temperatures and ablation durations. Employing robotics hardware has known to improve the deployability and scalability of solutions from underwater robotics to space research.[25-27] We relied on the outstanding experience and inventory of the Antal Bejczy Center for Intelligent Robotics, within the EKIK. [28]

2 Methods

2.1 Experimental Equipment

Our experimental setup was developed at the Antal Bejczy Center for Intelligent Robotics at Óbuda University, outside of the clinical operating room environment. Within this facility, we conducted robot-assisted studies to evaluate the impact of intervention time and catheter temperature on lesion size during RF ablation at 30 Watts. A sophisticated robotic and sensory system was employed to optimize the ablation process, enabling an objective assessment of various RFA treatment protocols [29].

In our experiments, we utilized porcine heart tissue, a widely accepted model for cardiovascular research. The tissue samples were obtained from whole porcine hearts sourced from a conventional market within 24 hours post-slaughter. The tissue sections were submerged in an experimental tank maintained at 37°C, with the saline solution diluted to achieve an impedance of approximately 100 Ohms, thereby, closely replicating the surgical environment [13].

The test surfaces were cut smooth for ablation and observation of lesions to ensure accurate measurements and reliable data. The porcine tissues were stored under refrigeration in the laboratory until the initiation of the ablation procedure, at which point they were positioned on a copper table to ensure proper grounding during the experiment.

Figure 1

The ex vivo porcine tissue RF ablation measurement setup. The figure shows the Stockert generator, the tank, the Universal Robots UR16e robotic arm, the OnRobot RG6 gripper and the Ambiano Sous Vide machine.

The equipment utilized for our measurements included a UR16e robotic arm (Universal Robots, Odense, Denmark) fitted with an OnRobot RG6 gripper head [30] to ensure stable catheter positioning. Ablation was performed using a standard Celsius 4 mm catheter (Biosense Webster, Johnson & Johnson, New Brunswick, NJ, USA) connected to a Stockert RF generator. Due to technical constraints, the power curve was not recorded. A constant temperature and brine circulation were maintained using an Ambiano (Frankfurt, Germany) sous vide system, with a circulation rate of 8-10 L/min. The tissue samples were secured on the copper table with a rubber elastic band. The experimental setup is depicted in Figures 1 and 2 [29].

Figure 2

Instrumentation setup. The ex vivo porcine tissue radiofrequency ablation (RFA) instrumentation set up. The picture shows the Robots UR16e robotic arm and the OnRobot RG6 gripper, the Ambiano Sous Vide machine in the tank, the copper table used for grounding, the custom designed force measuring device, the RF electrode, the porcine sample.

2.2 Contact Force Limiter Design

Robotic arms typically offer contact force adjustment with an accuracy of approximately 1 N. However, catheter ablation procedures require a much finer force control of around 0.3 N. To meet this requirement, we designed and fabricated a contact force measuring and limiting device (Figure 3), which was integrated into the gripper head of the robotic arm [31]. The mechanical device was engineered based on Hooke's law, employing two springs with individual stiffness values of s=0.13 N/mm in series, resulting in a combined stiffness of s=0.06 N/mm. This setup maintained a consistent contact force across all ablation sites throughout the experiments, thereby minimizing measurement inaccuracies.

The accuracy of the contact force limiter was checked on a balance with a freehand before each experiment and the measurement inaccuracy was below 5%. A constant contact force was achieved with a contact force limiter, the contacting gauge was validated using the robot arm and the catheter positioning was stabilized with robotic arm. We also made sure that the end of the catheter could only protrude a maximum of 1 cm from the end of the contact force limiter, to ensure the stability of the catheter. [29].

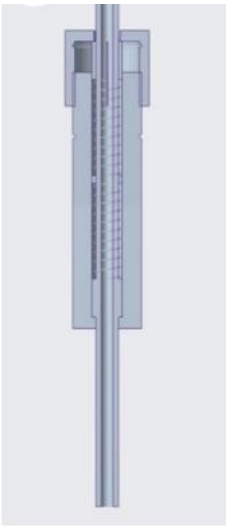


Figure 3

Our proprietary designed and manufactured contact force limiter, which is capable of setting the contact force stably at 0.3 N, through which the ablation electrode passes.

2.3 Measurement of Lesion Size

A computer program was employed to control the robotic arm, ensuring precise positioning, orientation, and consistent ablation duration. Manual control was also available when necessary to maintain these parameters. On several time, we transitioned to manual control; however, this did not affect the experimental outcomes. The catheter was placed within a custom-designed contact force limiter, and the generator was activated after setting the contact time. Our platform allowed for the creation of ablation lesions in both the atrium and ventricle, though lesion formation in the left ventricle was facilitated by its greater thickness. Increasing the temperature or extending the ablation time were the most straightforward strategies to enhance radiofrequency efficiency [17].Our experiments were conducted under constant contact force with temperature-controlled settings of 60°C, 65°C and 70°C, and ablation durations of 10, 20 and 30 seconds, resulting in the formation of 186 lesions. The power was adjusted according to the temperature and duration settings on the generator. Ablation was performed on a point-by-point basis, with careful attention given to the spacing between ablation points to prevent overlap and ensure the integrity of the evaluation results. In cases where necessary, excess tissue was excised from the samples prior to the experiment to achieve a uniform surface, thereby facilitating more accurate assessment (Figure 4).

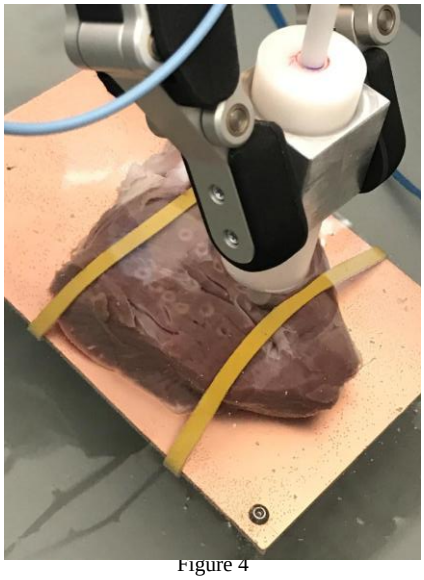


Figure 4
The place where the lesions were created: the force-measuring device we designed is visible in the gripping mechanism of the robot arm, through which the ablation electrode passes. On the copper table is the porcine tissue, which is fixed with a rubber band. The prepared lesions can now be seen on the tissue.

Following the completion of the ablation sequences, top surface images of each sample were captured to measure the surface diameter of the lesions. Additionally, cross-sectional photographs were obtained to later assess lesion depth (Figure 5). Staining was not utilized, as the visual characteristics of the lesions were sufficient for accurate localization. Inkscape software (https://gitlab.com/inkscape/inkscape, 1 January 2020) was employed to extract diameter and depth measurements, which were then recorded in a Microsoft Excel spreadsheet for subsequent analysis. All lesion measurements were conducted by a single blinded investigator who was unaware of the lesion parameters (contact force, temperature, and ablation duration) during the measurement process. The lesion volumes were subsequently calculated from the collected data using the formula depicted in Figure 6, under the assumption that the lesions conformed to the geometry of a spherical slice [29].

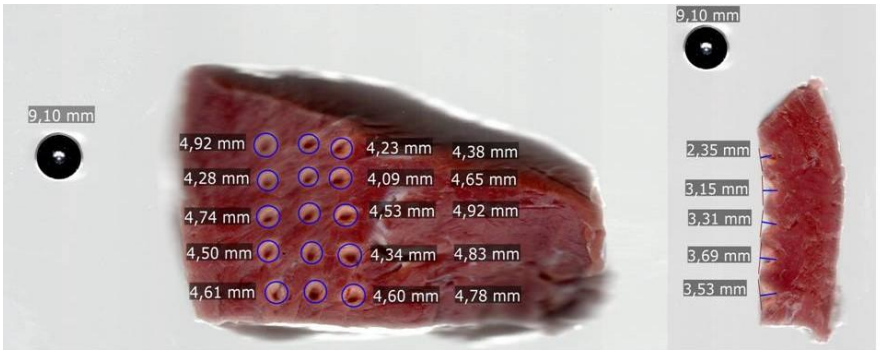
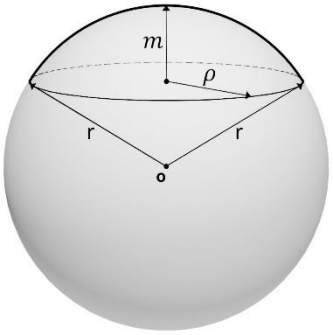


Figure 5
Lesions created by ablations, which are shown in the images together with the measured dimensions. The diameters can be read from the top view and the depths from the cross-sectional image.



$$V = \frac{\pi}{6} m(3\rho^2 + m^2)$$

Figure 6
Formula for the volume of a spherical slice

2.4 Statistical Evaluation

The collected data were recorded and stored in an electronic database. Continuous variables were expressed as means and standard deviations. To assess the impact of temperature and ablation time on lesion volume, a multivariate linear regression model was applied. In this model, lesion volume served as the dependent variable, while temperature and ablation duration were treated as explanatory variables. A p-value of less than 0.05 was considered statistically significant. All statistical analyses were conducted using R software version 4.4.0 [32].

3 Results

Table 1

Characteristics and parameters of ablation lesions at different temperatures and durations at the ex vivo model: averages and standard deviations of width, depth, volume of lesions in 9 different setting groups, based on 186 lesions according to the ablation protocol (see Methods section)

Temperature	Time	Width average	Depth average	Volume average
°C	sec	mm	mm	mm^3
60	10	4.58±0.60	2.06±0.68	23.57±12.81
65	10	4.79±0.62	2.74±0.82	38.42±16.86
70	10	5.13±0.59	3.01±0.58	46.88±15.62
60	20	4.74±0.60	2.30±0.58	28.52±12.50
65	20	5.02±0.65	3.27±0.71	53.90±20.66
70	20	5.37±0.80	3.33±0.47	58.27±15.05
60	30	4.66±0.64	2.53±0.71	33.09±18.88
65	30	5.16±0.80	2.90±0.61	46.64±22.58
70	30	5.15±0.44	3.17±0.71	53.13±24.27

Table 1 presents the dimensions of ablation lesions obtained from experiments conducted at temperatures of 60°C, 65°C, and 70°C with ablation durations of 10, 20, and 30 seconds, resulting in a total of 9 distinct lesion groups. For all 186 lesions, measurements of width and depth were recorded, and lesion volumes were subsequently calculated. Specifically, for the ablation parameters of 60°C and 10 seconds, the average lesion depth was 2.06 ± 0.68 mm, the average width was 4.58 ± 0.60 mm, and the average volume was 23.57 ± 12.81 mm^3. When the duration of ablation was kept constant at 20 seconds and the temperature was increased from 60°C to 65°C and 70°C, the average lesion width increased from 4.74 ± 0.60 mm to 5.02 ± 0.65 mm and 5.37 ± 0.80 mm, respectively. Similarly, when the ablation time was extended from 10 seconds to 20 and 30 seconds at 60°C, the mean depth of the lesions increased from 2.06 ± 0.68 mm to 2.30 ± 0.58 mm and 2.53 ± 0.71 mm, respectively. The largest lesion volume in our experiments was observed at the 70°C for 20 seconds setting. Figures 7 and 8 illustrate the effects of temperature and duration variations on lesion dimensions, as depicted in box plots.

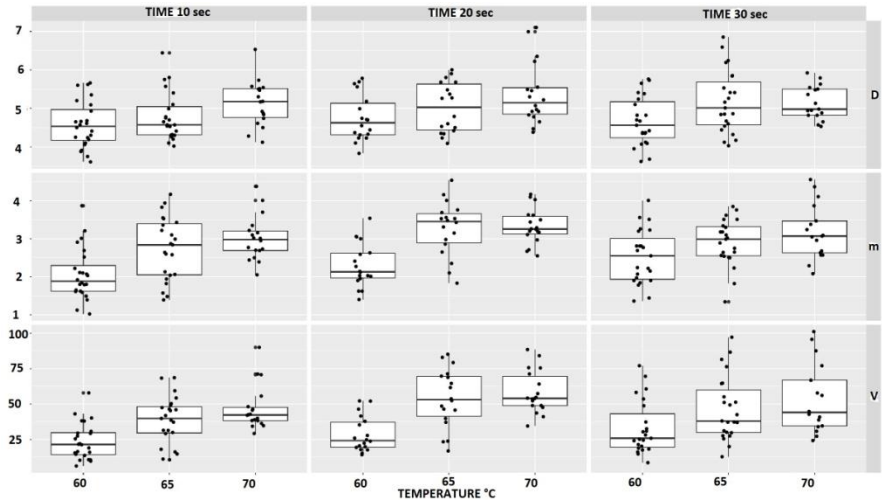


Figure 7

Box plot temperature: which shows the effect of temperature on the dimensions of the lesion as different parameters vary (time). (D: width (mm); m: depth (mm); V: volume)

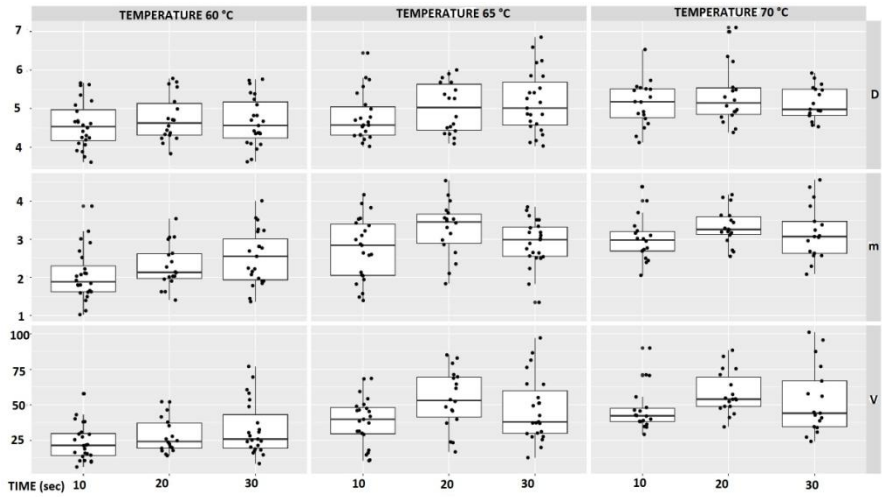


Figure 8

Box plot of time, which shows the effect of time on the lesion dimensions as different parameters (temperature) vary (D: width (mm); m: depth (mm); V: volume)

A multivariate linear regression model was employed to evaluate the impact of two primary predictor variables—temperature (65°C and 70°C) and ablation time (20 seconds and 30 seconds)—on lesion volume. The analysis quantified the relationship between these variables and the resulting lesion volumes.

The reference group consisted of lesions created at a temperature of 60°C with an ablation time of 10 seconds. When comparing this reference group to the lesions produced at 65°C with the same ablation time of 10 seconds, a significant increase in lesion volume was observed (23.57 ± 12.81 mm^3 vs. 38.42 ± 16.86 mm^3; $p<0.0001$), while all other parameters were kept constant.

When comparing the ablation group created at 70°C for 10 seconds to the reference group (60°C for 10 seconds), there was a significant increase in lesion volume (23.57 ± 12.81 mm^3 vs. 46.88 ± 15.62 mm^3; $p<0.0001$). Similarly, when comparing the group with ablation at 60°C for 20 seconds to the reference, a significant increase in lesion volume was also observed (23.57 ± 12.81 mm^3 vs. 28.52 ± 12.50 mm^3; $p=0.0016$). Additionally, the ablation group at 60°C for 30 seconds demonstrated a significant increase in lesion volume compared to the reference (23.57 ± 12.81 mm^3 vs. 33.09 ± 18.88 mm^3; $p=0.0114$).

Increasing the temperature from 60°C to 65°C and 70°C during a 10-second ablation significantly increased lesion volume (23.57 ± 12.81 mm^3; 38.42 ± 16.86 mm^3; 46.88 ± 15.62 mm^3; $p<0.001$). Similarly, at a constant temperature of 60°C, extending the ablation time from 10 seconds to 20 and 30 seconds also resulted in a significant increase in lesion volume (23.57 ± 12.81 mm^3; 28.52 ± 12.50 mm^3; 33.09 ± 18.88 mm^3; $p=0.0035$). The data indicated that temperature elevation had a greater impact on lesion volume than increasing ablation time. As there was no interaction effect in the model, the effects of temperature and ablation time were additive ($p=0.5939$). The additive effects suggest that each variable's impact on lesion volume was independent of the other, and their contributions were simply added.

In our experiments, we successfully generated precise and reproducible ablation patterns through the utilization of a contact force limiter in conjunction with a robotic arm. Our primary objective was to maintain a constant contact force and ensure fully stable catheter positioning. To achieve this, we employed a custom-designed and fabricated contact force limiter, which was integrated into the robotic arm's grip. This combination allowed us to consistently apply a stable contact force, thereby ensuring reliable and steady catheter positioning throughout the procedures.

Using this equipment, we achieved consistent and reliable results, particularly in controlling the depth and width of the lesions, which underscored the reliability and reproducibility of the robotically controlled technique. The ability to maintain volumetric consistency was a critical factor throughout the procedure. The robotic arm's precise controllability and stability significantly reduced the risk of unintended tissue damage by preventing the application of excessive temperatures. Our experiments demonstrated that the use of the robotic arm minimized operator influence, reduced the likelihood of human error, and enabled precise positioning of ablation points, thereby enhancing the accuracy of lesion measurement.

4 Discussion

During RF ablation, the formation of sharp-edged lesion contours is indicative of homogeneous tissue damage, which is crucial for the success of the procedure. In our experiments, we consistently observed the presence of sharp-edged contours. This characteristic allows for the accurate prediction of lesion depth and width, which is essential for optimizing the ablation process [33].

The literature indicates a significant correlation between lesion size and the increase in temperature and duration of energy application during RF ablation. Specifically, as temperature rises, both the depth and width of lesions tend to increase, demonstrating a linear relationship between applied temperature and lesion size. Our experiments corroborated these findings: when the ablation time was held constant and the temperature was increased, we observed a corresponding increase in lesion size. Additionally, extending the ablation duration resulted in a significant increase in both the depth and width of the lesions, underscoring a positive correlation between ablation time and lesion size. In our study, the largest lesion volumes were observed in the group subjected to a temperature of 70°C for 20 seconds [34][35].

Our current findings on lesion depth and width were compared with data from existing literature, which consistently shows an increase in both parameters with rising temperature during RF ablation. For instance, at a setting of 60°C, the literature reports lesion depths of 1-2 mm at 10 seconds, which aligns with our measurement of 2 mm. At 20 seconds, reported depths range from 2-3 mm, consistent with our results. However, at 30 seconds, while the literature cites depths of 3-4 mm, our average measurement was slightly lower at 2.5 mm. The reported lesion widths in the literature for 60°C vary from 3-4 mm to 5-6 mm depending on the duration, and in our study, the lesion widths ranged from 4-5 mm, increasing with longer ablation times.

When comparing results at 65°C, literature suggests lesion depths increase from 2-3 mm at 10 seconds to 4-5 mm at 30 seconds, with corresponding widths increasing from 4-5 mm to 6-7 mm. Our findings at this temperature showed lesion depths between 2-3 mm and widths between 4-5 mm, which are within the lower range of the published data. At 70°C, the literature typically reports lesion depths of 5-6 mm and widths of 7-8 mm [35-37]. In contrast, our experiments at this temperature produced lesion depths of 3-4 mm and widths of 5-6 mm.

In in vitro studies, lesion volume typically increases with both temperature and duration of RF ablation. At 60°C, lesion volumes are generally around 0.1 cm^3 at 10 seconds, 0.2 cm^3 at 20 seconds, and 0.3 cm^3 at 30 seconds. At 65°C, volumes increase to approximately 0.2 cm^3 at 10 seconds, 0.4 cm^3 at 20 seconds, and 0.4 cm^3 at 30 seconds. Similarly, at 70°C, the lesion volumes range from 0.3 cm^3 to 0.5 cm^3 over the same time intervals. Our results corroborate these findings, demonstrating that lesion volumes increased with both temperature and duration.

Specifically, at 60°C, we observed an increase in lesion volume from approximately 0.23 cm^3 at 10 seconds to 0.28 cm^3 at 20 seconds and 0.33 cm^3 at 30 seconds. At 65°C, the volume increased from 0.38 cm^3 to 0.53 cm^3, and at 70°C, from 0.46 cm^3 to 0.58 cm^3 over the same durations. Notably, our study identified the combination of 70°C and 20 seconds as yielding the largest lesion volume, which is consistent with the existing literature [37-40].

However, it is critical to acknowledge that in a clinical setting, lesion volume can be influenced by numerous other factors. For example, in our study, we did not record the energy curve of the delivered energy, the catheter position was kept stable, a non-irrigated catheter was used, and the contact force was consistently maintained using a contact force measurement device. These controlled conditions differ from the more variable clinical environment, which can impact lesion volume outcomes.

In our experiments, the use of a robotic arm facilitated the achievement of accurate and reproducible ablation patterns, highlighting its advantages in ensuring consistent and reliable outcomes, particularly concerning the depth and width of lesions. The precision offered by the robotic arm reduced the risk of unwanted thermal damage, as it enabled meticulous control over the ablation parameters. This precise control enhanced the reproducibility and uniformity of the lesions, thereby supporting the development of optimal lesion geometry.

The robotic arm also permitted real-time monitoring and immediate adjustment of energy delivery, contributing to both the safety and efficiency of the procedure. Although our setup did not incorporate real-time feedback to the robotic arm regarding energy delivery, the stability provided by the robotic arm was crucial. It allowed for rapid and reliable adjustments when necessary, significantly improving the consistency of results compared to manual testing. Overall, the robotic arm demonstrated substantial benefits in terms of procedural reliability and consistency, surpassing manual methods in accuracy and reproducibility.

The integration of robotic systems into interventional cardiology has introduced advanced, safe, and efficient tools that enhance procedural speed and accuracy while minimizing the risk of long-term injury to operating staff [41][42]. These systems enable operators to execute precise and intricate endoscopic maneuvers that are often challenging to achieve with traditional instruments. Such capabilities have been extensively investigated under in vitro conditions [19].

We selected the robotic arm for our experiments due to its proven relevance in contemporary robotic systems currently in use and under investigation. Manual catheter manipulators, such as the Sensei robotic navigation system (Hansen Medical Inc., Mountain View, CA, USA) and the AMIGO remote catheter system (Catheter Robotics Inc., Mount Olive, NJ, USA), operate on principles similar to manual techniques. Additionally, system-specific catheter manipulators, like the Niobe magnetic navigation system (Stereotaxis Inc., St Louis, MO, USA) and the catheter guidance control and imaging system (Magnetecs Corp., Inglewood, CA,

USA), offer targeted advancements in precision and control [44][45]. Hybrid systems, such as Stereotaxis combined with the V-drive system and V-sono platform, represent an integration of these technologies [20-22].

Robotic systems are designed to match or exceed the procedural efficiencies of manual techniques, with the ultimate goal of improving overall procedural effectiveness. This improvement enables a higher number of ablation procedures to be performed in shorter timeframes with reduced operator fatigue [22]. The sustainability of these systems is increasingly vital [46]. Recent studies indicate a growing preference for robotic-assisted interventions across various medical disciplines, including oncology, suggesting their anticipated expansion into invasive cardiology [47][48]. Such systems promise ethical and predictable application of advanced technology [49].

The practical implications of our research are significant in determining the optimal temperature and ablation parameters necessary to achieve the desired lesion size. This has the potential to enhance clinical procedures by increasing their efficiency and safety. Our findings may contribute to the further development of robotic ablation systems that produce more precise and consistent results, thereby improving the reproducibility of procedures and enhancing treatment protocols and clinical outcomes. Moreover, our results could encourage further research aimed at optimizing ablation techniques, particularly in the context of personalized medicine. In the future, ablation treatments could be tailored to individual patients, taking into account specific tissue and anatomical characteristics, thereby advancing the field toward more patient-specific therapeutic strategies.

We aim to enhance the clinical applicability, by integrating an irrigation catheter and employing a perfusion system to ensure tissue viability. We plan to further investigate the functional capabilities of the robotic arm configuration and offer detailed recommendations for clinical applications.

Limitations

In our experiments, the electrode used had a diameter of 4 mm, and the design led to occasional bending. However, the robotic arm was able to detect these deviations in real-time, allowing for corrections to ensure accurate measurements. In a clinical setting, various sheaths are typically employed to maintain electrode stability, but these could not be integrated into our experimental setup. Additionally, due to the endocardial structure of the heart tissue, the electrode could potentially penetrate beneath the surface, despite efforts to avoid sub-surface ablation. For optimal and reliable data, it is recommended to use heart tissue that is as fresh as possible, a point also emphasized by other researchers conducting in vitro experiments.

Another limitation of our study was that the contact force was kept constant throughout the experiments, and thus, we did not explore its impact on lesion formation. In a clinical environment, particularly in a beating heart, the contact force is inherently variable, which could influence the outcomes. Furthermore, the

catheter was positioned perpendicular to the tissue during ablation, which does not fully replicate the variability in catheter positioning encountered in vivo. These factors should be considered when interpreting the results and designing future studies.

Conclusions

Our study validates that the integration of robotic arm assistance and contact force limiter in RF ablation procedures, significantly enhances the precision and the reproducibility of results, particularly in in vitro experiments, using porcine tissues. By establishing optimal temperature and ablation duration parameters, we were able to minimize unintended tissue damage and achieve greater control over lesion depth, width and volume. The findings underscore the potential of robotics, in electrophysiological interventions, for reductions in operator error and enhancement of the safety and efficiency of these procedures. Moreover, our research provides a valuable contribution to the ongoing development of procedures involving constant contact force, paving the way for more refined and reliable ablation techniques.

Acknowledgements

The ex vivo porcine tissue RF ablation experiments were conducted at the Antal Bejczy Center for Intelligent Robotics. We utilized the Universal Robots UR16e robotic arm in conjunction with the OnRobot RG6 gripper. Valuable guidance for the experimental setup was provided by Tivadar Garamvölgyi from the University Research and Innovation Center at Óbuda University. The experimental work benefited from the assistance of Sándor Tarsoly (Óbuda University, University Research and Innovation Center), Givi Damenija, and Orsolya Utasi from Semmelweis University. The Stockert RF generator was kindly loaned to us by the Biosense Webster company, with special thanks to Ádám Sándor for his support in addressing technical issues. Zsolt Marton fabricated the copper table used for grounding. We also appreciate the professional advice of József Gulyás and Tibor Balázs from Biotronik Hungária Kft. Finally, we are grateful to Dr. habil Tamás Ferenci for his assistance with the evaluation methodology. T. Haidegger is a Consolidator Researcher, receiving financial support from the Distinguished Researcher program of Óbuda University. His research has been partially supported by the National Research, Development, and Innovation Fund of Hungary, financed under the TKP2021-NKTA-36 funding scheme, at Óbuda University.

No commercial financial support was provided for this study.

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