Assessment of Renal Artery Ablation Efficacy Based on Intravascular Ultrasound

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Abstract. Aiming at the problems that existing Renal Denervation (RDN) systems cannot evaluate ablation depth and whether renal sympathetic nerves are ablated, and that the Renal Nerve Stimulation (RNS) method has not entered the clinical application stage, this study proposes a method to assess the success of renal artery ablation surgery based on intravascular ultrasound observation. Leveraging the advantages of ultrasound in nerve imaging and the application characteristics of intravascular ultrasound, a 40 MHz high-frequency ultrasound imaging transducer and an ultrasonic ablation transducer were used. First, the transducer parameters were tested to ensure performance compliance. Subsequently, ultrasound imaging was performed on isolated porcine renal arteries to clarify the ultrasonic morphological characteristics of single renal sympathetic nerves, and ultrasound image changes before and after ablation were compared. On this basis, by observing post-ablation nerve image changes, the criteria for judging the feasibility and safety of ultrasonic ablation of renal artery sympathetic nerves were determined, which were then used to assess surgical success. Results show that the proposed method can clearly identify renal sympathetic nerves and has unique advantages in observing ablation effects, providing an effective basis for evaluating surgical implementation.

Keywords: Intravascular Ultrasound Imaging, Renal Sympathetic Nerves, Ultrasound, Ablation.

1. Introduction

Hypertension, a key modifiable risk factor for cardiovascular diseases and mortality worldwide, affects over 1 billion people. For refractory hypertension, traditional intensive drug therapy often faces challenges such as poor adherence, cumulative drug side effects, and ineffective blood pressure control in some patients. Against this backdrop, Renal Denervation (RDN) has emerged as an interventional treatment. Recent clinical trials, including the SPYRAL HTN [1-3] series (radiofrequency), RADIANCE-HTN [4] series (ultrasound), and TARGET BP I ON-MED [5] (alcohol), have confirmed the efficacy of RDN. By addressing the disappointing results of the SYMPLICITY HTN-3 [6] trial, these three clinical trials have ushered RDN into a new era for hypertension treatment [7]. However, all three systems fail to assess ablation depth or confirm whether renal sympathetic nerves have been ablated, making it difficult to judge RDN success. Renal Nerve Stimulation (RNS), a method that uses intravascular electrical autonomic nerve stimulation to select ablation targets and determine RDN endpoints [8], is currently considered the most effective approach but has not yet been clinically applied.

Ultrasound offers unique advantages in nerve imaging: high-frequency ultrasound (>10 MHz) can image small nerve fibers [9-10]. Clinically, ultrasound is widely used in diagnosing and treating conditions such as traumatic nerve transection and neurofibroma. While intravascular ultrasound is extensively applied in percutaneous coronary intervention, it has not been used to observe renal sympathetic nerves around renal arteries. Thus, careful observation of intravascular ultrasound images may enable the identification of renal sympathetic nerves parallel to renal arteries. Shunsuke Satou et al. [11] attempted to observe renal sympathetic nerves using intravascular ultrasound and detected them in images, but they neither observed ultrasound images of single renal sympathetic nerves nor compared images before and after ablation. Meanwhile, ultrasound energy is widely used in clinical ablation therapy. Due to the high sensitivity of lipid bilayer membranes (a unique structure of nerves) to acoustic energy, low-dose acoustic energy can achieve renal artery nerve ablation (RDN).

This characteristic not only improves RDN safety but also enhances treatment efficiency, making ultrasound energy an ideal energy source for RDN.

In this study, a high-frequency ultrasound imaging transducer (40 MHz) and an ultrasonic ablation transducer were used. Based on ultrasound imaging of renal sympathetic nerves, changes in ultrasound images before and after ablation were compared to evaluate the feasibility and safety of ultrasonic ablation of renal artery sympathetic nerves. This provides an effective technical means for clinically judging whether ultrasound-guided RDN therapy is performed standardizedly. The data is from “TRUEVISION Intravascular Ultrasound Imaging Catheter”

2. Transducer Parameter Testing

2.1. Parameter Testing of Ultrasound Imaging Transducer

The performance of the high-frequency ultrasound imaging transducer was tested using a KS107BG standard phantom. The measured operating frequency ranged from 34 MHz to 46 MHz, with an imaging radius of no less than 6 mm. Both axial and lateral resolutions exceeded 0.5 mm, meeting the phantom’s minimum resolution standards, and the geometric accuracy errors in longitudinal and transverse positions were within 10%.

2.2. Parameter Testing of Ultrasonic Ablation Transducer

The ultrasonic ablation transducer was immersed in degassed water, and the ultrasonic power receiving array element was aligned with the ablation transducer. The output power of the ultrasonic power host was adjusted to achieve acoustic power readings of 1.0 W, 1.5 W, 2.0 W, 2.5 W, and 3.0 W. The immersed ultrasonic ablation transducer generated visible water splashes. The experimental results are shown in Figure 1.

The ablation transducer was inserted into a temperature-testing model composed of coupling agent and 60°C thermochromic pigment. Thirty seconds after activating the ultrasonic power host, obvious color changes were observed in the ablation area of the model, indicating that the ultrasonic ablation temperature exceeded 60°C. The color-changing area was consistent with the direction of acoustic energy propagation.

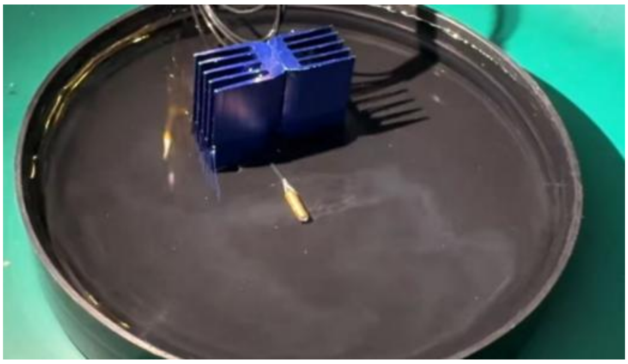

Figure 1. Water splashes generated by the ultrasonic ablation transducer during operation in water

3. Ultrasonic Imaging Observation of Renal Arteries

In this experiment, an ultrasound imaging transducer was used to perform ultrasound imaging on a segment of isolated porcine renal artery. After isolating a small number of single renal sympathetic nerve fibers from the tissue surrounding the renal artery, the catheter was rotated to ensure the renal sympathetic nerve fibers fell within the imaging range of the ultrasound imaging probe. Subsequently, the ultrasonic morphological characteristics of the single renal sympathetic nerve fibers were observed, and the relevant images are shown in Figure 2. This structure is highly consistent with the renal nerve fibers in renal artery section data reported by Sakakura K [12] et al., confirming that the structure in Figure 2 is a renal sympathetic nerve fiber.

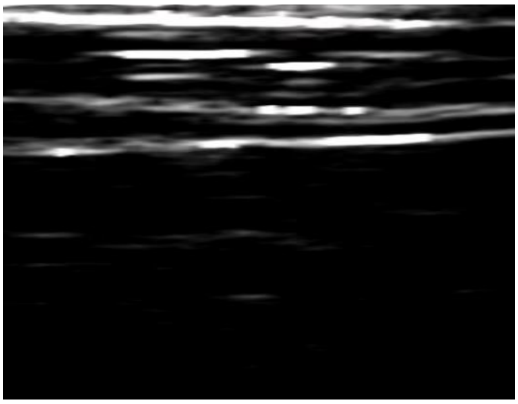

Figure 2. High-frequency (40 MHz) ultrasound image of a single renal sympathetic nerve fiber

In the ultrasonic tomographic images along the long axis of the renal artery, single renal sympathetic nerve fibers appeared as tubular hyperechoic structures. Image analysis revealed that this tubular structure consists of two relatively parallel linear hyperechoic bands with a distinct hypoechoic area between them, forming a typical "double-hyperecho surrounding hypoecho" imaging pattern.

This specific ultrasonic imaging pattern can be explained by the structural properties of nerve tissue and ultrasound propagation laws. On one hand, nerve tissue has a unique lipid bilayer membrane, whose acoustic impedance differs significantly from that of surrounding connective tissue and adipose tissue, resulting in hyperechoic signals in images. On the other hand, nerve fibers are rich in water, which weakly attenuates ultrasound and allows strong ultrasound penetration, making this area appear hypoechoic in images.

It should be noted that the resolution of ultrasound images is largely affected by the frequency of the ultrasound imaging transducer. Limited by the frequency characteristics of existing transducers, the lipid bilayer membrane structure of small renal sympathetic nerve fibers (diameter < 50 μm) cannot be clearly resolved. Thus, these fibers do not exhibit the "double-hyperecho surrounding hypoecho" layered feature in ultrasound images, but only appear as single, non-stratified hyperechoic lines.

4. Post-Ablation Ultrasonic Imaging Observation

Before ablation, a high-frequency ultrasound imaging transducer was used to image isolated porcine renal artery segments. In high-frequency ultrasound images, renal artery sympathetic nerves appeared as fascicular hyperechoic structures, with multiple parallel but discontinuous linear hyperechoic signals inside and interspersed hypoechoic areas. The specific imaging features are shown in Figure 3.

After ultrasonic ablation, the aforementioned echo structure underwent visible blurring: not only did the clarity of the structure’s edges decrease significantly, but the internal linear structures also showed obvious morphological changes. The post-ablation images are also shown in Figure 3 for comparison.

Physicochemical changes in renal artery tissue during ultrasonic ablation caused significant differences in ultrasound images. Under the action of ultrasonic ablation energy, the renal artery and surrounding nerve tissue undergo local ablation: on one hand, high temperatures denature tissue proteins, disrupting their ordered spatial conformation and forming irregular aggregation or coagulation. This structural change significantly alters the acoustic impedance of the tissue, increasing the impedance difference with unaffected surrounding tissue and enhancing ultrasound reflection in the denatured protein area. On the other hand, ablation accelerates water loss in nerve fibers; since water strongly penetrates ultrasound, reduced water content enhances ultrasound reflection in nerve fiber tissue. These two factors—increased impedance difference due to protein denaturation and enhanced ultrasound reflection due to reduced nerve fiber water content—collectively increase the brightness of the corresponding area in ultrasound images, resulting in visible image changes.

(a) High-frequency ultrasound image of renal sympathetic nerves in isolated porcine renal arteries (before ablation)

(b) High-frequency ultrasound image of renal sympathetic nerves in isolated porcine renal arteries (after ablation)

Figure 3. Comparison of high-frequency ultrasound images of renal sympathetic nerves in isolated porcine renal arteries before and after ultrasonic ablation

5. Conclusion

Ultrasound imaging offers unique advantages in nerve visualization. When observing renal sympathetic nerves in isolated porcine renal arteries using a high-frequency ultrasound imaging transducer, pre-ablation nerves appeared as clear hyperechoic linear structures with continuous morphology and distinct boundaries, easily distinguishable from surrounding tissue. Post-ablation, the ultrasonic structure of the nerves exhibited significant visible changes: first, echo intensity increased markedly with enhanced local signal brightness; second, the originally clear linear structure became blurred, showing an irregular, fuzzy morphology. By comparing pre- and post-ablation images, the effect of ultrasonic ablation on renal sympathetic nerves can be intuitively judged, providing direct evidence for evaluating ablation safety and efficacy.

Optical Coherence Tomography (OCT) is another intravascular imaging technique for vascular wall observation. Delgado et al. reportedly used OCT to observe the inner wall of renal arteries after RDN in a porcine mode. However, OCT has limited imaging depth and requires large amounts of contrast agent to fill the renal artery, which limits its clinical application for observing extravascular sympathetic nerves in renal arteries.

Therefore, observing morphological changes in nerves via ultrasound imaging after renal artery ablation surgery can evaluate the feasibility and safety of ultrasonic ablation of renal artery sympathetic nerves, providing a useful tool for clinically judging whether ultrasound-guided RDN therapy is performed correctly.

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