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A feasibility study of a novel spectral method using radiofrequency ultrasound data for monitoring laser tissue ablation

Enrico Vannacci [a], Simona Granchi [a,*], Luca Breschi [b], Elena Biagi [a]

[a] *Department of Information Engineering (DINFO), University of Florence, Via Santa Marta 3, 50139 Florence, Italy*
[b] *Elesta S.r.l, Calenzano, Florence, Italy*

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ABSTRACT

This paper presents preliminary results of a new non-invasive ultrasound monitoring method called TUV (Thermotherapy Ultrasonic View) able to investigate structural tissue modifications caused by minimally invasive percutaneous laser ablation. The method, based on the spectral analysis of the raw ultrasound radiofrequency signal, develops spectral parameters in a multidimensional space and its N dimensions are represented by the central frequencies of the sub bands the signal spectrum is decomposed into. Signal processing has been performed on the data related to 7 laser treatments performed on 4 samples of removed prostatic glands which underwent laser ablation at power of 3 W, 4 W and 5 W and energy of 1800 J. In this preliminary study, clusters of these parameters, referred to tissue areas at different distances from the light laser source, modified their shape and position in different ways, during ablation treatment. TUV results have been represented by a chromatic code superimposed to the corresponding ultrasound conventional image, in order to highlight the alteration intensities occurred in the ablated tissue. Resulting images of ablated area have been compared to histological specimens to evaluate the degree of similarity between them by means of Dice and Jaccard coefficients.

1. Introduction

The recent development of minimally invasive therapeutic tools and procedures can significantly change the approach to any early treatment of disease, thus improving the patient's quality of life and significantly cutting management costs. Heat ablation represents one the most effective minimally-invasive therapies [1–4]. Today, the most widely methods used in clinical practice for heat ablation therapy are radiofrequency ablation (RFA), microwave ablation (MWA), laser interstitial thermal therapy (LITT) and high intensity focused ultrasound (HIFU). [5–12]

Although the advantages and disadvantages of one technique with respect to the other ones are still under investigation in several fields [1,4–11], the LITT has shown peculiar features. Indeed, the intrinsic characteristics of laser light combined with tissue-penetration control, depending on the exploited wavelength, allow an optimal penetration associated with a lower temperature gradient throughout the ablation zone, thus granting less risk of carbonization and vaporization of tissue [12–14]. Furthermore laser ablation achieves good results in the treatment of tumours smaller than 2 cm thanks to its lower complication rates in respect of other techniques [12,15,16].

The success of ablation therapy is highly dependent on real-time monitoring of the ablation extent and monitoring the treated area is of vital importance to avoid necrosis of healthy tissue and ensure a complete treatment of the target area [17–22]. For this reason, real-time monitoring must have some important requirements, such as high frame/rate, minimal invasive standard and a user-friendly interface for the physician. Currently, non-invasive monitoring techniques have been used exploiting magnetic resonance imaging (MRI), computed tomography (CT) and also ultrasound imaging [23–25]. Despite their spatial high-resolution [26–28], MRI and CT-based ablation monitoring have several disadvantages, such as requiring specialized equipment for compatibility, together with limitations in real-time application. Meanwhile, ultrasound equipment has garnered interest [25,29] thanks to its wide availability, relatively low cost, portability and easiness to be used without adding any significant constraints. However its chief failing consists in difficulty in identifying the treated area by using conventional B-mode images, and sometimes, in overestimation of the ablation extension [30]. Several processing techniques such as the study of the pixel shift or ultrasound elastography [31–38] have been applied to augment conventional images for

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[*] Corresponding author at: Ultrasound and Non-Destructive Testing Lab, Department of Information Engineering (DINFO), University of Florence, via Santa Marta 3, 50139 Florence, Italy.

E-mail address: simona.granchi@unifi.it (S. Granchi).

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monitoring the ablation zone. The recent review article by Lewis [25] presents an extended overview of the different techniques for processing the ultrasound signal as to ablation monitoring and it highlights both the important improvements already achieved and the persistent difficulty in correctly correlating the temperature value with the effective tissue damage extension. The paper also mentions several algorithms based on spectral analysis of the radiofrequency (RF) ultrasound signal, which has opened up further potential in the use of ultrasound for tissue differentiation, so as to support physicians in early diagnosis and monitoring before, during and after mini-invasive operations [30,39]. Indeed, the ultrasound RF echo signal from soft tissue is the result of a close interaction between the mechanical energy of the wave and the structure it goes through [40].

In order to gain additional information for tissue characterization and differentiation purposes, it is essential to not only preserve the amplitude of the RF signal, as performed by the conventional ultrasound scanners for representing the B-mode images, but analyse the entire content of the signal: amplitude, phase and frequency. Therefore, out of the spectral features of this signal, it is possible to extract information concerning the encountered structures.

In this study, the proposed processing method, called TUV (Thermotherapy Ultrasonic View), analyses the evolution of spectral parameters in an N-dimensional hyperspace, as defined in [41–43] before, during and after laser ablation, in order to evaluate the correlation with the structural alterations suffered by the tissue. Preliminary processing has been performed on a dataset of RF signals from four ex- vivo prostatic glands with Benign Prostatic Hyperplasia (BPH) in order to distinguish the treated area from the surrounding tissues and monitor the evolution of the damage.

2. Materials and methods

2.1. Analysis algorithm TUV

The TUV investigation method proposed in this work is based on the study of spectral coefficients in N dimensional hyperspace generated as explained in details in the authors' previous papers [41–43]. The signal processing algorithm previously presented and called HyperSPACE [42], is able to characterize biological tissue in different physiological conditions by means of the RF ultrasound signal. Already tested for breast nodule characterization, it has obtained a sensitivity of 92.2% and a specificity of 93%, in Fibroadenoma and Infiltrating Ductal carcinoma differentiation [41].

HyperSPACE generates coefficients, named *hs*, by means of several processing steps. In the first step, the ultrasound RF signal is filtered through a bank of N filters, performing an N spectral sub-band decomposition of the signal spectral band. In the second step, coefficients are processed in order to make the signal independent from any amplitude variations determined by the settings of the instrumental acquisition set-up, such as Time Gain Control (TGC), emission power, or ultrasonic signal gain [42]. The algorithm normalizes the spectral coefficients by dividing each of them by the mean value of spectral coefficients referred to the sub bands covering the −12 dB bandwidth of the transducer and thus obtaining the *hs* coefficients [42]. For each RF frame, N matrices of *hs* coefficients are generated and analysed in a multidimensional spectral hyperspace the dimensions of which are represented by the central frequencies of the related sub-bands. In this hyperspace, which is a new domain, each point of RF frame is depicted by means of the *hs* coefficients which represent its new coordinates [42]. In this paper, the signal was decomposed into 24 sub bands with a band-

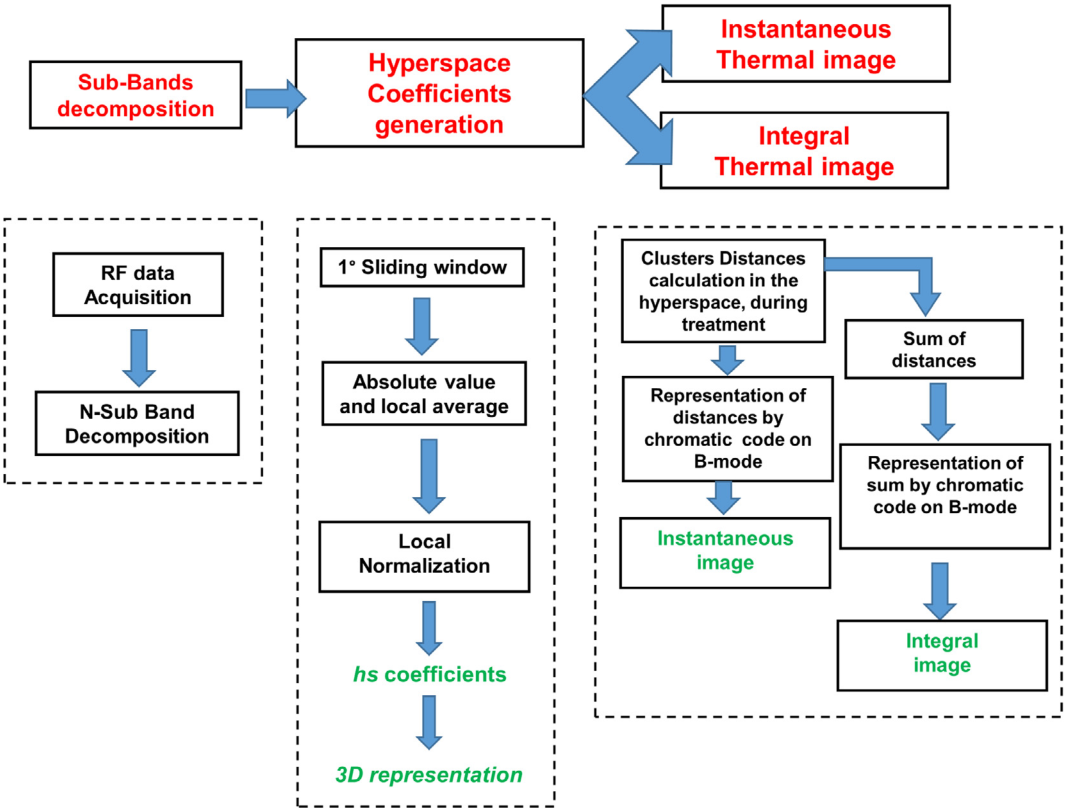

Fig. 1. Block diagram of TUV (Thermotherapy Ultrasonic View) procedure. In the first stage, a decomposition of the radiofrequency signal spectrum into 24 sub bands by means of a bank of filters is performed. In the second Hyperspace (*hs*) coefficients are generated and analysed in a multidimensional spectral hyperspace. The last step brings forth Instantaneous and Integral images, representing the distances between the positions at two different time steps of each point in the hyperspace. These distances are depicted by means of a chromatic code superposed to B-mode image.