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In-body ultrasound image processing for cardiovascular interventions: A review

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ABSTRACT

In this paper we have surveyed the recent developments in the area of in-body ultrasound imaging for cardiovascular interventions. With miniaturized ultrasound sensors integrated at the tip of the instruments (catheters, needles, endoscopes), the local anatomical sites can be imaged with high accuracy. We have covered the applications of TEE (Transesophageal echocardiography), ICE (intracardiac echocardiography) and IVUS (intravascular ultrasound) and the newly emerging therapy monitoring ultrasound. We particularly focus on advanced signal/image processing technologies and related topics such as tissue characterization, image segmentation, device tracking and multi-modality registration. In the context of in-body imaging, we are faced with more challenges than with the traditional external ultrasound imaging, particularly due to the cardiac dynamics. We need to strive for new solutions that provide more consistent, reliable and accurate analysis results for better clinical decision support.

1. Introduction

In recent years, more and more minimally or non-invasive interventional procedures have been replacing traditional open surgeries. Surgical instrumentation is being substituted by intelligent and miniaturized tools that navigate in the human body for the diagnosis and/or treatment. Examples of such devices are catheters, guide wires, needles and endoscopes. The advantages of using minimally invasive procedures are shorter patient recovery time, greater patient comfort, lower risks of complications and faster patient throughput [1,2].

Imaging is very crucial for image-guided interventions as it provides important information for the diagnosis and treatment. Mostly used imaging modalities include X-ray/fluoroscopy, computed tomography (CT), magnetic resonance imaging (MRI), ultrasound, nuclear imaging and optical imaging. They are used extensively during various steps in an interventional procedure, as illustrated below [1,3].

- Pre-operative imaging: prior to the intervention, usually CT/MRI images are acquired which are later used as references during the interventional procedure.
- Intra-operative imaging: The surgical instruments are inserted into the body and navigated to the target location. Usually X-ray or ultrasound is used to offer real-time navigation and monitoring. In many cases the real-time acquired images have to be registered and mapped to the pre-operative data to provide a clear view of the device relative to the patient anatomy. In some cases, the intra-operative imaging can offer on-the-spot therapy monitoring and provide real-time feedback to the physicians. During this stage, both external and internal imaging technologies can be used to track and monitor the interventional process.
- Post-operative verification and validation: after the intervention a confirming image is obtained to verify the successful completion of the procedure.

Intra-operative imaging plays a very important role in a complete interventional procedure. It provides a vision to the physicians during the procedure and gives real-time feedback that is of vital importance for the final outcome. Ultrasound is a promising modality to use nowadays for intra-operative imaging, largely because it is nonionizing and safe to use for both the patients and the physicians. Additional benefits are lower-cost and its ability to penetrate through the tissue structures. It is the only imaging modality that is capable of imaging soft tissue deformations quickly enough for interventional procedure guidance – information that fluoroscopy, CT or MRI cannot provide easily [4]. A disadvantage of using ultrasound is the lower signal quality which makes the image interpretation more difficult.

In addition to imaging, the instrument development has enabled the miniaturization of build-in ultrasound sensors that are safe to be used inside the human body. These sensors can be integrated into the catheters or guide wires and directly placed into the body of the patients. They provide a local anatomical view for the diagnosis and treatment, acquiring information that is not easily accessible by traditional external imaging modalities. A few examples in the area of cardiovascular interventions are ICE

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(IntraCardiac Echocardiography), TEE (Transesophageal echocardiography) and IVUS (IntraVascular Ultrasound). Recently we are exploring the possibilities to integrate the tissue imaging with therapeutic functions, e.g. radio-frequency tissue ablations for the treatment of atrial fibrillation [5].

In the rest of the paper, we first present a brief overview of the clinical use of the in-body ultrasound imaging and related challenges in the area of cardiovascular interventions. We particularly focus on the signal/image processing aspects and present a few promising research areas that could have significant impact on the current practice of minimally invasive cardiovascular interventions.

2. In-body ultrasound imaging

2.1. In-body echocardiography

The traditional transthoracic echocardiography (TTE) has been widely available and portable which offers excellent image quality. It has been used mainly in guiding percutaneous noncoronary interventional and electrophysiological procedures [6]. Different from the traditional use of TTE, in-body cardiovascular imaging employs small ultrasound transducers or transducer arrays that are positioned within (or near) the heart/vessels inside the human body. By doing so, the imaging device is closer to the targeted imaging area and provides better view of local anatomical sites. In addition, it offers great flexibility and can be manipulated for more complicated procedures.

2.1.1. TEE (transesophageal echocardiography)

TEE has a small transducer array integrated into the probe, which is inserted into the patient's oesophagus to get a closer and more detailed view at the back of the heart. TEE has been widely used as an alternative to TTE in guiding complex procedures [4,7]. It can be used to image interventional catheters and offers clearer images at the back of the heart, especially of structures that are difficult to view transthoracically. It has been used to monitor a number of interventions such as percutaneous transcatheter closure (PTC) of septal defects, transseptal catheterization, etc.

2.1.2. ICE (Intracardiac echocardiography)

Although relatively new, ICE imaging catheters have gained wide usage for monitoring and guiding interventions such as ventricular septal defect (VSD) device closure, pulmonary vavuloplasy and biopsy of cardiac masses. Recently, ICE is also widely used for the guidance of electrophysiological (EP) procedures in combination with electroanatomical mapping for imaging internal structures [8,9]. The ICE catheters are positioned inside the heart chamber and provide both near and far field views. The near-field view provides sufficient details of endocardial structures and the intracardiac tools themselves, and the far-field view provides perspective and orientation information. They are made either with a rotational shaft or with phased-array. In Fig. 1, an example is given to illustrate the imaging capabilities of an ICE catheter.

2.1.3. IVUS (intravascular ultrasound)

Similar to the ICE catheters, IVUS catheters employ a rotational single-element ultrasound transducer or phased array to image from inside of the blood vessels. It allows the applications of ultrasound technology to see from inside the blood vessels out through the surrounding blood, visualizing the endothelium of blood vessels, particularly for coronary arteries. It can help to assess the free lumen and plaque area, estimate the volume and provide guidance for the stent placement. Fig. 2 shows an IVUS grayscale image in polar and Cartesian coordinates along with an example of a cut in the longitudinal pullback direction [11].

Another interesting aspect about IVUS is that this is an application where the ultrasound tissue characterization is extensively studied, including the pioneer application for pattern classification and machine learning technologies. For example, automatic segmentation algorithms are needed to delineate the vessel wall and lumen borders. Various classification methods are invented to be able to differentiate plaques. In Section 3.1 we will give a more detailed overview of related image interpretation and classification methods. Fig. 3 shows an example where the IVUS echo-diagram is colour-coded based on the classification results.

2.1.4. Therapy monitoring ultrasound

In addition to the more established clinical applications, we can also envision new emerging applications using the in-body ultrasound imaging tailored for specific application needs. In [5], we have combined imaging ultrasound transducers and therapeutic functions in a single RF ablation catheter, as shown at the left of Fig. 4. The catheter is designed for treating atrial fibrillation in minimally invasive electrophysiological procedures [13–16]. The aim of the imaging is to provide an internal endocardial view for the physicians to monitor the tissue structural change during the ablation procedure. At the right of Fig. 4, we have shown an example M-Mode ultrasound image which visualizes in real-time a right ventricle endocardial lesion. The red line indicates the change in ultrasound tissue contrast upon the energy delivery.

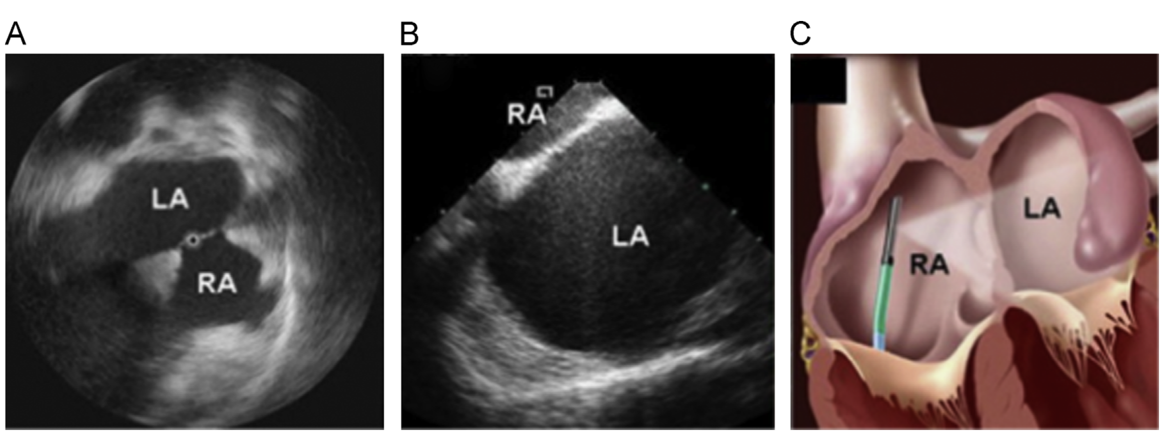

Fig. 1. (A) Rotational view of the right atrium (RA), left atrium (LA), and interatrial septum using a rotational ICE catheter. (B) 2D view of the interatrial septum using a phased-array ICE catheter. (C) Schematic drawing of a phased-array ICE catheter in the RA in the optimal position to image the interatrial septum [10].

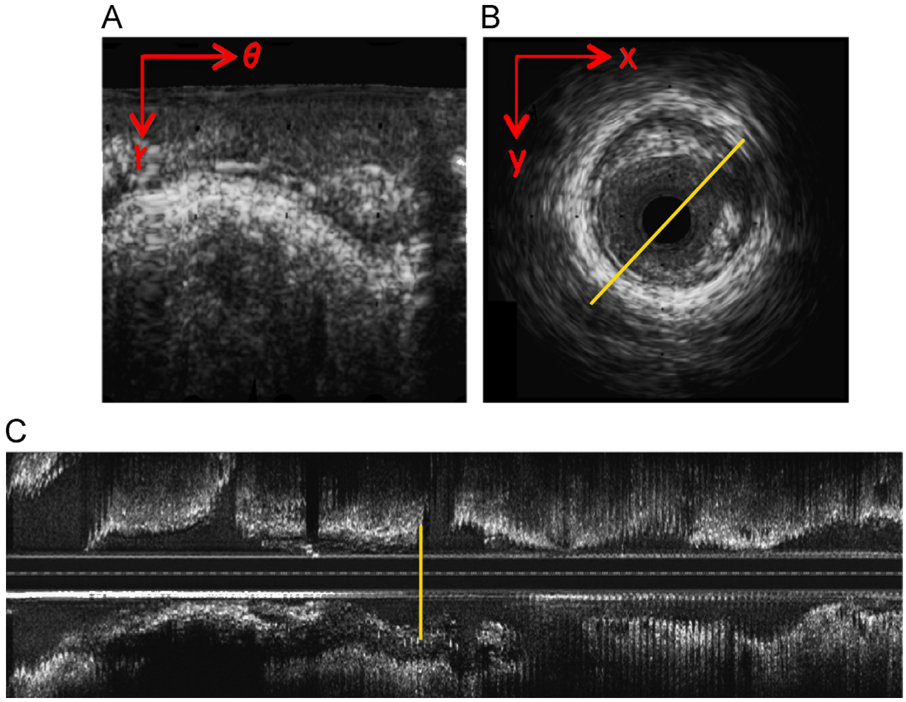

Fig. 2. IVUS grayscale image in (A) polar (r, θ) and (B) (x, y) Cartesian domains. (C) Longitudinal display along an arbitrary planar cut identified as the yellow line in (B) [11]. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

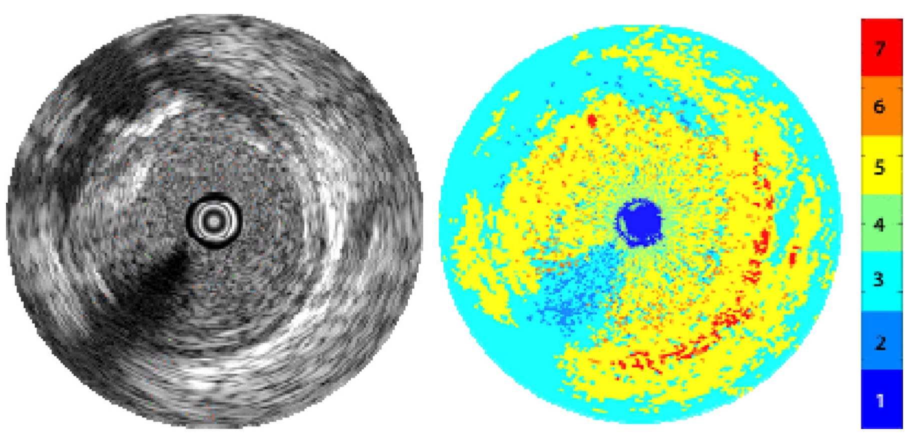

Fig. 3. Conventional IVUS image (left) and a colour-coded image showing automatic classification results. (1) catheter; (2) others; (3) shade of guide wire; (4) blood; (5) fibrous plaque; (6) media; (7) calcified plaque [12]. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

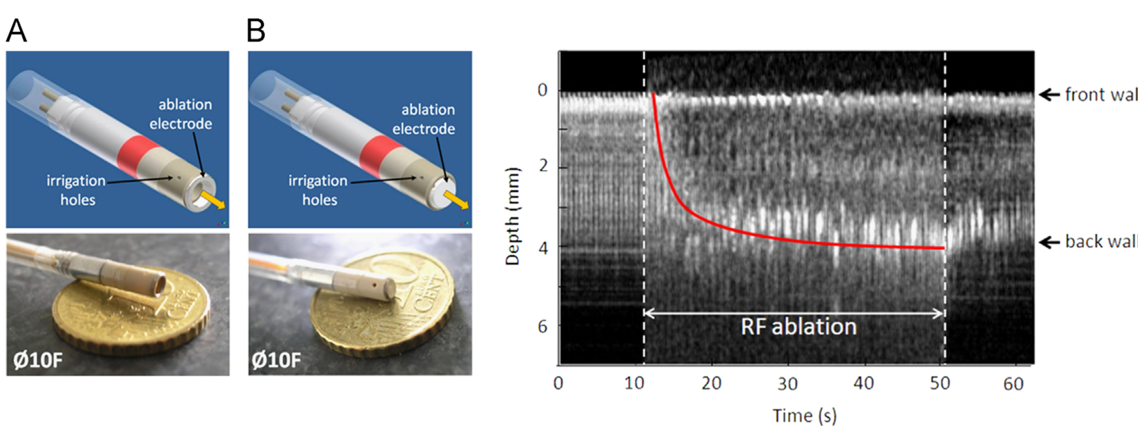

Fig. 4. Left: two different concepts of RF ablation catheters with integrated ultrasound imaging. (A) Catheter with platinum ring ablation electrode; (B) catheter with transparent ablation electrode, which is made of TPX; Right: Real-time visualization of an RV endocardial lesion [5].

2.2. Combination with other sensing modalities

Another trend in minimally invasive in-body sensing is to combine different imaging modalities as complementary means to achieve better understanding of the anatomic structures. In acoustic radiation force imaging (ARFI), short-duration acoustic radiation forces are applied to the tissue, which generate local sub-millimeter displacements that are monitored both spatially and temporally. These displacements represent a certain degree of tissue stiffness. In [17,18], an ICE catheter is used to acquire spatially registered B-mode and ARFI images, with the aim to quantify ablated lesion dimensions.

Another example is to combine the optical coherence tomography (OCT) with the intravascular ultrasound to offer both a finer resolution and higher penetration depth for improved tissue imaging [19]. Other examples include using ultrasound together with fluorescence spectroscopy or near-infrared spectroscopy [20]. Recently we have also observed a new trend to merge imaging sensors and functional sensors, integrating imaging, mapping and therapeutic functions into one single device.

2.3. Challenges

Compared to the traditional TTE imaging, in-body ultrasound devices are used in more complicated and highly variable imaging environment, giving rise to more challenges to the system design, image interpretation and system validation.

2.3.1. Instrumentation

Miniaturization is an important topic when building ultra-small ultrasound transducers. Compared to traditional piezoelectricity-based transducers, CMUT (capacitive micro-machined ultrasonic transducers) are new generation of ultrasound sensors where the energy transduction is due to the change in capacitance. CMUT sensors have much smaller dimensions and offer easy integration of large number of arrays. They provide higher bandwidth and higher sensitivity [21]. CMUT technology is particularly suited for high frequency arrays because the fabrication process used is routinely able to produce features several microns in size [22]. This is very suitable for imaging fine details over local structures. In [23,24], CMUT technologies have enabled the implementation of IVUS arrays for forward-looking imaging at the tip of a catheter.

2.3.2. Motion artefacts

For cardiac applications, the cardiac motion causes a lot of motion artefacts to the signals. In addition, due to the cardiac motion, it is very difficult to maintain a stable position for the imaging device, which results in a constantly moving imaging plane (or origin). This causes a lot of difficulties for the image interpretation and further analysis.

In addition to the cardiac motion, other physiological motions such as the respiratory motion also complicate the image interpretation. For example, in IVUS systems, the cardiac motion and vessel wall pulsation limit the accuracy and consistency of coronary lumen and plaque volume measurements. ECG-based gating is one of the commonly used methods to compensate for the motion [25]. However it requires the recording of ECG signals and may increase the image acquisition time. Other approaches using image-based gating are proposed to relieve these problems. For example in [26,27], image-based gating algorithms are proposed to find trigger times over the cardiac cycle without relying on the external ECG acquisition.

Instead of treating the motion as an interfering source, we can make use of cardiac motion to obtain information concerning the tissue properties such as used in the tissue Doppler imaging and the strain (rate) imaging. This topic will be revisited in Section 3.1.1.

2.3.3. Anatomical heterogeneity

For the in-body imaging, the imaging sensor has to be as close to the targeted site as possible, therefore the imaging results highly depend on local anatomical structures. Sometimes this can cause inconsistencies for the image interpretation. However, the localized view may be used in a positive way to help increase our understanding of detailed anatomical structures that might not be easily achievable with the external imaging. For example, in [28], the cavotricuspid isthmus (CTI) is located at atrium and crucial in the ablation of typical atrial flutter. It is typically trabeculated and has high anatomical variability. ICE has been shown to be a useful tool for determining detailed anatomical information in this case.

3. Signal/image processing for in-body ultrasound imaging

In this section, we focus on advanced signal/image processing algorithms that have been applied for the in-body ultrasound imaging, such as tissue characterization and image registration. These technologies have been of great assistance for the improved understanding of the myocardial functions and properties. The image formation process such as signal acquisition and beamforming is outside the scope of this review.

3.1. Ultrasound tissue characterization

In addition to more traditional signal/image processing such as echo imaging, Doppler imaging and 3D imaging, we have witnessed a new trend to have quantitative signal analysis to derive high-level information such as tissue types [29]. Ultrasound tissue characterization makes use of the knowledge of ultrasound physics and its interactions with the biological tissue, and applies advanced signal/image analysis to differentiate various types of tissues such as healthy and diseased tissue. Tissue types can be found by extracting relevant features (or signatures) from signals such as:

- classical backscatter, echogenicity, attenuation coefficient and scattering;
- spectral features from frequency-based analysis;
- texture features for measuring speckle patterns;
- motion features, tissue/flow Doppler, strain and strain rate imaging, and elastography;

3.1.1. Strain and elastography

The classical tissue Doppler imaging and strain imaging have turned out to be very useful in accessing tissue properties [30,31], especially for assessing the cardiac motion. Tissue Doppler Imaging (TDI) measures the motion and velocity of myocardial tissues relative to the imaging transducer and provides quantitative assessment of global and regional functions and timing of the myocardial events. Due to the translational motion or the tethering of the myocardium, the TDI does have limitation for clinical interpretation, since the wall motion alone cannot differentiate between active and passive moments of a myocardial segment [31]. In order to cope with this problem, strain and strain rate are typically used to quantify the myocardial contraction and deformation. Strain provides a measure of tissue deformation, which is defined as

$$\varepsilon = \frac{L - L_0}{L_0} = \frac{\Delta L}{L_0}, \tag{1}$$

where ε is the strain, L_0 is the baseline length and L is the instantaneous length at the time of the measurement. Strain rate measures the rate at which the tissue deformation occurs, defined as

$$\varepsilon' = \frac{\Delta\varepsilon}{\Delta t} = \frac{\Delta L/L_0}{\Delta t} = \frac{\Delta L/\Delta t}{L_0} = \frac{\Delta V}{L_0}, \tag{2}$$

where ΔV is the velocity gradient in a given tissue segment.

In Fig. 5, a schematic overview of the Doppler-derived strain imaging is shown. Due to the ease of calculation of tissue Doppler, it is often used as the first step to encode the myocardial velocities, which are then employed to derive strain and strain rate to characterize tissue deformation properties. It is worth mentioning that the speckle-tracking-based echocardiography is often used as an alternative to the tissue Doppler imaging especially for B-mode images.

Tissue Doppler imaging and strain/strain rate imaging have been used in echocardiography extensively [30,32–34]. The application of these technologies is also emerging for in-body imaging applications. For example, in [35], shear-wave velocimetry is applied to an ICE catheter to measure the myocardium stiffness, where non-rigid elastic registration is performed to find the tissue motion and strain. In another paper [36], a speckle tracking method for myocardial motion estimation is developed for ICE image sequences to provide a means for regional functional imaging. In this method, non-rigid myocardial deformation is estimated by optimizing an energy function within a framework of parametric elastic registration.

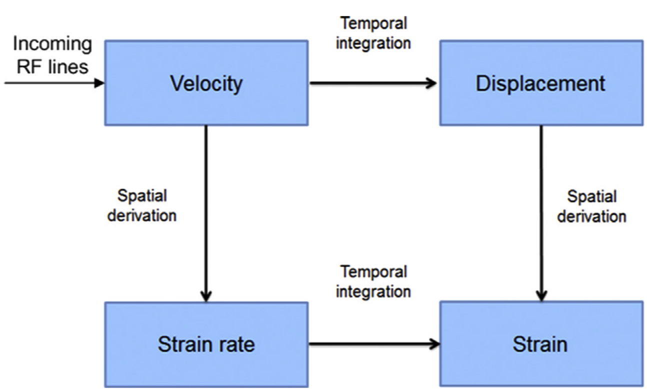

Fig. 5. Doppler-derived strain imaging [30].

In the IVUS domain, intravascular elastography has been well studied and used to assess the local strain in the artery wall and plaque [37–40]. This is achieved by measuring a systemic pressure difference via e.g. a controlled intravascular balloon. Fig. 6 shows the basic principle of intravascular elastography measurement. An IVUS echogram is acquired with a low and high intraluminal pressure (left), and the radial strain in the tissue is then calculated and displayed on the right. The eccentric soft lesion is visible on the right (green area) from the elastogram which is not directly identified from the B-mode images on the left.

3.1.2. *Speckle and texture features*

Speckle or texture features are commonly used in general ultrasound-based image segmentation. Statistical texture analysis methods have been shown to characterize tissue properties [41,42] very well and provide complementary information to echogenicity. Image texture is intrinsically a function of the microstructure of tissue and the imaging system, with different system parameters leading to different texture patterns. It is still under debate whether it has a strong link to the true characterization of the physical properties of tissues. Commonly used texture features include first-order or second-order statistics, frequency domain features such as Fourier and wavelet-based descriptors, and fractal models. The choice of the texture features depends on specific application needs and image characteristics. As most texture features are sensitive the image scale that is chosen, multi-resolution approaches have been proposed for improved robustness.

In [43], texture operators based on gray-level run length statistics are used to separate different tissue regions from IVUS images and morphological processing is applied subsequently to refine extracted contours. In [44], a set of texture features are evaluated for the use in IVUS systems for plaque classification, including the classical co-occurrence matrix based features and local binary pattern (LBP) based features. In [45], a set of texture descriptors are used in combination with a new seeded growing method to facilitate the segmentation of ICE images into infarcted, ischemic and normal myocardium regions. A multi-feature vector space is constructed which consists of the gray-level variance, the gray-level run length

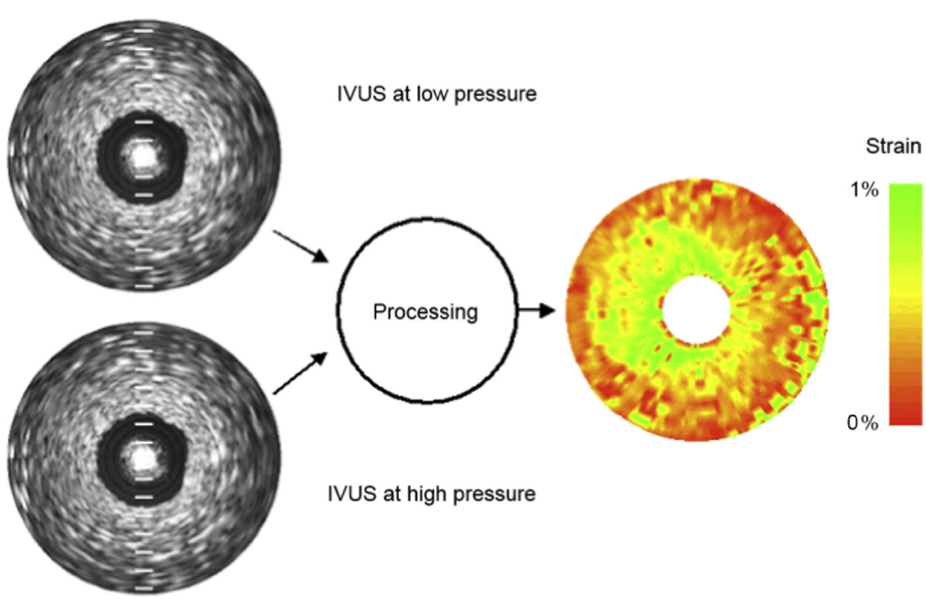

Fig. 6. Principle of intravascular elastography measurement procedure [38]. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

statistics, local wavelet energy and the inertia of the gray value co-occurrence matrix. This is also a trend we have observed in recent literatures in dealing with more complicated tissue characterization problem. If no single feature is predominantly superior than others, we could still make use of multiple features and rely on the measured statistics for improved overall algorithm performance.

3.1.3. Spectral features

Spectral features (parameters) for tissue characterization have been well studied in the general ultrasound image analysis. It has been shown in [46–48] that spectra computed from ultrasonic backscatter signals are related to intrinsic physical properties of tissue microstructures, e.g. size, shape and acoustic impedance. In intravascular ultrasound [12,49,50], spectral descriptors have also shown highly discriminating power in differentiating various plaques. Typically a region of interest is selected from the RF signals and the selected RF signals are converted to frequency spectrum. These spectra are calibrated and processed (e.g with specific spectral parameters extracted) and used subsequently for eventual coronary plaque classification. For example, in [50], autoregressive model has been adopted to calculate the spectra of a pre-defined region of interest, which has outperformed the Fourier-based spectra estimation. In total eight spectral parameters have been extracted (maximum power, corresponding frequency, minimum power, corresponding frequency, slope, y-intercept, mid-band fit, and integrated backscatter) for each region of interest. In [49], instead of using a limited number of spectral parameters for the classification, the authors proposed to use the full spectrum of the RF signals which according to [49] increases the chances of correctly recognizing tissue type by avoiding discarding any potentially useful information.

3.2. Automatic classification and interpretation

The recent advances in the area of pattern classification and machine learning research have triggered new applications in the medical imaging area. In order to directly provide high-level interpretation results to aid clinical decisions, classification technologies are often used to reach more objective and statistically solid conclusions. It offers a means to merge multiple features (e.g. spectral, texture and motion-based) to provide more reliable interpretation results. We have seen a growing interest in applying more sophisticated learning and classification algorithms in general ultrasound [51–53]. A few considerations need to be taken into account when designing such a system:

- Choice of features: the performance of a classifier depends heavily on the features that are used. Feature extraction as described in previous sub-sections is a crucial step and the choice of features (e.g. motion, spectral, textures) needs to relate very well to the characteristics of the specific application and system.
- Data collection and preparation: a well-known phenomenon in the machine-learning community is the 'small sample size' problem. To reach a statistically solid and unbiased decision, usually a large number of data are required to be able to capture the complete pattern variance. In addition, the importance of acquiring reliable and accurate ground-truth data should not be underestimated, particularly for supervised learning algorithms. Although current research relies mostly on pathology and/or histology for the ground-truth data verification, they are not always reliable and may have a large deviation from the in vivo measurements.

As mentioned before, tissue characterization is one of the most studied research areas in IVUS. An IVUS system typically uses a colour overlay to the traditional echogram to indicate different tissue types such as fibrous, fibro-lipid, calcium and calcified necrosis. Example classifiers include self-organizing maps (SOM) [12], classification trees [50] and K-nearest-neighbour classifiers [49]. The idea of using a combination of classifiers to boost the classification performance has also been explored in [49], as shown in Fig. 7.

Many toolboxes exist in the machine learning research which have made it possible to solve complicated classification problems in an easy way. However it is still not completely clear why a certain classifier performs better than others for a certain application and data set. Mostly the best classifier is chosen based on heuristics and experiments. More insights are needed in this area to provide a more systematic way to construct high-performance classification algorithms.

In addition to tissue characterization, we can also envision the use of pattern classification technologies to classify cardiac events into normal and abnormal based on relevant signal/image features.

Image segmentation is a closely related area to classification, which typically involves the (semi)-automatic delineating of the boundaries of an object or tissue regions [42]. Typically some prior knowledge are used of the object shape, motion and textures. In recent years, we have seen a growing trend in using machine learning algorithms to train a segmentation algorithm in order to provide a robust solution to cope with large variability encountered in ultrasound imaging. A comprehensive survey on segmentation algorithms has been presented in [11] focusing mainly on IVUS applications. Various approaches are reviewed for the detection of media-adventitia and luminal borders from IVUS images, which are acquired with different transducers at centre frequencies ranging from 20 to 45 MHz. In terms of classification, one example

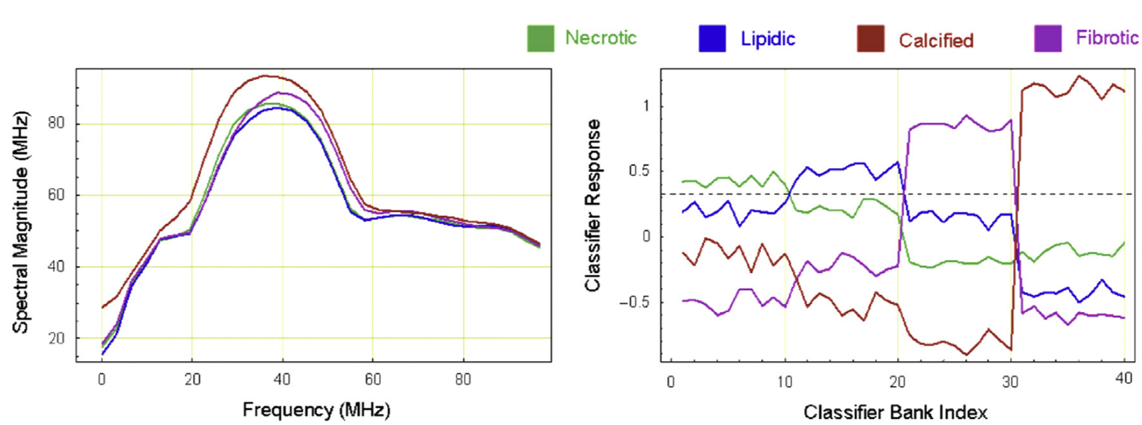

Fig. 7. Comparison of distinctness of spectra and classifier bank output across tissue types. The left plot shows four example spectra from each tissue type. The corresponding classifier bank output on the right shows each tissue type peaking in a distinct band [49].

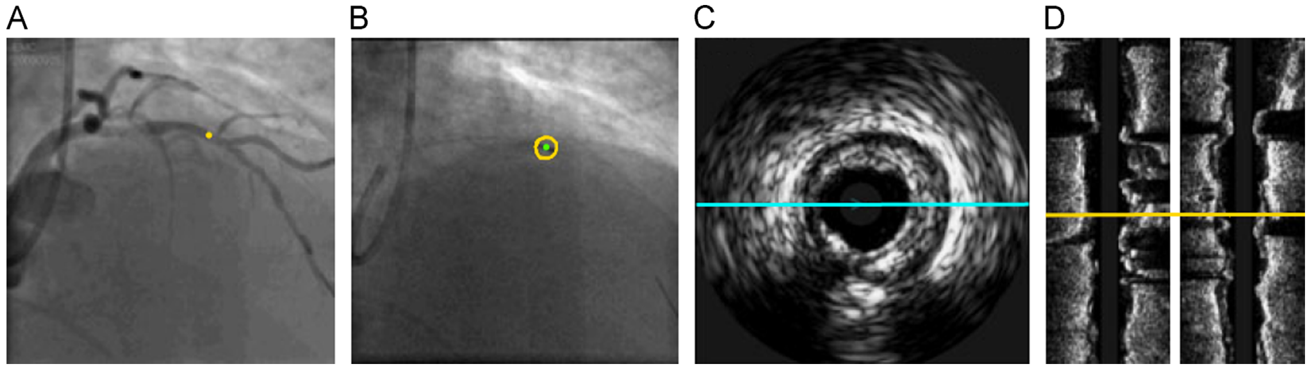

Fig. 8. Device tracking for the co-registration of IVUS and angiography images. (a) An angiogram frame. The yellow cross indicates a registered IVUS imaging plane; (b) a fluoroscopic frame. The yellow circle represents a tracked IVUS transducer; (c) and (d) cross-sectional and axial view of IVUS images. The yellow lines in the axial view indicate the registered IVUS image [59]. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

is to use supervised classification (e.g., support vector machine (SVM)) of blood versus non-blood regions by extracting appropriate spatial/temporal/spectral features. In [54], a semi-automatic segmentation algorithm has been proposed to find the endocardial boundary in ICE images which has enabled accurate and efficient reconstruction of 3-D geometry of the heart cavity.

3.3. Device tracking and image registration

With catheter/needle/endoscope based interventions, an important aspect is to track these devices during their navigation in the body via means of external fluoroscopy or ultrasound, or in combination with specifically designed tracking devices as those based on optics and electromagnetics. The tracking devices are able to track the instruments inside the body relative to the patient anatomy. For example, the development of miniaturized electromagnetic tracking systems, in which tracking coils can be embedded in the tips of surgical instruments such as catheters and needles, has allowed new opportunities for image-guided interventions. Another trend is to use image-based instrument tracking due to the straightforward integration into existing medical equipments [3,4,55]. Needless to say, instrument tracking provides important information for better interpretation of the in-body imaging results.

In this review, we pay special attention to the tracking of imaging ultrasound devices within the body. One example is to locate a catheter-mounted transducer in the 3D ultrasound imaging field [56]. During the interventional procedure, real-time 3D ultrasound imaging has the potential to provide a safe means for tracking catheter position in 3D while simultaneously imaging the heart's anatomy. In this design, the internal catheter-mounted transducer is used to actively detect the external ultrasound beam strength and direction to determine the catheter's position within the image volume directly. Mean accuracy between 0.22 ± 0.11 mm and 0.47 ± 0.47 mm have been reported in in vitro experiments, depending on the distance between the catheter and the ultrasound transducer. In [57], a family of passive echogenic markers is presented by which the position and orientation of a surgical instrument can be determined in an external 3D ultrasound volume. The acoustic properties and shape of the markers can be designed in such a way that they are easily detectable from the external 3D ultrasound volume.

In addition, real-time device tracking is also closely linked to image registration between different imaging modalities, especially when various imaging modalities are used at the same time during the interventional procedure. Registration between the different device views is needed to provide physicians with a consistent and simplified view of the anatomical structures. With the location information from the tracking, registration becomes possible between the in-body imaging devices and the external real-time 3D ultrasound/fluoroscopy and/or pre-operative CT/MR. In [58], the authors have proposed to integrate 3D TEE imaging with X-ray fluoroscopy, providing the capability to co-visualize both the interventional devices and cardiac anatomy, by accurately registering the images using an electro-magnetic tracking system. In [59], a method is presented to register external imaging modalities, a.k.a. angiography images with the in-body IVUS imaging, two modalities commonly used in interventional cardiology (see Fig. 8). The proposed system includes learning-based detections, model-based tracking, and registration using the geodesic distance.

Another example is to register 3D intracardiac echo to pre-operative images with an electromagnetic sensor [60]. In [9], an automatic 3D reconstruction is performed using the real-time ICE images of the left atrium to facilitate the image integration with the CT/MR pre-operative images. High accuracy has been reported for the reconstruction, which offers new uses to ICE in addition to its more traditional uses for the treatment of atrial fibrillation.

4. Conclusions

Ultrasound has evolved in the fields of general medical imaging and image-guided interventions, in spite of the rapid growth of competition from other imaging modalities such as MRI and CT. It is particularly suitable for miniaturized devices that can be used inside the human body for targeted imaging and monitoring. We have presented in this survey a scan of recent developments in this area, covering the transesophageal echocardiography, intracardiac echocardiography, intravascular ultrasound and the newly emerging therapy monitoring ultrasound. We have particularly focused our attention on the intelligent signal/image processing which is crucial for providing clinically relevant information from the ultrasound data. Topics such as tissue characterization, image segmentation, device tracking and image registration are as important for the in-body ultrasound imaging as for the general ultrasound. However, in the context of in-body imaging, we are faced with even more challenges such as device instabilities caused by the large physiological motion.

The use of in-body ultrasound imaging has opened a new area for new clinical applications. At the same time new challenges have arisen for imaging scientists and engineers to provide consistent, reliable and accurate analysis results for better clinical decision support.

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