Intelligent system for accurate measurement of intima-media thicknesses as markers of atherosclerosis

M.Mani, O.Bener, A.Bener, A.N.Kalashnikov
Department of Electrical and Electronic Engineering
The University of Nottingham
Nottingham, NG7 2RD, UK
eexmhm2@nottingham.ac.uk, Alexander.Kalashnikov@nottingham.ac.uk

Abstract – One of the anatomical methods for diagnosis of atherosclerosis involves measurement of intima-media thickness (IMT) using ultrasound. However these measurements are quite complicated using conventional approaches; for this reason we are developing an intelligent measurement system that will potentially enable inexpensive and accurate IMT measurements. In this paper the IMT measurement system architecture is discussed along with the algorithm to post-trigger the ultrasonic scans. Experimental results obtained in vivo are presented and discussed.

USE OF IMT MEASUREMENTS FOR THE DIAGNOSIS OF ATHEROSCLEROSIS

Arteries carry oxygenated blood from the heart, and their walls are composed of three layers: tunica intima, which contacts the blood, outer tunica media, and tunica externa [1]. If an artery wall thickens substantially due to an accumulation of fatty materials, such as cholesterol, infarction, heart attack, or claudication can develop. Carotid intima media thickness (IMT) is the thickness of the two a.m. arterial layers, and it is used for anatomic diagnosis of the disease [2]. These two layers are bounded by substances with quite different acoustic impedances, which makes ultrasound the most expedient method for measuring IMT. It is important to note that in some cases, for example, with so-called adaptive IMT thickening, blood flow is not affected by the IMT changes [3]. Nevertheless, IMT is widely regarded as a useful marker for the diagnosis of atherosclerosis [4].

In vivo IMT measurements are complicated due to the variations in arterial thickness. This thickness can change from 645 to 705 µm during a single heart cycle, but an annual increase between 10 to 30 µm should raise some concern [5]. Consequently, an accurate IMT-measurement instrument should have a high resolution, capable of detecting minute annual changes, and should provide measurement results that are independent of variations related to the heart cycle. In this development, we addressed the first issue by using a high-accuracy FPGA-based ultrasound instrument [6] and modifying it in order to trigger the ultrasonic scans from an external signal related to the heart activity. Electrocardiogram (ECG) signals were selected for monitoring of the heart activity, and an autonomous ECG monitor with wireless output was developed for this purpose, as reported previously [7]. This paper discusses the design choices adopted for the intelligent IMT measurement system and presents the ECG post-trigger generation algorithm and related experimental results.

ARCHITECTURE OF THE IMT MEASUREMENT SYSTEM

The IMT measurement system under development consists of an ECG monitor with wireless output and an ECG processor that analyses the ECG samples and generates the trigger signal, activating the ultrasound instrument operating in the pulse-echo mode (Fig. 1). The IMT is estimated from the delay between the beginning of the echo from the outer interface of the intima layer and that of the media layer [4].

The ultrasound instrument uses on-the-fly averaging to reduce the effect of noise and interleaves sampling to increase the time domain resolution [6]. When triggered, it generates a burst of excitations for a few milliseconds as during this short time the IMT can be considered stationary.

The ECG monitor is powered by a low-voltage battery, which eliminates any potential health risk associated with electrocution from main-powered equipment. The infrared (IR) link was selected in order to reduce electromagnetic interference from the device, which can severely affect medical electronic equipment located nearby [8].

The ECG processor receives the ECG samples wirelessly and triggers the ultrasonic scans after the selected delay from the ECG R-wave. The processor can potentially operate in a pre-trigger mode, in which it guesses the time of arrival of the new ECG R-wave based on estimates from the past samples. If the guess were wrong, the processed waveform would be discarded. For this development, we selected the post-trigger mode, in which the processor detects the R-wave first and then generates the trigger with the required delay to the detected R-wave. The developed post-trigger algorithm and experimental results observed *in vivo* are presented in the following sections.

ALGORITHM FOR TRIGGERING THE ULTRASONIC SCANS

The algorithm was developed and tested using experimental data collected from a healthy male subject in an electronic laboratory environment. The algorithm was first developed for ECG signals simulated in MATLAB with varied degrees of noise. It was found that detection of the R-wave required the use of an adaptive threshold because of the variability of the R-wave amplitudes. An IR sniffer was used to collect records of the experimental *in vivo* data transmitted by the ECG monitor for dozen of heart cycles. These records were processed in MATLAB, and the post-trigger algorithm was further refined to account for the rather high level of noise observed during the experiments. Finally, the algorithm was applied to the continuously streaming *in vivo* ECG, and the need to adaptively track the ECG baseline was identified.

The final version of the algorithm included the following stages (Fig. 2):

- each received ECG sample was used to update the accumulated average value (the baseline value) using a moving average;
- a new threshold level was calculated above the updated baseline at the level of 75% of the difference between the baseline and the previously detected peak amplitude of the R-wave;
- the presence of an R-wave was considered to be detected if three consecutive samples exceeded this threshold;
- after the detection, the following 20 samples were buffered, and the maximum value among them was considered as the R-wave;
- the number of samples remaining to the trigger generation was calculated based on the required delay from the R-wave and the ECG sampling frequency;
- after counting these remaining samples, the trigger signal was generated.

EXPERIMENTAL RESULTS

Figure 3 presents, on the left, an ECG waveform of substantial duration recorded using an infrared sniffer that was later processed in MATLAB. It shows the drift of the baseline, the variable amplitude of the ECG R-wave peaks, and the substantial level of noise. The upper trace is related to the recorded ECG samples, and the lower trace indicates the simulated triggers. The zoomed part on the right of Figure 3 shows the levels for the maximum ECG value and the threshold by dotted lines. The ECG samples are connected by straight lines, the buffered samples are marked by crosses, the peak value is marked by a diamond, and the samples that were counted until the required delay occurred are circled.

Both the *in vivo* ECG trace taken at the ECG monitor and the trigger trace taken simultaneously at the ECG processor using a dual channel oscilloscope are shown in Figure 4. It shows that, despite the relatively high level of noise, most of the R-waves were correctly detected and the right trigger was generated. In one instance, when the amplitude of the R-wave was lower for some reason, it was missed. Such misses could potentially be reduced by lowering the detection threshold at the cost of an increased probability of triggering the ultrasonic scan from a T-wave instead of the R-wave.

SUMMARY AND CONCLUSIONS

The undertaken development aims to address the issues associated with accurate IMT measurement by triggering a high-accuracy ultrasound instrument only at the particular stages of the heart cycle only by processing the ECG signal from the patient. Wireless IR communication is used to eliminate the possibility of electrocution and reduce electromagnetic emissions from the device.

The developed ECG processor operates in the post-trigger mode and utilizes adaptive techniques for tracking the baseline, calculating the detection threshold, and reducing noise interference. The algorithm was developed iteratively, based on both the simulated and recorded *in vivo* ECG waveforms, and operated correctly for the streaming ECG data.

The next stages of the development will be the integration of the developed ECG monitor and processor with the ultrasound instrument for operation *in vivo*, analysis of the recorded experimental waveforms for different preset delays related to the R-wave, and estimation of the IMT.

Successful completion of this development of an intelligent measurement system will potentially enable inexpensive monitoring of IMT that, combined with conventional cardiovascular disease risk analysis, will improve diagnosis and lead to timely treatment of atherosclerosis.

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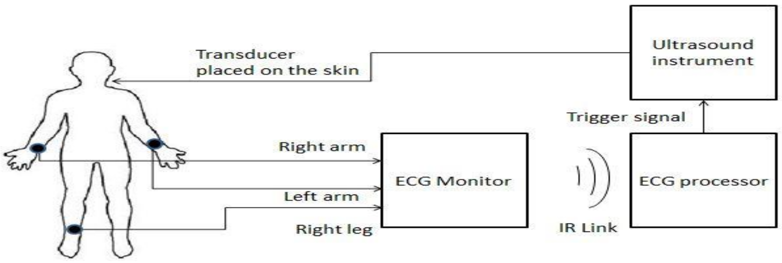
Ultrasound instrument
Transducer placed on the skin
Trigger signal
Right arm
ECG Monitor
ECG processor
Left arm
Right leg
IR Link

Fig.1. Intelligent IMT measurement system

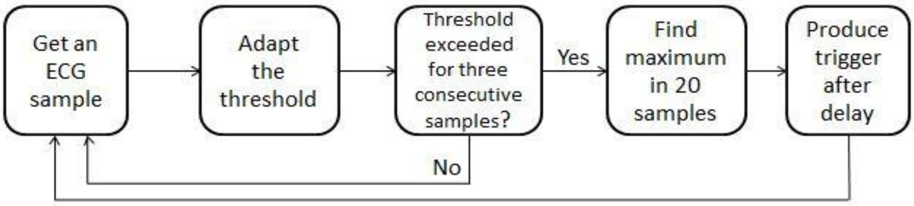

Fig.2. Algorithm for post-trigger generation

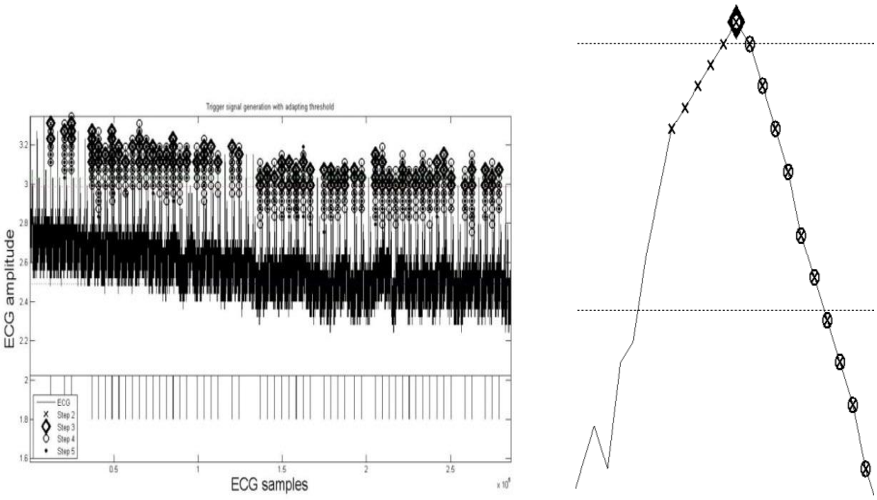

Fig.3. Captured *in vivo* ECG signal processed in MATLAB

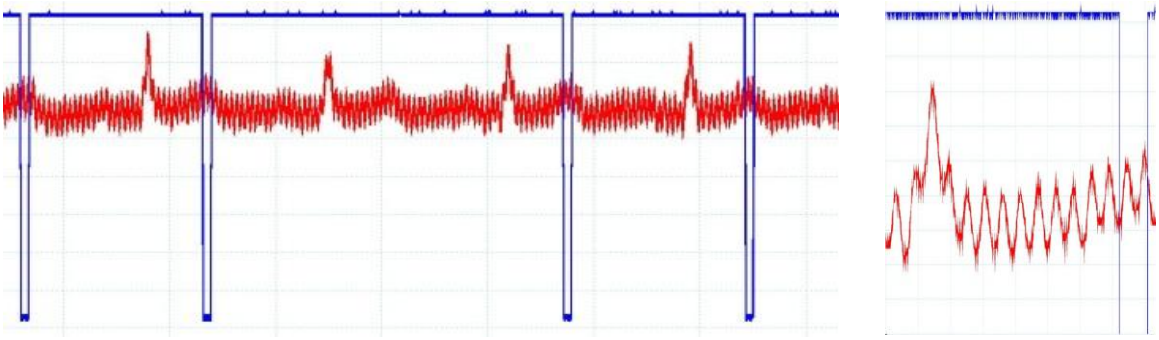

Fig.4. Experimental *in vivo* ECG and trigger signals recorded simultaneously