Thermal Imaging of the Superficial Temporal Artery: An Arterial Pulse Recovery Model

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Abstract

We present a novel model[1] for measurement of the arterial pulse from the Superficial Temporal Artery (STA) using passive thermal Infra Red (IR) sensors. The proposed approach has a physical and physiological basis and as such is of fundamental nature. Thermal IR camera is used to capture the heat pattern from superficial arteries, and a blood vessel model is used to describe the pulsatile nature of the blood flow. A multresolution wavelet-based signal analysis approach is used to extract the arterial pulse waveform, which lends itself to various physiological measurements. We validate the results using a traditional contact vital-sign monitor as a ground truth. Eight people of different age, race and gender have been tested in our study consistent with IRB approval. The resultant arterial pulse waveforms exactly matched the ground-truth readings. The essence of our approach is the automatic detection of Region Of arterial pulse Measurement (ROM), from which the arterial pulse waveform is extracted. To the best of our knowledge, the correspondence between non-contact thermal IR imaging based measurements of the arterial pulse in the time domain and traditional contact approaches has never been reported in the literature.

1. Introduction

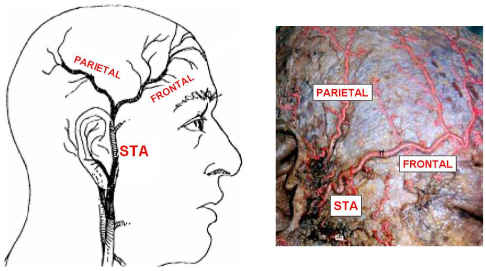
The arterial pulse is produced by heart contractions which are mechanical events activated electrically. Doppler ultrasound and arterial tonometry are traditional approaches to track the hemodynamics changes in the arteries. This work attempts to build an alternative computer vision methodology for accurate measurement of the effect of the arterial pulse propagation by non-intrusive and non-contact thermal IR imaging of the superficial arteries of the human body. The idea is to measure the events of pulse propagation through a superficial artery by the measurement of heat variations on the skin surrounding the artery.

Passive thermal sensors have a short, but bright history in the monitoring of human vital signs. Recently, this area has been greatly advanced by Pavlidis et al. [10], [9] who applied thermal imagery for the measurement of heart rate from the superficial blood vessel network. In their approach, they estimate the dominant heart rate frequency by averaging the power spectra of each pixel in the preselected segment of the superficial vessel. This procedure is well-supported by a set of experiments as discussed in [10]. One of the limitations of their approach is the manual selection of the skin segment to be used for the heart rate measurements. Another limitation is that only the dominant heart rate frequency is reported, not the actual heart rate waveform. The difference between their and our approach, from the physiological and signal processing prospectives, is discussed in section 3.

In our previous work [4] we demonstrated the possibility of measurements of the arterial pulse in the vicinity of major superficial arteries with the use of multiresolution analysis. The novelty was the ability to automatically identify the ROM and to report the arterial pulse waveform in the time domain. The limitation of that work is that no actual mechanism was explained why the multiscale edge data provide rich features for the automatic detection and measurements of the arterial pulse. It was an observation without a physiological hypothesis explaining it. Another limitation was the validation of the results. The reported arterial pulse waveforms agreed with the ground-truth monitoring device by the number of the heart contractions per minute, but the actual time behavior of the measured arterial pulses was not validated.

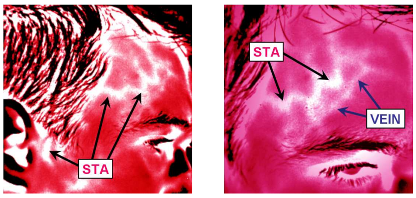
In this paper, we present a model which is based on the physiology of the circulatory system and has a very solid experimental validation. The paper is organized as follows:

[1]A Patent Application has been Filed. Provisional Patent has been approved.



(a) (b)

Figure 1. (a) Anatomy of the STA (courtesy Exergen Corporation, Watertown, MA www.exergen.com) [7]. (b) Dissection of the STA and its branches (adopted from [3]).



(a) (b)

Figure 2. Thermal imaging of the STA. (a) The locations of the STA where the arterial pulse can be measured. (b) A closer view of the forehead region. The frontal branch of the STA and the facial vein can be clearly observed and seen to be parallel. The vein goes straighter and is less tortuous than the STA.

Section 2 is dedicated to the anatomy of the STA. Section 3 introduces our measurement model of the arterial pulse. In section 4, we discuss our experiments and results. Finally, conclusions are presented in section 5.

2. Anatomy of the STA

A good anatomical knowledge of the STA is needed for successful measurement of the arterial pulse using thermal imaging. In this section we provide a brief overview. The STA can be thought of as the narrowing continuation of the external carotid artery which becomes quite superficial after it passes the ear area (marked on the Figure 1 (a, b) as the STA). In the upper head the STA splits into parietal and frontal branches as shown in Figure 1 (a, b). A very good anatomical study of the STA is given in [3]. In that study, the STA and its branches were dissected in 27 specimens. High variability in the topology of the STA was observed, though the absence of the frontal branch of the STA was not encountered. In only one sample, the STA's parietal branch was missing and the STA continued as a frontal branch. The diameters of the frontal branch were bigger than those of the parietal branch in 15 samples. The diameters of both the frontal and parietal branches were equal in four samples. In the remaining eight samples the diameter of the parietal branch was bigger than that of the frontal one.

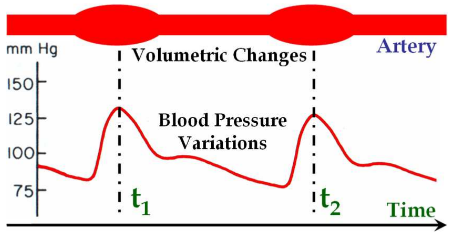


Figure 3. Arterial Blood Pressure Wave Propagation.

Typically, the STA and facial veins produce very prominent thermal imprints in thermal images as shown in Figure 2 (a, b). The facial veins (as other veins of the body) travel parallel to the arterial system. In contrast to the arteries, the veins typically tend to go straighter and be less tortuous. This is illustrated in the Figure 2 (b).

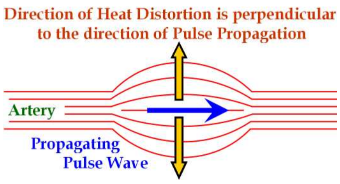
3. Method

The main branch of the STA (close to the ear) and the frontal branch (Figure 2 (a, b)) are ideally suited for the thermal-based arterial pulse measurements: they are easily accessible, contain no mucous membranes and negligible amounts of fat and muscle tissues. Moreover, the skin in the area of the STA is less subject to various deformations like those observed in the carotid artery area (volumetric changes due to: breathing, speech, muscle contractions, swallowing). The results presented in this paper are completely based on the measurements from the frontal branch of the STA.

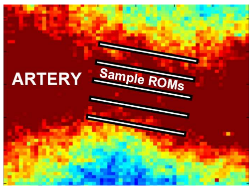
We formulate the problem of measurement of the arterial pulse in the form of registering the so-called thermal delegates of the arterial pulse propagation events along the most accessible branches of the STA. The goal is to catch those changes in thermal patterns, the delegates, which are directly linked with a sequence of arterial pulse waves propagating throughout the artery. Our experiments suggest the monitoring of the longitudinal fine edges of the heat distribution along the artery for the role of providing such delegates which are discussed in the following subsections.

3.1. Thermal Delegates of the Arterial Pulse

The arterial blood pressure wave is created during the ventricular systole and propagates along the arterial tree pumping the blood in the circulatory system. Propagating along the arterial network, the pressure wave causes the distention of arterial walls which palpate as an arterial pulse from the major superficial arteries of the body. Figure 3 schematically illustrates this process. The aortic pulse wave velocity reported in the literature [6] varies around 8.7 m/s. The shape and the speed of the arterial pulse wave



(a)



(b)

Figure 4. Distortion of heat distribution along the artery caused by the arterial pulse propagation. (a) A rough sketch of difference in thermal map along a linear segment of an arterial tube when it is dilated by the increase in blood pressure and contracted after the pulse wave is moved forward. (b) Thermal image of a segment of the frontal branch of the STA and a sample ROM configuration.

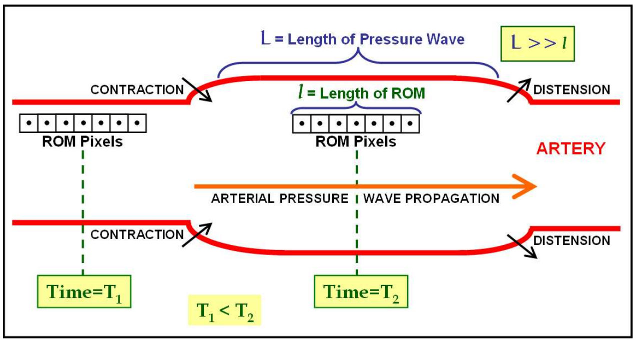


Figure 5. Registration of arterial pulse propagation events from the periodic distortions of fine longitudinal edges of heat distribution along the artery.

changes when it propagates along the arterial tree. This is mainly because of the change in mechanical properties of arterial walls (elastic tapering) and the decrease of the cross-sectional areas of the arteries (geometric tapering).

In our model, we simply consider the arterial tree as a network of cylindrical tubes. Our hypothesis is that the arterial wall volumetric response to a pressure variation disturbs the heat distribution along the artery. We further assume that these distortions are more pronounced in the radial, rather than longitudinal, direction. This assumption is roughly sketched in Figure 4 (a). The heat variations are further passed to the skin surface where they can be registered by a thermal IR camera. Since the length of the pulse wave is much longer than the length of the ROM, it is logical to catch the pulse components in some strip-like ROM oriented along the longitudinal direction of the artery (Figure 4 b). In this case, the radial heat distortions caused by the pulse propagation would be in-phase at each of the ROM pixels and their averaging at each frame would give the desired result. Unfortunately, this scheme is impractical since there is a strong contribution of irrelevant heat patterns on the skin destroying or dramatically corrupting the arterial pulse signal. We suggest constructing such ROMs in their wavelet subspaces. This way, there is a chance to separate different heat phenomena into different subspaces and successfully recoverer the signal of interest from one of the subspaces that is not overlapped with others. The coarse wavelet layers should not be of interest since the periodic arterial pulse waves do not contribute much to the overall heat changes on the skin. The prominent pulse components with respect to other patterns should reside in the horizontal or equally saying in the longitudinal components of the fine wavelet layers which can be referenced as the fine edges since they encode the fine variations of the heat distribution. This model is quite different from the model proposed before by Pavlidis et. al [10] who directly measured the longitudinal temperature variations along the blood vessel. In their work they do not specify where exactly the measurements are performed: on the superficial veins or on the arteries. The heat exchange mechanism that they use for linking of the thermal IR measurements with actual heart contractions is also not specified in their work [10]. The next subsection presents more details on our approach.

3.2. Wavelet Analysis

We use the Mallat [8] wavelet framework and Haar filters to decompose thermal images into disjoint bands encoding Horizontal (H), Vertical (V), Diagonal (D) edges, and residual coarse band. Depending on the image resolution, we choose a certain fine scale where the data from the H band is used to compute the mean value within the ROM (Figure 5) for all frames (k) and plot it with respect to time/frame, obtaining 1-D arterial pulse waveforms. In particular, the multiscale edges computed at each frame k are as follows:

$$W_j^H(m,n|k) = I(k) * \psi_j^H(\widetilde{m},\widetilde{n}) \mid_{m=2\widetilde{m},n=2\widetilde{n}} \quad (1)$$

The ψ_j^H is a wavelet function which captures the variations along the columns of a thermal image. $I(k)$ is k^{th} thermal image, j is a decomposition level. The magnitudes of the horizontal components are averaged within the ROM, producing the $Arterial\ Pulse$ value $AP(k)$ at each frame k:

$$AP(k) = \frac{1}{ROM} \sum_{(m,n)\in ROM} [W_j^H(m,n|k)^2]^{\frac{1}{2}} \quad (2)$$

Figure 5 schematically visualizes a sample ROM configuration. By ROM configuration we mean that all frames are processed with certain $\psi_{j=j_{fixed}}^H$ and certain frame orientation with respect to the $\psi_{j=j_{fixed}}^H$. Other ROM configuration parameters are the ROM's size and its location. In the Figure 5, the ROM pixels are displayed as a one dimensional array along the longitudinal direction of the artery. Time T_1 corresponds to relaxed, undilated state of

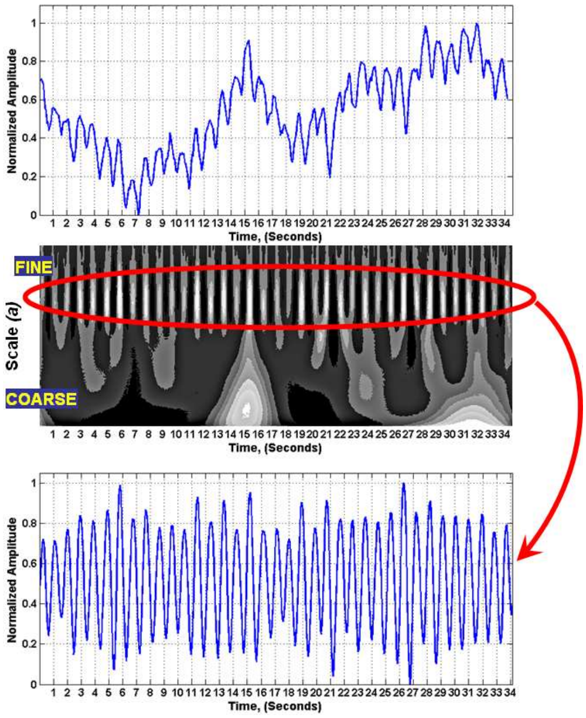


Figure 6. Example of continuous wavelet analysis of a raw arterial pulse waveform. (Top) The raw thermal waveform measured from the frontal branch of the STA. (Middle) Corresponding continuous wavelet transformation plane. The Mexican Hat wavelet was applied. (Bottom) The inverse transformation.

the artery. At time T_2 the artery is distended by the blood pressure increase. This causes the noticeable redistribution of heat in the radial direction. The horizontal edges shift and change the values within the ROM. Longitudinal heat distortion due to the artery distention is not that observable. However, some other heat processes can vary the longitudinal heat distribution which may corrupt the signal. Properly tuned wavelet scale, frame orientation with respect to wavelet direction, ROM's size and location yield the waveform with the best periodicity measure as discussed in our previous work [4]. During this optimization, the intermediate arterial pulse waveform candidates corresponding to different configuration states are analyzed with the one dimensional Mexican Hat wavelet, known for its excellent spatial resolution. The Mexican Hat is used to isolate local fine-to-coarse minima and maxima of the waveforms and to compute their periodicity measures [4]. Modelling the arterial pulse as a quasi-periodic signal within a short period of time makes the automatic detection of the optimal ROM configuration to be possible when the periodicity detection algorithm [4] is applied. The result of the ROM detection procedure is visualized in Figure 6. The raw signal measured from the frontal brunch of the STA was selected based on the best periodicity measure and is plotted on the top

Figure 7. Experimental setup. The thermal sensor used in the experiments for this paper is a long-wave Phoenix IR camera from FLIR [1]. Multi-parameter contact vital signs monitor "Advisor" was used for ground-truth measurements [2].

of the figure. The corresponding continuous wavelet transform plane [5] in the middle of the same figure, shows the scale-space representation and allows the identification of the scale region where the most periodic pattern is located. The bottom waveform is a result of the inverse continuous wavelet transform after thresholding the irrelevant patterns. This waveform is reported as the final arterial pulse waveform.

Applying the inverse continuous wavelet transform we do not attempt to recover a particular harmonic as is done in the Fourier Transform based filtering techniques. Actually, we recover the structures belonging to a particular scale. Their time behavior is not restricted to a particular spacing rate. This makes our approach quite valuable in dynamic, real-life applications where the momentary changes in the heart rate are of particular importance.

4. Results and Discussion

Eight subjects (seven males and one female) with ages in the range of 25-45 years old participated in our study consistent with IRB approval. Four Caucasians, two Africans and two Middle East participants have been tested. The experimental setup mainly consists of a long-wave Phoenix IR camera from FLIR [1], a multi-parameter vital signs monitor from Smiths Medical Inc. [2], and a PC to store and process the data. The experimental setup is illustrated in Figure 7. All subjects were seated stationary on a chair 1-4 feet away from the camera zoomed to display their foreheads. The acquisition time for the arterial pulse measurement was 20-40 sec with a frame rate of 30 fps. The oximetry sensor was attached to record the peripheral pulse waveforms (Figure 7) which are referenced as the ground-truth data in this study. The thermal and ground-truth data acquisition was synchronized to observe the correlation between the two modalities. The results of the arterial pulse measurements for all eight subjects are presented in Figure 8. The 12-seconds arterial pulse waveforms measured from the ther-

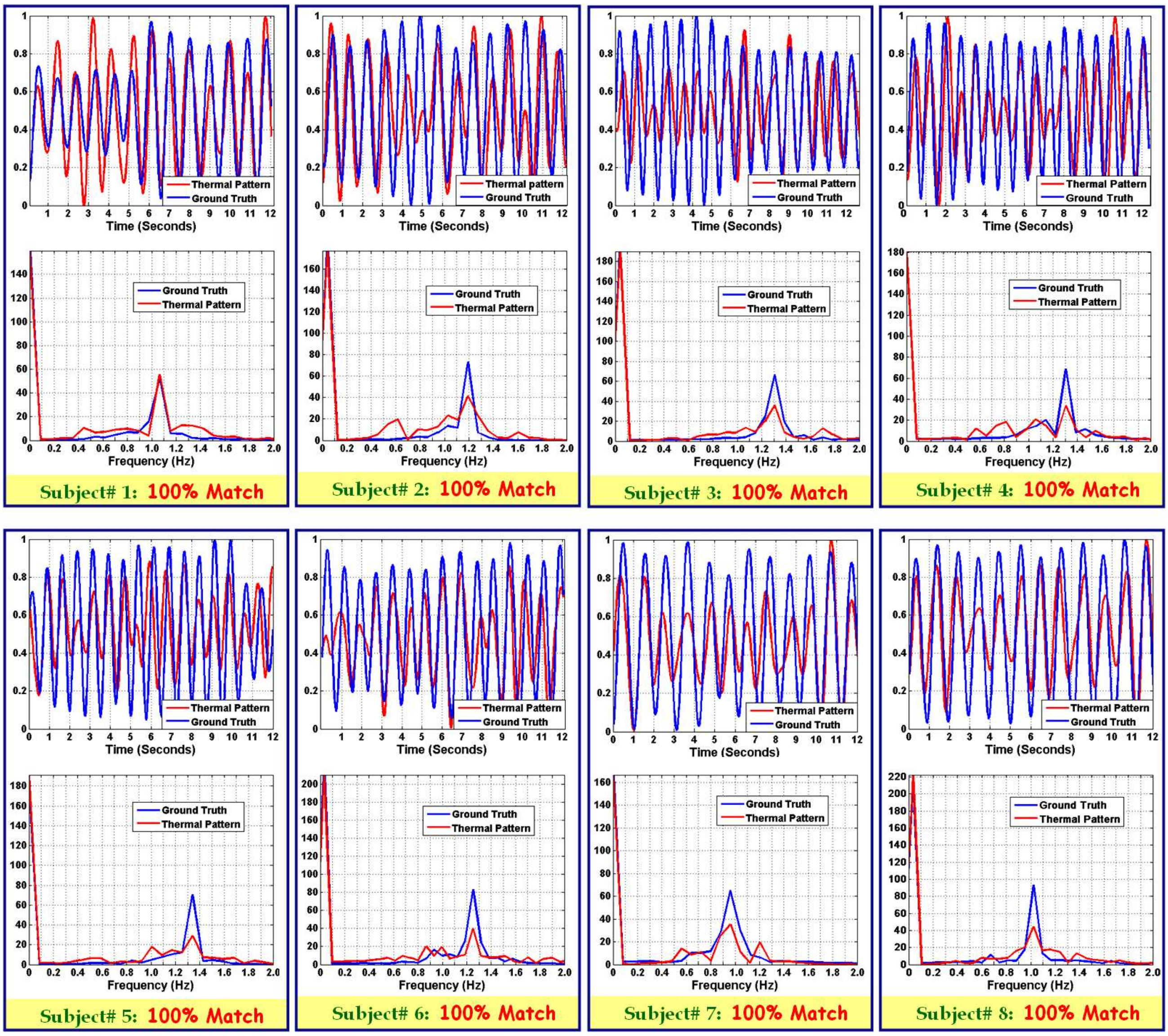


Figure 8. Experimental results. All measurements were performed on the frontal branch of the STA.

mal IR data are plotted in red. The corresponding ground-truth data are plotted in blue. The frequency content of the waveforms is given underneath each plot. Since the subjects were relaxed and did not have heart conditions, all the heart-beats appeared equally spaced in the time domain, and the corresponding power spectrum has one dominant frequency component associated with the heart rate. In all eight cases we obtained perfect correlation between thermal-based and the ground-truth pulse data with a perfect match to heart rate.

In this paper we do not address the issue of tracking the region of interest. The conceptual proof of our model and a solid experimental validation is the primary goal of this study. In the experiments, in order to cope with the motion artifact, aluminium foil markers were attached to the skin in the field of view of the camera as shown in Figure 9. The metal markers look significantly colder in contrast to the surrounding tissue and can be accurately segmented and tracked from frame to frame.

Another important issue is the localization of the STA. In our approach we refer this issue as the identification of the optimal ROM configuration as discussed in subsection 3.2. The arteries are typically located deeper in the tissue than the veins. In addition, the arteries tend to be more tortuous and may not produce a sharp thermal imprint. Moreover there can be a case when an artery hides in the venous net-work as illustrated in Figure 10 (b). In this case it is hard to manually distinguish between the artery and a vein, and

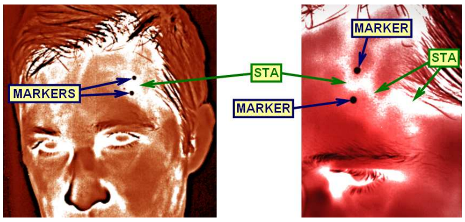
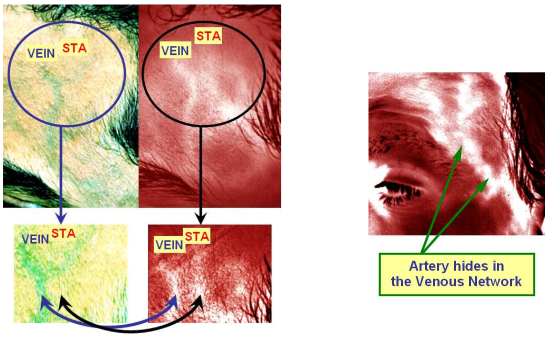


Figure 9. Thermal Images of the frontal branch of the STA. Aluminium foil markers were used to eliminate most of the motion artifacts.



(a) (b)

Figure 10. STA Localization. (a) Video and corresponding thermal image where a vein and the STA go in parallel. (b) A thermal image of the forehead where the STA hides in the venous network.

make a proper ROM selection. In Figure 10 (a) there are sample video and thermal images of the forehead region where the venous network produces sharper and brighter imprint than the STA. A segment of STA goes in parallel with a vein. This segment can not be seen on video and barely could be seen in the thermal imagery. In our approach the region close to the prominent superficial vessel (which could be a vein or an artery) is automatically scanned with different configurations of the ROM (such as scale, orientation, size and location) and the optimal configuration yields the location where the arterial pulse is the most pronounced.

The results presented in this paper are obtained from the frontal branch of the STA. As an alternative, the branch of the STA before it splits into parietal and frontal branches, located close to the ear, can also be used for the arterial pulse measurements. In fact, according to [3], this segment of the STA is bigger in diameter than both of its branches and is well accessible by the thermal IR camera.

5. Conclusion

A novel model is presented for measurement of the arterial pulse from the STA using passive thermal IR sensors. The measurements are performed in a non-contact and non-intrusive way. The proposed mechanism assumes that the arterial pulse propagation causes measurable periodic distortions of the fine horizontal edges of the heat distribution along the artery. Our model is quite different from the models proposed before in the literature and has a very solid experimental validation. Eight people of different age, race and gender have been successfully tested with 100% accuracy in matching the heart rate with that obtained with the ground-truth device.

The strength of our model is the capability to measure the interbeat intervals, not the estimation of the heart rate frequency only. Accurate monitoring of heart rate and heart rate variability in both time and frequency domains is essential in medical testing of cardiovascular and autonomic regulatory functions, estimation of mental and emotional loads, assessment of health in general. We believe our novel and advanced research work will find great applications in the fields where the non-contact and non-intrusive monitoring of heart rate and its variability is needed.

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