PPGI: New Development in Noninvasive and Contactless Diagnosis of Dermal Perfusion Using Near InfraRed Light

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ABSTRACT

To obtain a 2D mapping of the dermal perfusion measurement, a CCD-based Photoplethysmographic Imager (PPGI) system have been developed to diagnose the skin perfusion using near-infrared (NIR) light. The PPGI is a computer-based CCD imaging system to visualize the skin vessels and analyze the local changes of dermal perfusion. The experimental setup and preliminary results of the PPGI system are presented in this paper. The system has been shown to be capable of assessing various disorders of the peripheral venous system by standard test methods derived from the classical photoplethysmographic (PPG) practice in a noninvasive and contactless way. It also provides information of spatial distribution which allows the investigation of locations and causes of vascular disorders. Both the venous hemodynamics and arterial pulsation can be mapped in two dimensions.

Keywords: Photoplethysmography (PPG), Photoplethysmographic Imager (PPGI), dermal perfusion

1. INTRODUCTION

Nowadays there is a growing research interest in biomedical optics which utilize the light to probe structure and function in biomedicine and leads to several noninvasive and non-ionized diagnostic and therapeutic methods such as laser surgery, photodynamic therapy, laser Doppler flowmetry (LDF), and Photoplethysmography (PPG)[1-4]. To understand the fundamentals of such methods, it is necessary to investigate the phenomena of photon-tissue interaction[5-9]. Among the theoretical methods and their approximations such as transport theory, diffusion theory and Kubelka-Munk theory, Monte Carlo simulation is the most popular method[10-13].

Photoplethysmography (PPG) is nowadays widely used and has been accepted by physicians because of its simple design and relatively low cost per examination. A PPG system with NIR optical sensors can measure the blood volume changes in the skin surface layers by registering the attenuation change in the near infrared spectrum. Its biophysical principle is based on the fact that there is a strong contrast in absorption of NIR light between the blood-filled vessels and the ambient bloodless tissue. So through detection of the light remitted from the skin, it is possible to measure the blood volume change of the skin. The PPG system provides a simple and noninvasive method to detect venous diseases at early stage through certain functional tests like VOT (Venous Occlusion Test) and MPT (Muscle Pump Test)[14]. One disadvantage of PPG is that it can only measure one small area at one time and thus very difficult to get a spatial distribution of the blood volume change of the skin. Because of the spatial variation of the circulation system, it is necessary to get a mapping of the venous hemodynamics. Multichannel PPG device has been developed to monitor the skin perfusion at different sites, but it introduces more problems with sensor attachment, which makes the test person uncomfortable and introducing more movement artefacts. Also a high spatial resolution is impossible with multichannel PPG because the probe size of PPG is often more than $1cm^2$. Another disadvantage of PPG is that the test person has to be measured contactly, which restrict its application to some clinical situation such as monitoring the wound healing process.

In this paper, a new noninvasive and non-contact method called Photoplethysmography Imaging (PPGI) is presented. A PPG Imager which arranges a high-quality CCD camera with auxiliary optical system combines the features of both classical PPG measurement and CCD imaging. It can visualize the structure of skin vessels and evaluate the venous hemodynamics as well as the arterial pulsation. PPGI avoids the time-consuming scanning by using CCD as an array of photon detectors so that it can monitor the dynamic changes of dermal perfusion on different parts of skin surface simultaneously and flexibly.

2. METHODS

The PPG Imager is a computer-based CCD imaging system containing both hardware and software components (Figure 1). It is capable of recording, processing and displaying image sequences of skin to visualize the skin vessels and analyze the temporary and spatial variation of the dermal perfusion[15].

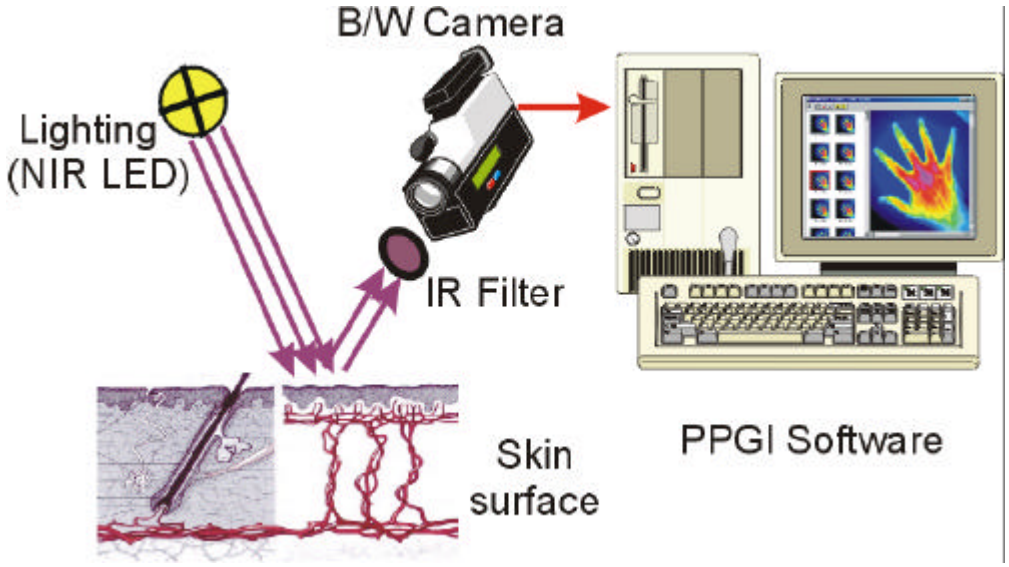


Fig. 1. Experimental setup of PPG Imager.

2.1 HARDWARE

CCD Camera

The key part of PPGI system is a CCD camera to collect the reflected or transmitted photons coming from skin. Because black/white CCD cameras are also sensitive in the near infrared region, a B/W digital camera (Ultrapix FE 250, LSR, UK) is used. The Ultrapix camera is a cooled CCD camera with a low operating temperature (-40°C), wide dynamic range (14 bit resolution, about 84 dB) and high readout rate (5.5 MB/s). The imaging sensor used in the camera is EEV 37-10, a silicium frame-transfer CCD with the pixel resolution of 512 x 512. The sensible spectral range is 400 ~ 1100 nm. The camera has the flexibility of choosing variable readout speed, sensitivity, and exposure time. In its normal setup, the camera can capture a full size image (512 x 512 pixels) at a speed of about 5 frames per second. Through programmable binning and subarray selection, the speed can be increased up to more than 25 frames per second, which is very useful for detection of the arterial pulsation. In order to change the position and orientation easily, the camera is mounted on a tripod to acquire the image sequence during measurement.

Optical System

The optical system is also very important for measurement because it influences directly the quality of the useful signal received by CCD. It is mainly composed of lighting, objective and filters. Two lighting system with different wavelength were developed. For near-infrared measurement, a NIR LED (HP's HSDL-4220 30) ring designed for diffuse and even lighting is attached around the objective of the camera. The LEDs are emitting at the central wavelength at 875 nm with a viewing angle of 30°. A small controlling circuit was designed to give the power supply and adjust the light intensity manually. In order to suppress the influence of the non-NIR light furthermore, an infrared filter (RG830) is put in front of the camera to block the visible light (in range less than 830 nm) coming from the ambient light. Another lighting system is designed for multiple-wavelength measurement. It contains three kinds of LEDs: green (Sharp's GL-5EG23), red (Kingbright's 453SRC1000) and infrared (Infineon's LD271). The power supply to these LEDs is provided by a D/A converter (Maxim's MAX528). This D/A converter has 8 outputs which can supply different values of voltage for different LED. These output values are controlled by computer through parallel port (LPT). Therefore this lighting can be adjusted more accurately and easily than the first one. Also it can give a feedback during measurement so that the lighting condition can be kept constant.

2.2 SOFTWARE

The camera is connected to a high performance PC through a specially designed camera controller. The PPGI software was developed to control the camera settings, capture the image sequence, and perform the post processing and analysis. Currently, the PPGI software is capable of acquiring the video in on-line mode and saving it for off-line processing.

In the on-line mode, the live video can be dynamically displayed. By changing the sensitivity, readout speed and acquiring only subarray or through binning, the sample rate can be changed in a wide range according to different requirement. Different size and position of ROI (region of interest) can be selected so that "virtual" PPG sensors of variable measuring window can be placed freely at different positions. Through calculating the average pixel values of the ROIs, the reflected optical signal (PPG signal) which corresponds to blood volume change can be monitored. For the off-line processing, the video acquired will be calibrated first. The calibration includes equally intervaled resampling and motion compensation. The resampling is done by linear interpolation so that the time-varying PPG signal can be analysed by Fast Fourier Transform (FFT). The motion compensation based on "polynomial warping model" is intended to overcome the movement artifact of the patient during measurement to make the result more accurate[16]. Like in online mode, different ROIs can be chosen to investigate the spatial variation of dermal perfusion change. The software has also a lot of routines for image processing and signal processing like filtering, convolution, or statistics.

The software was written in Microsoft Visual C++ 6.0 under Windows platform. It utilizes the advantages of Windows programming environment like graphical user interface, large memory management and powerful painting function which are essential for imaging and image processing. The acquired video can be played back, displayed with different colormap scheme or zooming to increase the visual effects. The calculated PPG signals for ROIs give a description of the skin hemodynamics in time domain. Figure 2 is a typical program window of PPGI software.

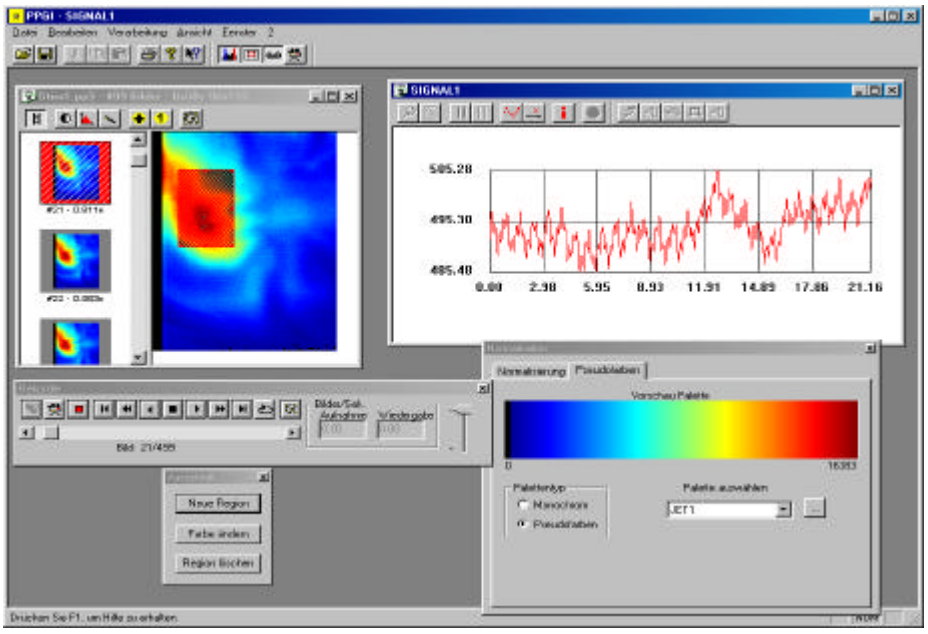


Fig. 2. PPGI software system.

3. RESULTS

With the newly developed PPG Imager, several measurements have been carried out. During the measurement, the test person just puts his hand, arm or lower leg quietly in front of the camera. If necessary he can also perform some standard exercises such as VOT and MPT.

3.1 VISUALIZATION OF VESSEL NETWORKS

Using PPG-Imager as a normal camera, a mapping of the structures of veins can be visualized. Figure 3 shows clear the improvement in the image contrast between tissue and vessels by using NIR light. The veins can easily be detected in NIR region, and become clearer after some digital processing (Laplace Operator and histogram stretching). The PC screen quality of these is far better than the printed images.

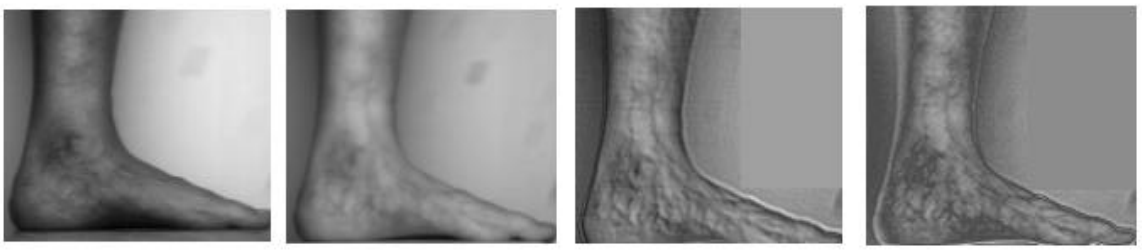
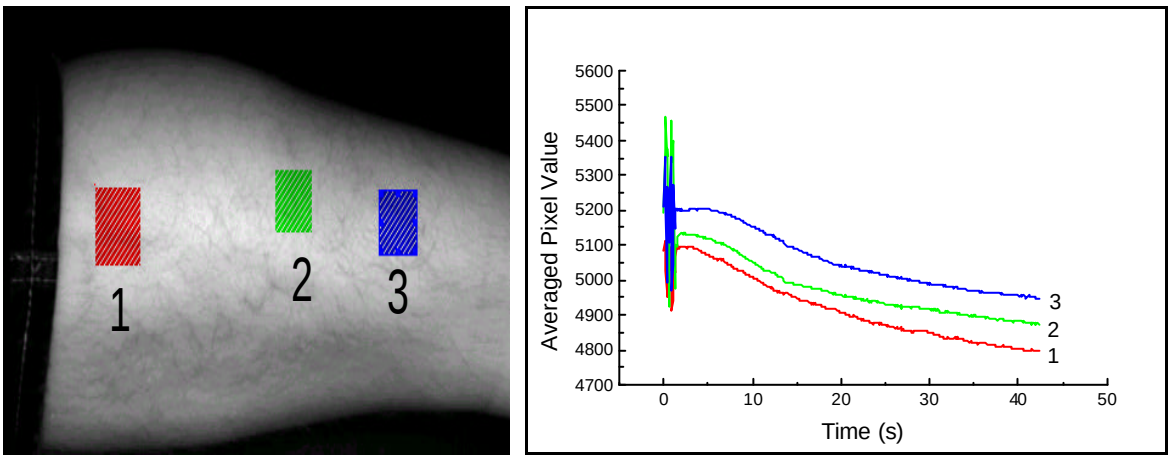


Fig. 3. Image taken from the ankle, from left to right: visible light (VIS), near infrared (NIR), filtered by Laplace Operator and histogram stretching.

3.2 MAPPING OF VENOUS FUNCTIONAL TESTS

Nowadays, venous disorders such as chronic vein insufficiency (CVI) and deep vein thrombosis (DVT) makes a large part of health care expenditure in developed countries. PPG provides a simple and fast screening method to detect these diseases at early stage through certain functional tests. The successful application of PPG for assessing venous hemodynamics includes the Muscle Pump Test (MPT) and the Vein Occlusion Test (VOT). For the PPGI, because the photons coming out of the skin (i.e. backscattered photons) arrive into the CCD cells too, we can also obtain information about spatial distribution of the blood volume change. So taking PPG Imager as an array of photon detectors, it is possible to obtain a 2D-mapping of functional parameters on skin for those typical test procedures in which the classical PPG has found successful application.



(A)

(B)

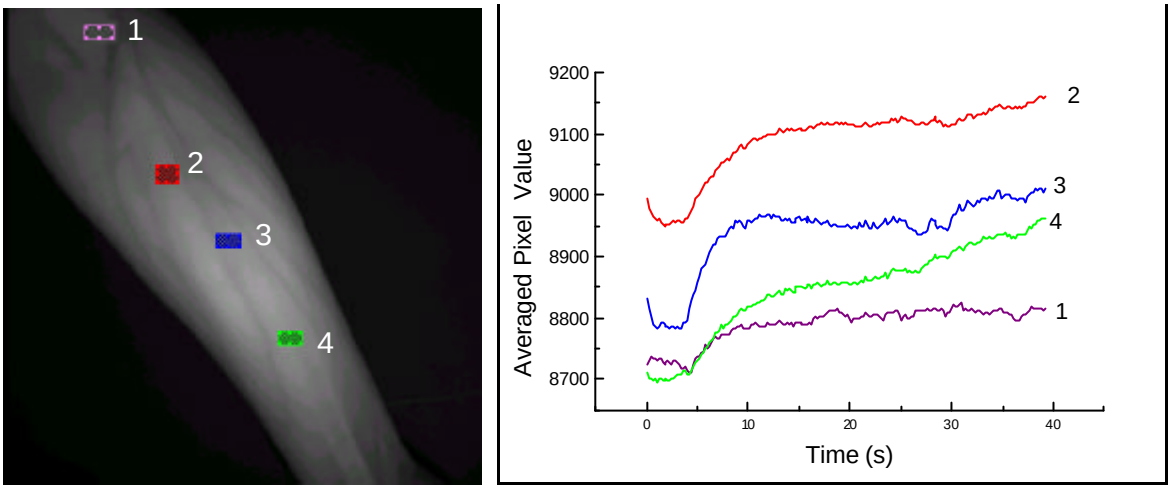
Fig. 4. ROIs selected for MPTM and the calculated average pixel values.

Muscle Pump Test Mapping (MPTM)

MPT is used for the functional evaluation of the total blood displacement in the peripheral venous system under muscle stress. The main application of this examination procedure is to diagnose the pathological reflux in varicose vein by patients with CVI. Figure 4 is an example of MPTM, in which venous blood is pumped out and is let to flow back afterwards. Several ROIs are selected (Figure 4A), then the averaged pixel values over time are calculated (Figure 4B). The higher the value, the less the light absorbed, indicating less blood volume. It shows clearly the arterial reflow which increases the blood volume and therefore decreases the reflected light.

Vein Occlusion Test Mapping (VOTM)

The functional parameters of the venous system at rest can be determined with the VOT. It can be used for screening diagnosis of DVT and other outflow obstructions in the lower extremities or the pelvis. Figure 5 shows an example for VOTM, in which venous blood is held by an inflated cuff and then is let to flow out after a sudden release of the pressure. Similar to the case in MPTM, some ROIs are selected (Figure 5A) and then the averaged pixel values of these ROIs over time are calculated (Figure 5B). The outflow of blood can be seen clearly and the time constant of the outflow is a useful parameter for assessment of possible venous obstructions.



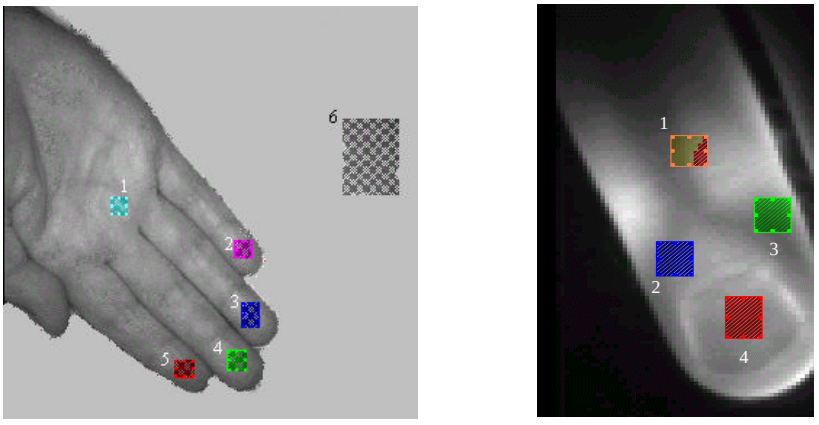
(A)

(B)

Fig. 5. ROIs selected for VOTM and the calculated average pixel values.

3.3 ARTERIAL MEASUREMENT

From the experience of PPG where the source and detector are separated, we know that arterial component contributes only a very small portion of the whole PPG signal. It is even more difficult to measure arterial pulsation in PPGI because there is a strong disturbance from the surface reflection. Owing to the high dynamic range of the CCD, it is still possible to use PPG Imager to analyze the arterial functions. Figure 6 shows two examples with different measurement setup. Figure 6A is a measurement of the reflection image sequence of a hand. By selecting some ROIs and calculating the averaged pixel values both in time domain and in frequency domain (Figure 7), the small fluctuation of arterial can be seen in time domain and it is more clearly in frequency domain where there exists a peak (about 1.2 Hz) corresponding to the heartbeat.



(A)

(B)

Fig. 6. Images for arterial measurement (left: reflection mode, right: transmission mode).

The above example works under the reflection mode, in which there is a large portion of the direct reflection from the skin surface making it difficult to distinguish the relatively small fluctuation of the arterial pulsation (only about 0.2% of the total amplitude). There fore another measurement working under transmission mode was taken. A transilluminated image sequence (Figure 6B) of a small area of finger was acquired with a high speed (25 frames per second) by using subarray capturing ability of the camera. Both the arterial pulsation (about 2%) and the slowly changing respiration rhythm can be seen clearly in the time domain. In frequency domain, the exact frequency value of the heartbeat (about 1.0 Hz) with its higher-order harmonic and the low frequency of respiration rhythm can be determined too (Figure 8).

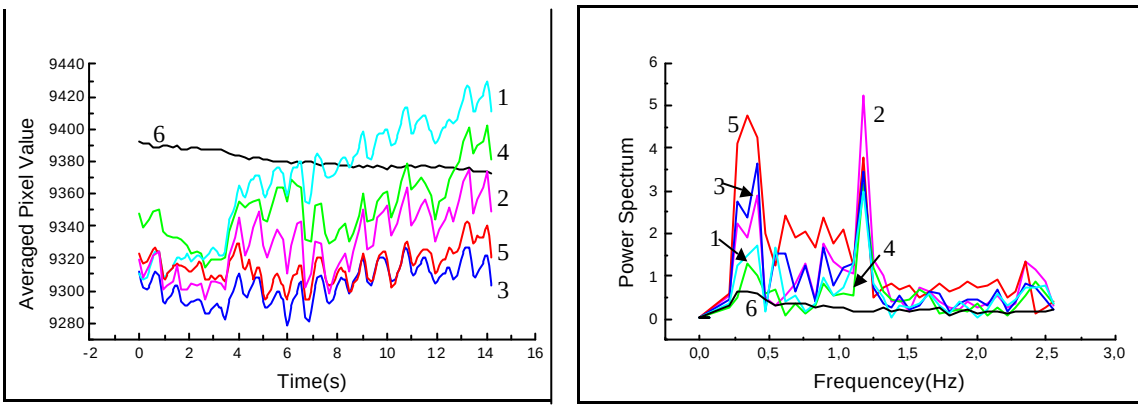


Fig. 7. Time domain and frequency domain representation of the arterial signal measured from the figure 6A. The difference between the background (6) and the skin area (1~5) is very clear.

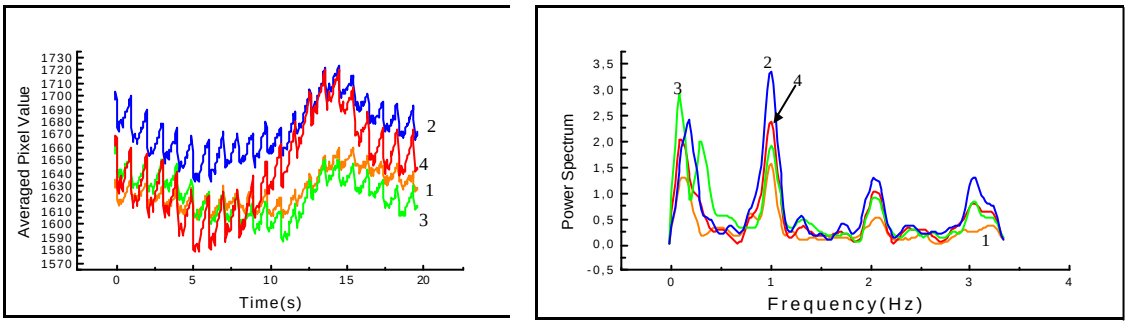


Fig. 8. Time domain and frequency domain representation of the arterial signal measured from Figure 10B.

3.4 CLINICAL MEASUREMENT

To evaluate the potential of its clinical application, the PPG-Imager has been used to measure the dermal perfusion of patient in hospital. Muscle pump test of a patient with CVI including venous ulcera has been measured by both classical PPG and PPG-Imager (Figure 9 and Figure 10). There is fairly well accordance between the PPG measurement and PPGI measurement.

4. CONCLUSION AND DISCUSSION

The Photoplethysmographic Imager uses a CCD as a normal imaging device to visualize the venous structures as well as an array of photon detectors to obtain a mapping of the dermal perfusion changes by measuring the PPG signal in two dimensions. The system has been shown to be capable of assessing various disorders of the peripheral venous system by standard test methods derived from the classical photoplethysmographic (PPG) practice in a noninvasive and contactless way.

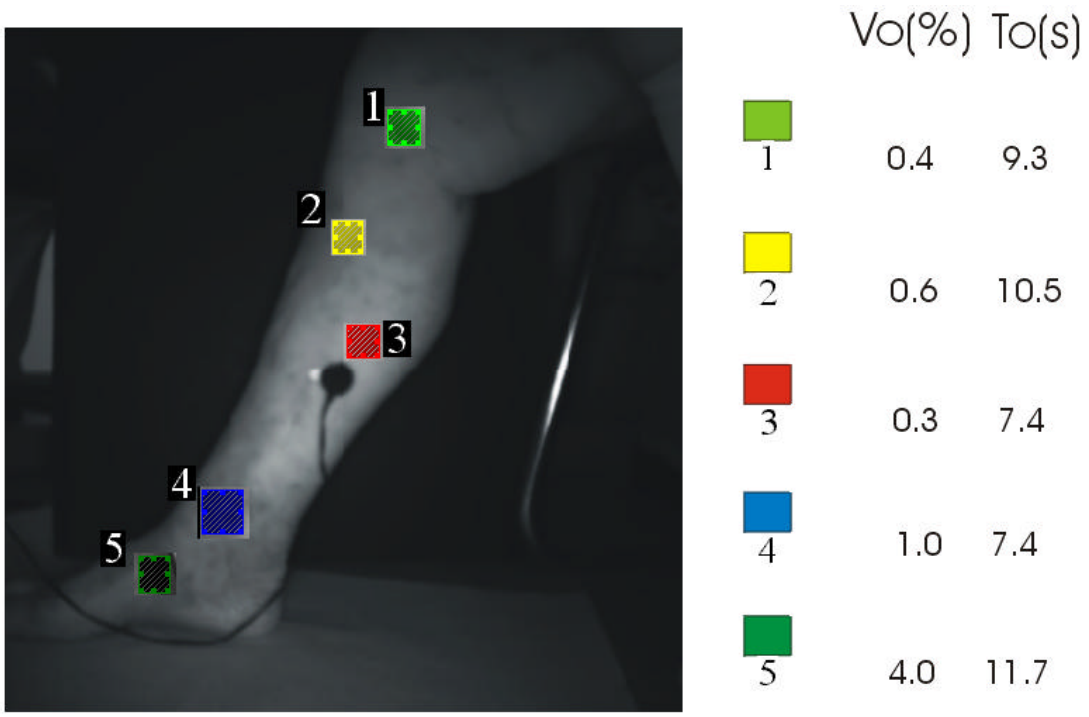


Fig. 9. PPG-Imager measurement of MPT with a patient: the spatial variation in functional parameters is evident.

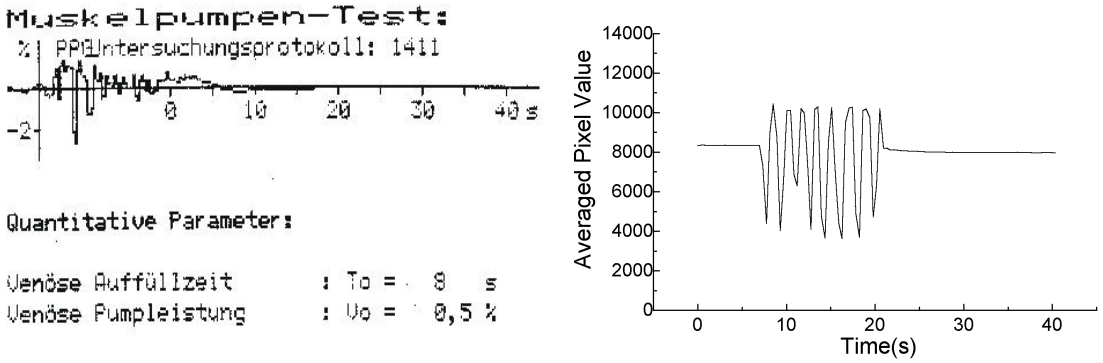


Fig. 10. MPT curve of a patient measured by commercial PPG and MPT curve of ROI No.3 in Fig. 9 measured by PPG-Imager

Our results show that this system performs as well as the currently available commercial PPG system by adding information of spatial distribution which allows the investigation of locations and causes of vascular disorders. Both the venous hemodynamics and arterial pulsation can be mapped in two dimensions. In contrast to the normal PPG used for continuous monitoring of temporal changes in dermal perfusion at a single site, the PPG Imager makes it possible to study the spatial variation of the peripheral hemodynamics at the same time. Furthermore, it is not only noninvasive, but also contactless. So the artifacts known in the normal PPG like sensor movement, deformation of the skin by incorrect sensor placement are eliminated.

However it introduces some new problems. Compared with the normal PPG which separates the light source and detector, the PPG-Imager working in the reflection mode introduces more direct reflection light which is not useful for assessment of the peripheral hemodynamics. This can be partially overcome by using polarized light and filters. In some special cases like finger and ear lobe, it is also possible to work under the transmission mode. Also, the design of homogenous illumination on the skin surface is essential for the quantitative and standardized assessment. Moreover, it is of promise to measure the

oxygen saturation of the skin surface with PPG Imager by taking multiple wavelength measurement so that a mapping of dermal oxygenation status can be obtained[17,18].

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NASA RESEARCH TEAM SUCCESSFULLY FLIES FIRST LASER-POWERED AIRCRAFT

Huntsville, AL | 14 October 2003 -- Since the dawn of powered flight, all aircraft have had to carry onboard fuel to stay aloft. But a team of researchers from the Marshall Center, NASA's Dryden Flight Research Center in Edwards, CA, and the University of Alabama in Huntsville (UAH) is trying to change that. The team has developed and demonstrated the first-ever small-scale aircraft that flies solely from power delivered by an invisible, ground-based laser.

They have now chalked up a major accomplishment and a first. The team has developed and demonstrated a small-scale aircraft that flies solely by means of propulsive power delivered by from the ground by a laser. The laser tracks the aircraft in flight, directing its energy beam at specially designed photovoltaic cells carried onboard to power the plane's propeller.