RHYTHMICAL PHENOMENA IN DERMAL PERFUSION – PROVED ASSESSMENT STRATEGIES AND NEW DISCOVERIES

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Summary The phenomena of rhythm fluctuation of arterial blood pressure were discovered already in the first continuous recordings in the 18th century. However the formation of such rhythms hasn't been explained until now. This work presents two concepts which could aid in bringing new insights into the understanding of these rhythms. One development is a multisensor system capable to acquire multiple PPG channels, ECG and additionally breathing signals to correlate local and central driven oscillations. The second new development is Photoplethysmography Imaging which allows contactless measurements of cutaneous perfusion with spatial resolution. Together with the necessary mathematical analysis tools like the Wavelet Transform a sound basis for assessment and evaluation of rhythm fluctuations in human hemodynamics is provided. Using the presented framework new, previously unreported phenomena of distributed blood volume movements in dermal perfusion could be observed.

Abstrakt Studie se zabývá rytmickými fenomeny v perfuzi kůže. Přestože jsou tyto fenomeny parcielně známy již od 18 století, není z fyziologického a biofyzikálního pohledu jejich generace, vzájemná interakce a lokální distribuce dodnes kompletně objasněna. Popsány jsou dva experimentální systémy, z nichž první sestává z kombinace klassických fotopletysmografických senzorů (PPG) pro detekci změn krevního volumenu v dermální mikrocirkulaci spolecně s EKG a detekcí respirační dynamiky. Druhý optoelektronický system (PPGI) umožňuje bezkontaktní detekci uvedených fenomenů s vysokou prostorovou a časovou rozlišovací schopností. První testy a klinické výsledky potvrzují mimořádně zajímavé diagnostické možnosti této nové optoelektronické zobrazovací metody.

1. EPILOGUE

„Rhythms are a basic phenomenon in all physiological systems. They cover an enormous range of frequencies with periods from the order of milliseconds up to some years. They are described by many disciplines and are investigated usually in the context physiology of the respective function or organ. The importance given to the research on rhythmicity is quite different in different systems. In some cases where the functional significance is obvious rhythms are at the centre of interest, as in the case of respiration or locomotion. In other fields they are considered more or less as interesting epiphenomena or at best as indicators without essential functional significance, as in the case of cardiovascular or EEG rhythms." [1]

2. INTRODUCTION

Complex rhythmical changes in dermal perfusion patterns have been known since the first continuous recordings of blood pressure. However the formation of these rhythms hasn't been explained until now. Actual research concentrates especially on the frequency range of about 0.1 Hz [2,3], however the assessment and interpretation of these perfusion rhythms are especially hindered by the fact that these patterns have very strong spatial variability and are highly transient.

This contribution tries to aid in the understanding of the cause and implication of the observed rhythmical phenomena in dermal perfusion by the introduction of a multi sensor system, capable to simultaneously acquire different optoelectronical sensor channels (Photoplethysmography, short PPG) together with ECG and breathing signals. Our latest research results show high local variations in the dermal perfusion behavior. For the study of distributed perfusion patterns are therefore mapping sensor concepts required. For this purpose we developed a new contactless, spatially resolving and functional measurement technique called Photoplethysmography Imaging (PPGI).

3. MULTI SENSOR SYSTEM FOR SKIN CONTACT APPLICATIONS

In the first part of this study a simple device has been designed which includes 5 classical PPG sensors (working in transmission or reflection mode, also in fiber optic configuration), two respiration sensors and one ECG channel [4].

Fig. 1. Multi sensor measuring system capable of simulataneously reading multiple PPG channels, ECG and breathing signals.

All analogue signals were digitized and processed by an integrated microprocessor. Sensor settings, measurement control & signal visualization were managed by custom software on a standard PC (figure 1 and 2). Our multi sensor concept allows additional insights for the determination between local and central rhythmical phenomena like heart rate synchronous blood volume changes (figure 3).

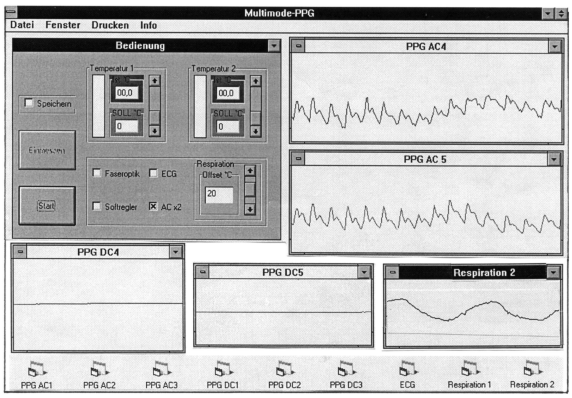

Fig.2. Selected windows in the screenshot allow the measurement control and visualization of the detected signals.

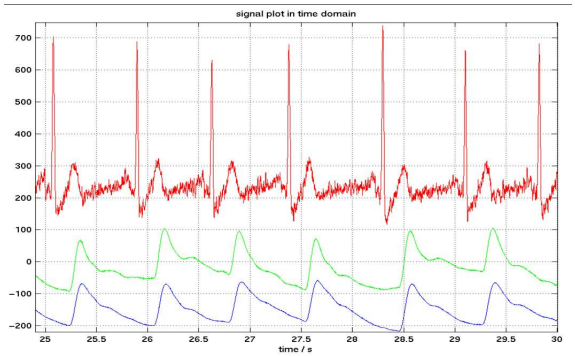

Fig.3. Perfusion recordings in comparison: both PPG signals detect the arterial blood volume pulse on the index fingers and show nearly the same pulse wave delay to the QRS complex. In addition the beat-to-beat heart rate variability is clearly visible in all signals.

In addition to the heart synchronous rhythms also a spectrum of other rhythmical phenomena in dermal skin perfusion can be detected if the sensor/amplifier system allows a non filtered data analysis (fg < 0.05 Hz).

Selected results from an indo-german project which was focused on the endogenous influence of dermal perfusion using Yoga are shown in figures 4. By positioning the PPG sensors on the forehead and chest of the subject who practiced Yoga relaxation techniques one could notice certain interesting periodical perfusion patterns as show in figure 5. First of all one could notice from this dataset that the PPG signal from the forehead region is much larger compared to the one from the chest region thereby indicating that the microcirculation in the forehead region is relatively stronger. The FFT analysis reveals that beside the heart beat (approx. 1 Hz) and breathing (approx. 0.35 Hz), the 0.15 Hz rhythms formation is present in the signal from the forehead region. According to the results from other research groups [5,6,7] these low frequency "relaxation" rhythms have a very important bearing on the human physiology and have potential therapeutic implications e.g. in psychosomatic medicine.

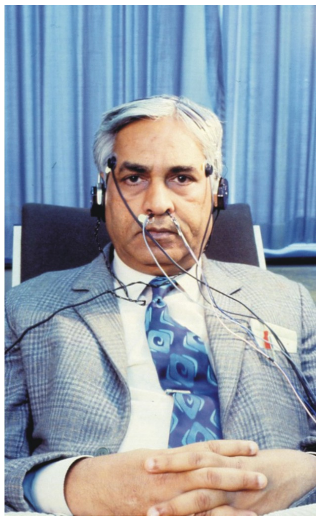

Fig 4.Investigation of the rhythmical phenomena in the human hemodynamics with PPG and respiratory sensors during Yoga exercise.

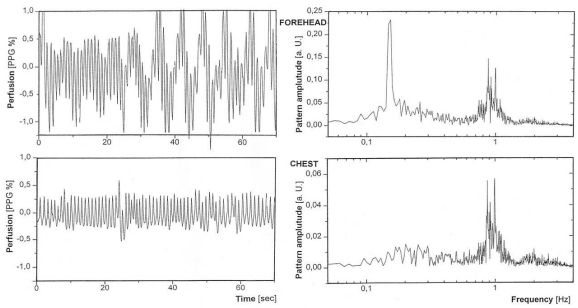

Fig. 5 Two-channel time domain registration (left) and FFT analysis (right) of skin perfusion rhythms, recorded with classical PPG sensors in the forehead and chest regions.

4. NEW CONTACTLESS ASSESSMENT STRATEGIES

The Photoplethysmography Imaging technique is a contactless and spatially resolving advancement of the classical and well established Photoplethysmography [8]. A part of the skin surface is illuminated by illumination panels consisting of multiple LEDs and as optical detector a high sensitivity camera is used. To detect also the weak light modulation, which is caused by the arterial pulsation, our setup utilizes the UltraPix FE 250 camera from Life Science Resources because of

it's high dynamic range of 84 dB and it's high readout speed of 5.5 MB/s. The imaging sensor is EEV 37-10, a silicon frame-transfer CCD with a pixel resolution of 512x512, the spectral range is 400 - 1100 nm with a quantum efficency of 40 % at 800 nm. To reduce the readout noise, the camera is cooled down to -40° C.

Using the setup shown in figure 6 it is possible to measure arbitrary parts of the skin surface and to simultaneously assess the dermal perfusion in different skin regions. The PPGI system allows to assess local changes in perfusion patterns and to do a functional mapping of the perfusion status. Of great importance is the novel possibility to measure even in wounds or transplanted skin.

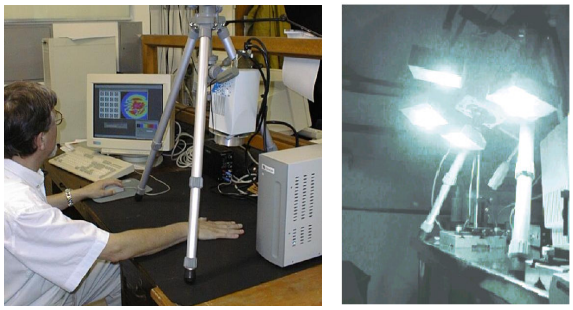

Fig. 6. Portable Photoplethysmography Imaging setup, the skin surface is illuminated by a custom LED floodlight and the backscattered light intensity is recorded by a high sensitivity CCD camera.

After recording of a short video sequence of the skin surface the operator can choose different regions of interest (ROI, "virtual sensors") for which the backscattered light intensity is calculated. The resulting signals contain the same information as classical PPG signals.

5. ADVANCED SIGNAL PROCESSING AND VISUALISATION OF DERMAL PERFUSION PATTERNS

A typical recording with corresponding PPGI signals can be seen in figure 7. The recording was done on a left hand with a small wound in the skin of the middle finger. As can be seen in the figure the perfusion patterns from healthy skin and the wound on the middle finger show significant differences. When looking only at the heart beat, it is slightly increased inside the wound, however the slow rhythms of about 0.1 Hz are strongly reduced inside the wound. Not only is it possible to discriminate the wound and the healthy skin when comparing the different frequency components, it is also apparent that the slow frequency component has strong local variations. Even the two ROIs on healthy skin, which are adjacent, show differences in the 0.1 Hz band.

When trying to further analyse the perfusion patterns with the classical Fourier Transform not much new information is revealed. It is possible to recognise differences at low frequencies, however the resolution is quite limited. The frequency spectrum can't reveal much advanced information, the reason is that the Fourier transform is not well suited for analysis of transient signals. It is not possible to judge only from the power spectrum of a signal if an oscillation is stationary or occurs only during a limited time and at which instance in time. To assess non stationary characteristics of a signal a joint time – frequency representation of a signal is needed. This problem is illustrated in figure 8.

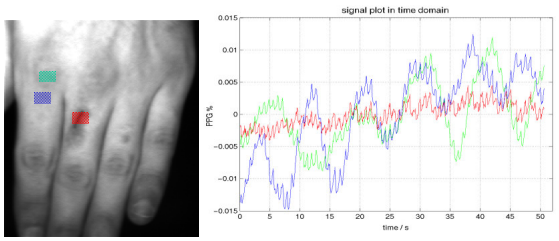

Fig. 7. left: PPGI recording of a hand with a wound on the middle finger. right: Calculated perfusion signals for selected ROIs.

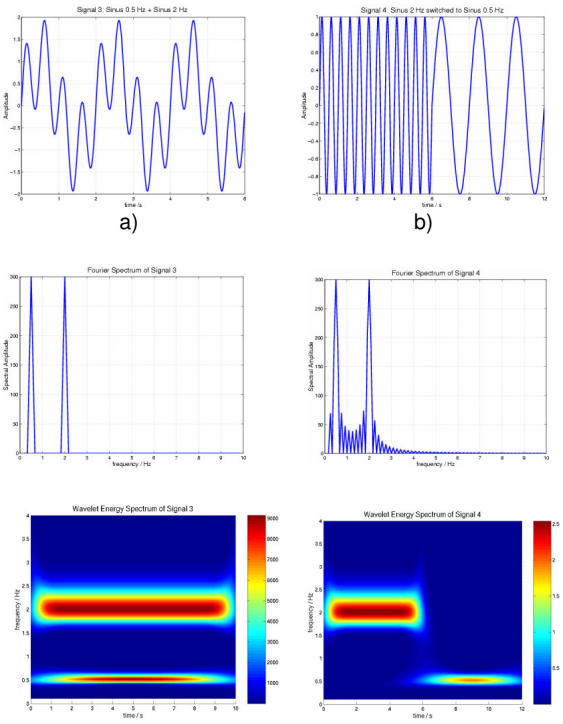

Fig. 8. Example of analysis of transient signals. top: synthetic signals a) and b). middle: Fourier Transform of example signals. bottom: Wavelet Transform of signals.

6. WAVELET TRANSFORM

The Wavelet Transform of a signal leads to a 3 dimensional time - frequency representation where

the spectral evolution over time can be directly assessed [9]. It is in reality a family of transformations where a signal $g(t)$ is transformed by an analysing function $\psi(t)$. The analysis function $\psi(t)$, which is called the "mother wavelet", is not fixed but can be chosen from a collection of functions. All of these have to meet certain restraints (see [10]), most notably are localisation in time as well as in frequency domain. To analyse the signal $g(t)$, the mother wavelet is shifted across the time axis (by parameter b) and also scaled by different factors a. Thus a family of basis functions

$$\Psi_{a,b}(t) = |a|^{-1/2} \psi\left(\frac{t-b}{a}\right)$$

is obtained.

The continuous Wavelet Transform is defined as:

$$\tilde{g}(a,b) = \int_{-\infty}^{\infty} g(t) \Psi^*_{a,b}(t) dt$$

Utilising this transform a higher dimensional representation of the signal $g(t)$ can be obtained where the dimension b is responsible for the time information and the other dimension a for the scaling information which is inversely proportional to the frequency.

The original function can be recovered from $\tilde{g}(t)$ by the inverse transform

$$g(t) = C_\psi^{-1} \iint \tilde{g}(a,b) \Psi_{a,b}(t) \frac{da\, db}{a^2}$$

where the normalising coefficient C_ψ is determined by the shape of the mother wavelet:

$$C_\psi = \int_{-\infty}^{\infty} |\hat{\psi}(\omega)|^2 |\omega|^{-1} d\omega$$

($\hat{\psi}$ designates the Fourier transform of ψ).

To fully describe the Wavelet Transform also the mother wavelet $\psi(t)$ has to be specified. An often applied function is the Morlet Wavelet, which is a wave modulated by a Gaussian of unit width (see figure 9):

$$\psi(t) = e^{\frac{t^2}{2}} \left(\cos(\omega_0 t) - i \sin(\omega_0 t)\right)$$

The parameter ω determines the time versus frequency resolution, the relation between scaling and frequency becomes $f = 2\pi\omega_0 / a$.

When using the Morlet wavelet the resemblance to the windowed Fourier Transform becomes apparent. The Gaussian can be interpreted as the windowing function. In distinction to the windowed Fourier Transform the width of the function is not fixed but is scaled together with the wave function.

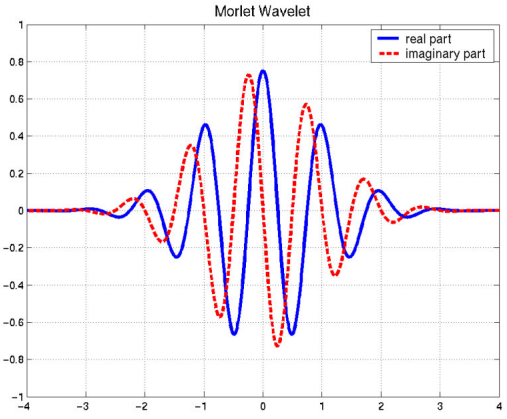

Fig. 9. Morlet mother wavelet consisting of a complex wave modulated by a Gaussian.

So for every frequency the same number of oscillations is taken into account, i.e. if we search for slow rhythms of 0.1 Hz the window function will be ten times wider than if we would search for 1 Hz components. This makes the Wavelet Transform admissible to investigate a very broad frequency range of multiple decades.

7. NEW INSIGHTS IN THE PHENOMENON OF DISTRIBUTED DERMAL RHYTHMICITY

The wavelet transform of a PPGI signal is shown in figure 10. The resulting spectrum is a joint time-frequency representation of the signal, the evolution of different frequency components (vertical axis) can be directly recognised versus the time (horizontal axis). The classical FFT power spectrum can be interpreted as a projection of the Wavelet spectrum in horizontal direction and thus looses any time representation.

The generated advanced signal visualisation reveals on first sight, that the slow rhythms of about 0.1 Hz are not stationary but fluctuate in amplitude and also slightly in frequency. Additionally the heart rate variability can instantly be recognised and shows a good correlation to classical beat-to-beat analysis of PPG signals or ECG signals.

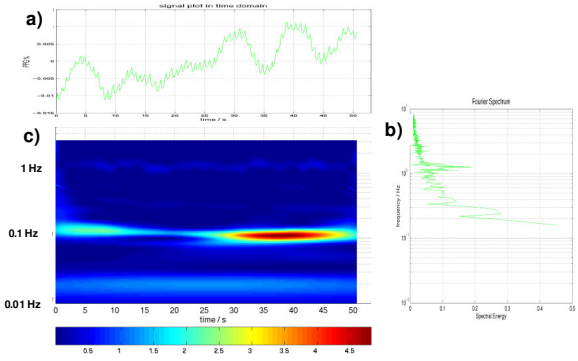

Fig. 10. Wavelet Transform of a PPGI signal. a): time signal. b): FFT frequency spectrum. c): Wavelet spectrum.

Apart from the strong temporal fluctuations in dermal perfusion also a new phenomenon of distributed spatial rhythm fluctuations could be observed using Photoplethymography Imaging. Figure 11 shows a recording of about 3 minutes of a forehead. The PPGI time signals corresponding to the selected ROIs contain very strong oscillations with frequencies of about 0.1 Hz. In contrast to the centrally controlled and uniformly detectably heart synchronous rhythms, the slow oscillations show a high local variability and autonomy. Due to strong differences in the perfusion signals despite the adjacent measurement sites, these slow blood volume changes have to be attributed clearly to local oscillators in the human body.

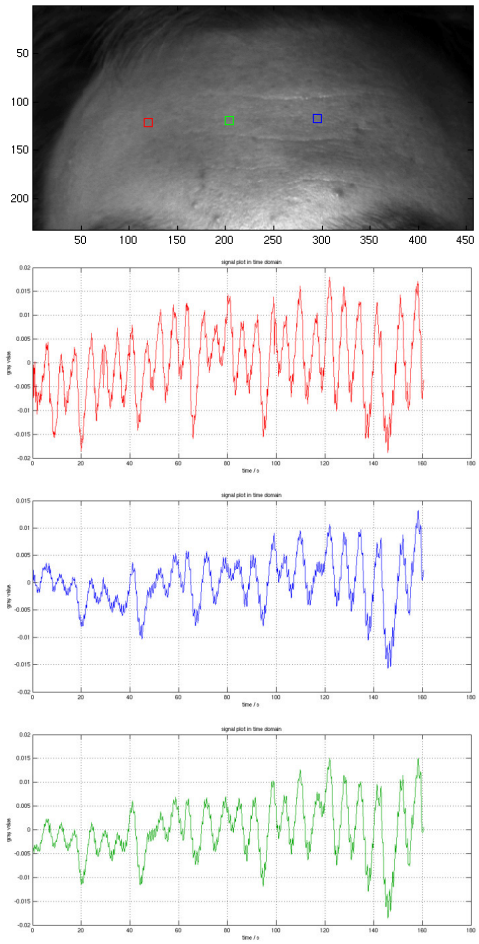

Fig. 11. Distributed spatial rhythm fluctuations can be observed using the novel PPGI technology. Top: Image of the recorded PPGI video sequence with 3 selected "virtual sensors". Bottom: corresponding PPGI time signals, the spatial variability in the rhythms of about 0.1 Hz can clearly be recognized already in the static signal representation. For an animated and more detailed signal representation please visit our homepage at http://www.ihf.rwth-aachen.de/English_Pages/Forschung/Ppgi/ppgi.html.

Another phenomenon which can only be observed in animated video representations of the PPGI recordings is "blood volume clouds" which move on the forehead in a coherent but complicated pattern. Figure 12 tries to illustrate this with screenshots of a recording, for the animated video representation please refer to the web page *http://www.ihf.rwth-aachen.de/English_Pages/Forschung/Ppgi/ppgi.html*. The physiological cause of these distributed "blood volume clouds" can so far not be explained but the presented results clearly indicate a strong local autonomy of the dermal perfusion rhythms around 0.1 Hz.

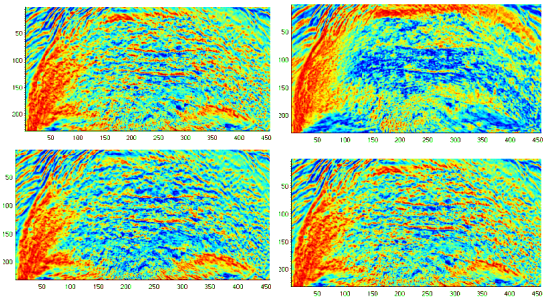

Fig. 12. Previously unreported phenomenon of distributed "blood volume clouds" observed by PPGI. The pictures show images taken at 14s, 16s, 50s, and 69s of a video sequence. The animated video sequence can be found on the authors homepage (http://www.ihf.rwth-aachen.de/English_Pages/Forschung/Ppgi/ppgi.html).

8. CONCLUSION

The analysis of complex rhythmical changes in dermal perfusion requires sophisticated assessment strategies. Using selected multisensor concepts it is possible to acquire undistorted vital signals in a very broad frequency range, correlation of the different sensor signals reveals that besides the known central rhythms certain local oscillations especially around 0.1 Hz occur, which show endogenous influencability.

The local variability of the perfusion patterns can further be assessed by novel imaging techniques. The presented Photoplethysmography Imaging is capable of assessing the skin perfusion of arbitrary skin surface regions in a completely contactless manner and at the same time provides results with high spatial resolution. This allows even perfusion studies in wounds or transplanted skin. Altered skin perfusion can already be detected in very small skin wounds.

Together with advanced joint-time-frequency signal processing the local autonomy of slow rhythms even in adjacent skin regions can be visualised. The Wavelet Transform allows the analysis of a signal over a wide frequency range, while providing good resolution also at low frequencies. At the same time also the temporal evolution of different frequency components over time can be revealed.

A completely new, previously unreported phenomenon of distributed blood volume movements in dermal perfusion could first be

observed using the PPGI technique. Latest results clearly document the existence of local oscillators which show high autonomy and local variability. The physiological cause and implications of this phenomenon are so far unknown. However it is expected that the low frequency "relaxation" rhythms around 0.1 Hz have a very important bearing on the human physiology and have potential therapeutic implications i.e. in psychosomatic medicine.

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