Transillumination of peripheral parts of the body with the use of optical radiation

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ABSTRACT

In the paper a result of hand fingers transillumination is presented. During experiments, an robot arm equipped with an optoelectronic system has been used. The object scanning was realized in the rectangular coordinates system. Optical radiation at the wavelength 880 nm was emitted by a high power LED to be supplied in pulse mode while a photodiode PIN was used as the photodetector. Both light source and photodetector were set into the special diaphragms in order to collect all ballistic photons. The signals obtained from the photodiode allowed determining the object optical attenuation occurring in particular sites of the transilluminated surface in a form of two-dimensional image. Also selected examples of current modern transillumination applications in medical diagnostics are presented.

Keywords: medical imaging, transillumination, optoelectronics

1. INTRODUCTION

Transillumination of biological objects is a diagnostic technique in the course of intensive development at the moment. The information on the first attempts of transillumination with optical radiation date back to 1929.[1] The fast development of such techniques, however, occurred in 1980's. This is related to the development of opto-electronic elements and the arrival of new possibilities of numerical transformation. Numerous transillumination attempts have been made since then leading to object imaging. At the beginning a technique called diaphanography was used, which consisted in illuminating the object on one side and observation of the same with a camera on the other. The use of a camera instead of naked eyed allowed for illumination with infrared radiation. This technique was most frequently used in devices called mammoscopes.[2] The images of the transilluminated object, however, were not sufficiently clear. Simultaneously some tests were made in relation to transillumination for purposes other than imaging. The most common example of such transillumination is the observation of arterial blood pulsation allowing for measuring the blood pulse and blood oxygenation. The techniques developed at present are those of efficient transillumination of thick layers of tissues and effective processing of data obtained that way. The purpose of such processing is the conversion of optic figures into information on the anatomic and functional properties of the tested object in possibly the shortest time. In devices called tomographs (tomos - dividing, graphos - record) the 3D space is represented by means of sequence of 2D images. Optical tomography OT is an imaging technique using the optical properties of the transilluminated tissues. The interactions occurring between the light and the tissues result in scattering, absorption and fluorescence, providing information on the structure, physiology, biochemistry and molecular functions. Optical imaging is used for description of surface structures (back radiation detection) and voluminous (detection of radiation penetrating the object). With the use of optical radiation, harmless to humans, (within near infrared and visible light range), it is possible to determine the parameters of tissues allowing for the reproduction of anatomic and functional properties. Due to strong scattering of the light, the practical implementation of optical transillumination is an immensely difficult task. The transillumination image resolution is lower than that of X-ray images. However, it enables to disclose information on the functional condition, unavailable in the X-ray technique. The scanning times of modern optical tomographs are a few minutes. During that time the test object (i.e. selected human body part) should remain immobilized in relation to the scanning system. The immobilization may not disturb the object's function maintaining simultaneously the examined person's comfort. During the scanning process the examined object is illuminated with optical radiation of several wavelengths. The radiation is modulated with a harmonic signal of

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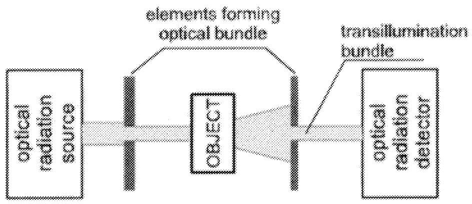
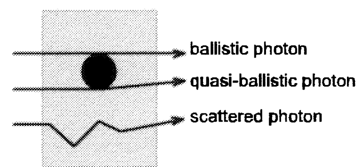
70-100MHz frequencies[1] or creates a sequence of impulses. Modulation with very short impulses lasting 0,4ns[5,6] or ca. 1s can be distinguished. Very short impulses are used in measuring photon flight times. In clinical tests medical imaging based on X-ray (X-ray imaging), ultrasonic waves (USG imaging), magnetic resonance (MRI imaging), infrared radiation (thermography) dominate. The above listed imaging techniques use various physical phenomena. The associated application of various methods is presently developed, allowing for obtaining a more complete set of information on the object, compared to the tests made in one diagnostic technique only.

2. TISSUE LAYERS TRANSILLUMINATION

Tissue layers transillumination is made in systems of typical configuration presented in Fig. 1(a).



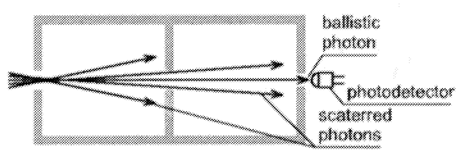
(a) Block diagram of the system



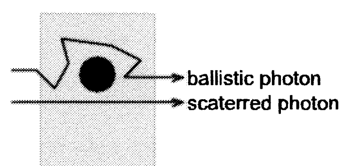
(b) Types of photons transmitted

Figure 1. Basic configuration of the system for tissue transillumination.

The basic issue related to the transillumination of (optically) thick layers of tissues is strong scattering and absorption. During transillumination the radiation source illuminates the examined object from on e side. The detector placed on the opposite side (in relation to the source) collects part of the radiation coming out of the objects. By trajectory, three types of photons falling on the photodetector's surface may be distinguished (Fig. 1(b)): ballistic, quasi-ballistic and scattered.[3] In a strongly scattering environment, the ballistic and quasi-ballistic photons constitute a scarce part of the scattered photons. It is possible to separate ballistic and quasi-ballistic photons from the scattered ones, by their direction after leaving the object (Fig. 2(a)).



(a) Detection of photons



(b) Propagation of photons[4]

Figure 2. Detection and propagation of ballistic and scattered photons.

The division is not entire. A situation is possible when a scattered photon leaves the object in the same way as a ballistic one (Fig. 2(b)). The probability of such event, however, is lower than that of a ballistic photon occurrence. There is a fundamental difference between optical imaging of surface structures and large organs. The surface structure imaging allows for high resolution representation (below one millimeter). Due to strong scattering by large organs the imaging is characterized with one millimeter resolution. Radiation out of near infrared range is used for the transillumination of large organs. This is the consequence of a relatively low absorption and resultant possibility to penetrate the object up to a few centimeters, maintaining the radiation power. The basic application difficulty in an effective transillumination of thick tissue layers is the low power of radiation subject to detection. Therefore, it is necessary to force the optical power of the source and to apply sensitive photodetectors. The power increase is restricted by the permitted energy density of $329 mJ/cm^2$.[7] The photodetectors are most frequently photomultipliers or - seldom - avalanche photodiodes.
The backscattering of photons is employed for testing the surface layers of tissues. The measuring system configuration is changed in such a way that the source and optical radiation detectors are optically joined to the object's surface on the same side (Fig. 3).

During transillumination of soft tissues or when the transillumination process is long enough, it is appropriate

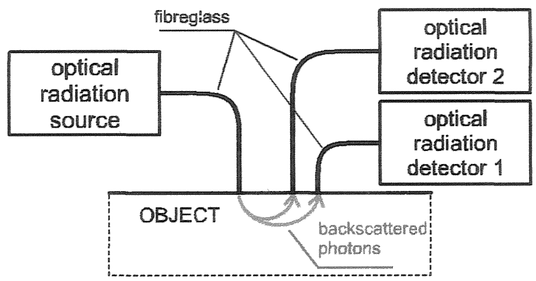


Figure 3. Tissue transillumination system configuration with the use of backscattered photons.[8]

to position the object in relation to the measuring system. The immobilization may not influence the object's functional condition maintaining the examined person's comfort at the same time. The methods used in positioning objects in relation to the sources and optical radiation sources are presented in Fig. 4. Positioning consisting in a free overhang (gravitational) is also applied. The necessity to force a weaker pressure than in X-raying, due to a longer optical imaging time is worth noting.

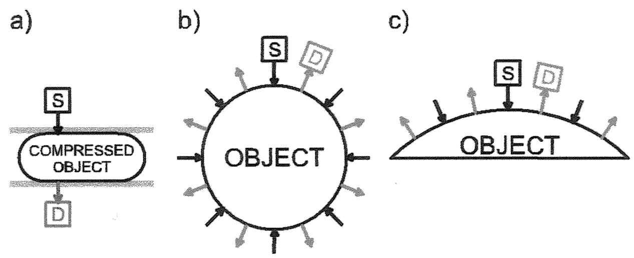


Figure 4. Methods of positioning an object in relation to optical radiation S sources and D photodetectors.[9]

2.1. Estimation of detector's optical radiation input signal for ballistic photons

To estimate the optical radiation detector's input signal, it was assumed that an optical wave of optical power P_{opt} =1mW for λ=780nm and ballistic photon flight probability $p_{bal} = 10^{-10}$ falls on the transilluminated surface. The number of input photons per second N_{in}:

$$N_{in} = \frac{P_{in}}{E_f} = \frac{1\,\mathrm{mJ/s}}{2.55 \cdot 10^{-19}\,\mathrm{J}} = 3.92 \cdot 10^{15}\,\mathrm{photons/s}\,, \tag{1}$$

of which

$$N_{in} = \frac{h \cdot c}{\lambda} = 6.63 \cdot 10^{-34}\,\mathrm{J} \cdot \frac{3 \cdot 10^{8}\,\mathrm{m/s}}{780 \cdot 10^{-9}\,\mathrm{m}} = 2.55 \cdot 10^{-19}\,\mathrm{J}\,. \tag{2}$$

Number of ballistic photons per second after penetration N_{out} through layers of tissues

$$N_{out} = N_{in} \cdot p_{bal} = 3.92 \cdot 10^{15}\,\mathrm{photons/s} \cdot 10^{-10} = 3.92 \cdot 10^{5}\,\mathrm{photons/s}\,. \tag{3}$$

The optical radiation output power P_{out} is:

$$P_{out} = \frac{N_{out}}{t} \cdot E_f = 3.92 \cdot 10^{15}\,\mathrm{photons/s} \cdot 2.55 \cdot 10^{-19}\,\mathrm{J} \cong 0.1\,\mathrm{pW}\,. \tag{4}$$

In case of a detector like silicon avalanche photodiode with M=100 amplification and $S(\lambda)$=0.45A/W the output current I_{PD}:

$$I_{PD} = P_{out} \cdot S(\lambda) \cdot M = 0.1\,\mathrm{pW} \cdot 0.45\,\mathrm{A/W} \cdot 100 = 4.5\,\mathrm{pA}\,. \tag{5}$$

3. EXAMPLES OF TRANSILLUMINATION'S SYSTEMS

3.1. Transillumination "lighting" the object from the other side

Lighting the object from the other side is historically the first transillumination technique. It consisted in the use of a strong source of visible light lighting the object from one side and naked eye observation from the other. Selective optical radiation is presently used for lighting the object from the other side, selected by the object's parameters. The naked eye has been replaced with a camera, which allows the use of infrared radiation. This type of transillumination used in rheumatic lesions diagnostic systems[10] is presented in Fig. 5. The source of light is a 675nm laser diode of 2mW power. The assessment of a joint is made basing on the camera recorded image and then computer processed. The original image of 255 x 415 pixel resolution is cut and then compressed to the 43 x 83 pixel resolution. In the images so processed two basic features were specified: the general illuminance of the light transmitted by the joint and light intensity curva closing the joint horizontally. In virtue of the second characteristic, the third one is determined - the finger perimeter. The perimeter value allows for the assessment of rheumatic lesions progress between the subsequent examinations. The characteristics specified constitute input data of the classifier built with the use of neuron networks.

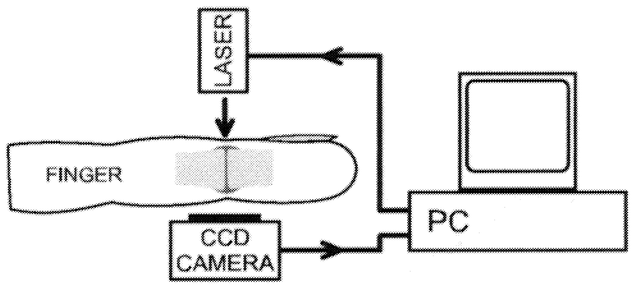


Figure 5. Transillumination diagnostics of joints.[10]

3.2. Early caries imaging

For early caries transillumination imaging, radiation of near infrared range is used with $\lambda = 1310$nm in a system[11] as presented in Fig. 6. In the sample system a 150W halogen bulb or LED 1310nm diode is the light source. The

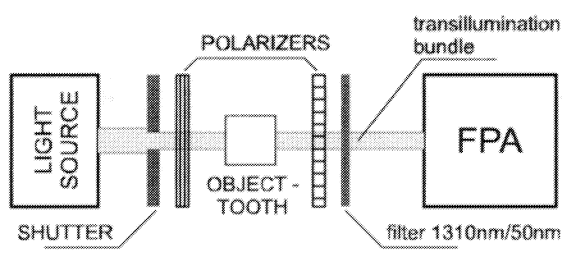


Figure 6. Tooth transillumination system.[11]

caries area is characterized with double refraction. The polarization originating from double refraction combined with polarization filters allows to reduce the influence of the detector's overloads on the teeth edges. The signal from the object is processed in the focal plane array (FPA) matrix InGaAs of 318x252 pixel size. The 1310nm band transfer filter of 50nm bandwidth filters the radiation processed in the FPA matrix. In order to obtain possibly the best contrast between the area of pathological lesions and surrounding enamel without saturating the FPA matrix, the light intensity, distance between the source and the object and the shutter diameter are selected each time.

3.3. Transillumination "cup"

An example of using transillumination in testing a voluminous object may be a "cup" used in mammographic tests.[12] The objects under examination is placed in a cup (or kitchen drainer) shaped bedding. The optical system consists of a fiber optic network, 255 of which conduct the radiation to the object and the other 255 fiber optics conduct the optical response (Fig. 7). The measurement consists in subsequent switching on one of the illuminating fiber optics and determining the response in each receiving fiber optic. The object's analysis uses the dependency of the blood optical properties on oxygenation. The application of three wavelengths selected appropriately allows for detecting areas of pathological lesions that are characterized with strong blood flow of weakly oxygenated blood.

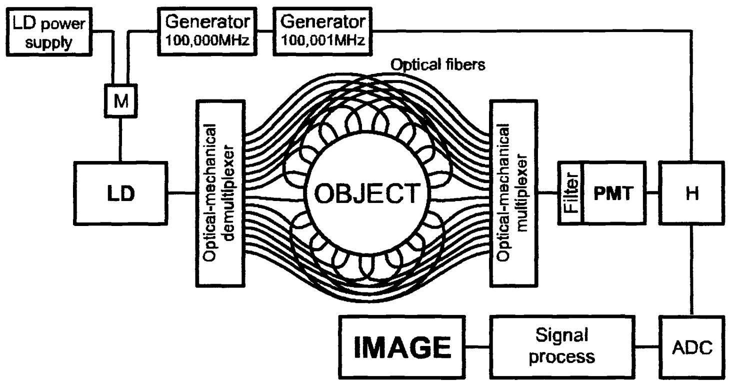


Figure 7. Block diagram of transillumination "cup" measuring system: M- modulator of current controlling the laser diode LD, PMT - photomultiplier, H - demodulator, ADC - analog-digital converter.[12]

3.4. Photoacoustic method

The photoacoustic method consists in illuminating the examined object with radiation impulses with simultaneous detection of the acoustic signal in such object (Fig. 8). The acoustic signal arises in consequence of pressure growth due to heating the particular cells of the object. Considering the optical properties, there are differences in heating the particular cells. The photoacoustic imaging progresses in the following steps: absorption of optical radiation impulses - adiabatic heating of the absorber - growing pressure - propagation of the acoustic signal - detection of the acoustic signal changes - signal analysis and processing. The examined object is placed between two panels. The object is illuminated through the upper panel. The optical signal from the Nd:YAG laser of 1064nm wavelength (providing deep penetration) is directed onto the object by a fiber optic. The lower panel incorporates piezoelectric microphones connected to amplifying systems. The object image is reconstructed in virtue of detected time delays of the signals received by the microphones.[13]

3.5. Structures of systems for transillumination measurements of tissue layers

The systems for transillumination of layers of tissues described in literature, built according to the general block diagram from Fig. 1, differ in the method of optical input functions generation and their detection. Two basic groups of systems can be differentiated:

- measuring the amplitude and phase of the transmitted optical radiation,
- using the photon time-of-flight analysis.

The first group includes systems with processing the frequency area allowing for measurement of the amplitude and optical output signal phase values related to the input signal. The systems with impulse modulation with the amplitude value of the optical output signal measured constitute a subgroup. A separate and specific group includes systems in which the photon times of flight through the transilluminated layer of tissues are measured and analysed. The specific character is in the necessity to measure the time below 1ns.

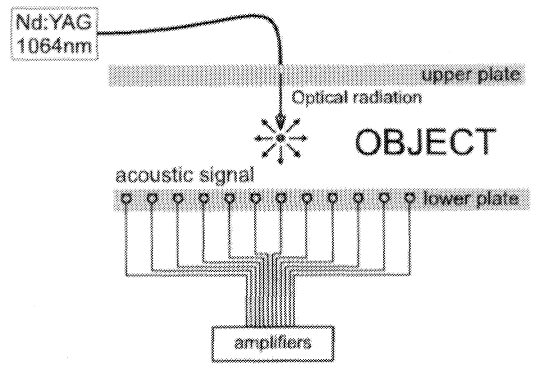


Figure 8. Photoacoustic system concept.[13]

3.5.1. Scanner measuring system with processing in frequency domain

Fig. 9 presents the block diagram of a sample measuring system processing in the frequency domain.[1] The test object is illuminated with five wavelengths. The free fiber optic terminals situated opposite one another respectively constitute the movable part of the optical system, scanning in a rectangular system of coordinates. The 1310nm radiation modulated with f_p =500kHz frequency functions as a pilot observing the object's shape and at the same time preventing the PMT photomultiplier's overload. Detection of radiation exceeding the permitted level causes disconnection of keys S by the Disc discriminator. The radiation used in the object's optical properties measurements is modulated with frequencies close to 70MHz values. For such frequencies a phase shift takes place by ca. 20° per 1cm of the object thickness. The radiation from the laser diodes is conducted by fiber optics divided into two sections: the first one consisting of five fivers of 100μm diameter, the other one is one fiber of 400μm diameter. The object is illuminated with radiation creating a spot on the object's surface of more than 1mm diameter. The optical signal coming out of the object is collected by a fiber optic bundle of resultant diameter 5mm. About 90% of this signal is directed to the PMT photomultiplier, while the remaining part - the PD photodiode.

3.5.2. Scanner system using the time distribution analysis of the photons received

Fig. 10 presents the block diagram of a monochromatic scanning system using the time distribution analysis of photon flight.[5,6] There are two critical blocks in the system: laser diode block generating radiation impulses and a block generating light impulses - 785nm of 2mW average power and 400ps duration, repeated with 80MHz frequency. The scanner system shifts the Fi and Bu fiber optics in relation to the object, scanning in a rectangle system of coordinates. The overload signal from the PA preamplifier controls the Sh shutter preventing the overload of the PMT photomultiplier. The TCSPC module makes the acquisition of photon times of flight through each scanning point for 100ms. Based on this the distribution of time of flight (DTOF) is made. The DTOF characteristics are the input data of data processing algorithms. The processing results include the adjustment of the transilluminated object edges as well as scattering and absorption coefficient values. This, in turn, is the basis for estimation of figures determining the object's anatomic and functional condition. The central block of the system using the DTOF analysis is the photons time-of-flight measuring module[6] presented as a diagram in Fig. 11. Counting photons in the TCSPC system is effected in the following way: synchronizing impulse (start) from the radiation source (laser) through the CFD block initiates the time counting through the TAC block, time is converted into the analog signal value until the (stop) impulse arrival from the CFD photodetector, the analog signal amplitude value at the TAC block output (proportional to the time between the start and stop impulses is totalized with the analog signal from the DAC converter and then converted in the ADC block, the output code from the ADC after subtraction of the counter abacus value, determines the address of the memory cell subject to incrementation. In order to reduce the ADC non-monotonicity, conversion with component constant with cyclically varying value, was introduced. Basing on the values measured in

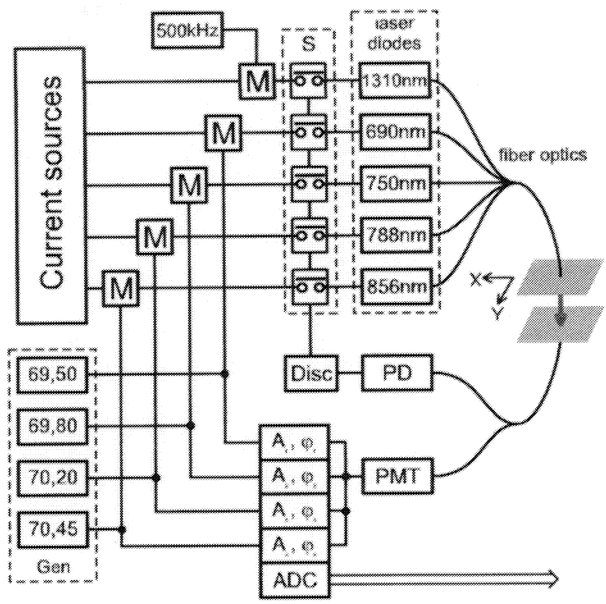


Figure 9. Measuring system configuration processing in frequency domain: M - modulator, S - set of keys, PD - photodiode, PMT - photomultiplier, Gen -generator of modulating frequencies, Disc - discriminator, ADC - analog-digital converters block, (A_x, φ_x) - amplitude and phase of optical signals received from the object for the particular modulating frequencies.[7]

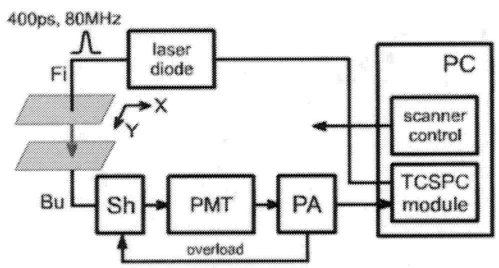


Figure 10. Basic structure of the system using the time distribution analysis: PMT - photomultiplier, PA - preamplifier, Sh - shutter, Fi - sending fiber optic, Bu - receiving fiber optics bundle, TCSPC -time correlated single photon counting block.[5]

the system presented in Fig. 11 distribution of time of flight is created (Fig. 12). The sample time of flight histograms measured for two conditions, i.e. without and with the transilluminated object are presented. The system response without the object serves to evaluate the measuring track. The time of flight through the object histogram is flattened in relation to the histogram without the object. In the object's histogram the early time window describing the balistic and quasi-balistic photon flight can be distinguished. The sample late time window describes the time of flight of a certaing balistic phonon group. The distinguished time windows constitute the final results of scattering equations used for the estimation of the optical parameters of the transilluminated object.

4. TRANSILLUMINATION SCANNING THE FINGERS

The experimental transillumination of a body peripheral is possible in a simple sending-receiving system presented in Fig. 13.

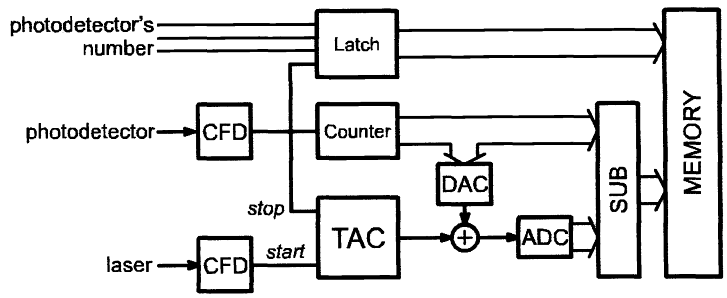


Figure 11. Block diagram of the TCSPC system: CFD - discriminator, TAC - time-amplitude converter, DAC - digital-analog converter, ADC - analog-digital converter, SUB - subtracting unit.[6]

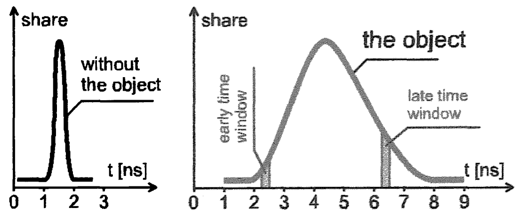


Figure 12. DTOF: without the object - measuring system response and with the examined object.[5]

Due to the easiness of setting the location in relation to the measuring system of the measuring system and due to the variability of the optical properties, a convenient object in the transillumination tests is a finger. The optical part of the transmitting-receiving system are LED diodes placed opposite the PIN photodiode PD. Several radiation lengths were used for the tests, but the best effects were found for the 870nm and 660nm radiation. The LED diodes were fed with current impulses of ca. 1μs and repetition frequency 1kHz. As the optical properties (transmission) measure, the U_M amplitude of voltage impulses $u_{PD}(t)$ was assumed. Despite the measuring system simplicity the imaging obtained was as anticipated. Differences between the U_M amplitude variability for fingers without and with joint degenerations were observed. To transilluminate some optically thicker body parts it is necessary to increase the system's sensitivity, better concentration of the optical bundle and possibility to select the detectable photons. Nevertheless, the optical radiation modulation method used is an alternative for solutions with modulation by means of a harmonic course.

4.1. Finger transillumination results

Finger transillumination results were selected for the presentation. The selection of fingers made it possible to carry out tests with the use of a simple optoelectronic - electronic measuring system. The mechanical structure of the measuring system, its block conforming with the diagram of Fig. 13, was constructed in the form of letter C fixed to the robot's arm[14] (Figs. 14(a) and 14(b)). A LED transmitting diode and PD photodiode (without the additional systems focusing the optical bundle) were incorporated at the structure ends in optical channels of 3 mm diameter and ca. 20 mm length. The object's scanning is made in a rectangular $x - y$ coordinates system. Trajectory of C-system (x =var, y =var, z =const) presented in Fig. 14(c). The hand examined is laid on a transparent panel stabilizing its position. Various high power LED diodes are used in the tests. The results presented were obtained for an ELJ-880-228B17[15] transmitter with λ =880nm fed with current impulses I_m = 7A, T_i = 1s, T_{rep} = 1ms. The receiver is the PIN BPW24R photodiode PD. The transverse motion of the scanning system in relation to the fingers was input. Figure 15(a) presents relationships U_M =f(y) for selected cross-sections at the x-coordinate while Fig. 15(b) shows a transillumination image of hand fingers that was obtained with measurements. Based on the 2-dimensional set of particular amplitude values $U_M(x, y)$ lines connecting the points of selected values U_M have been defined. Such specific isolines illustrate transmission properties of fingers at the used optical radiation.

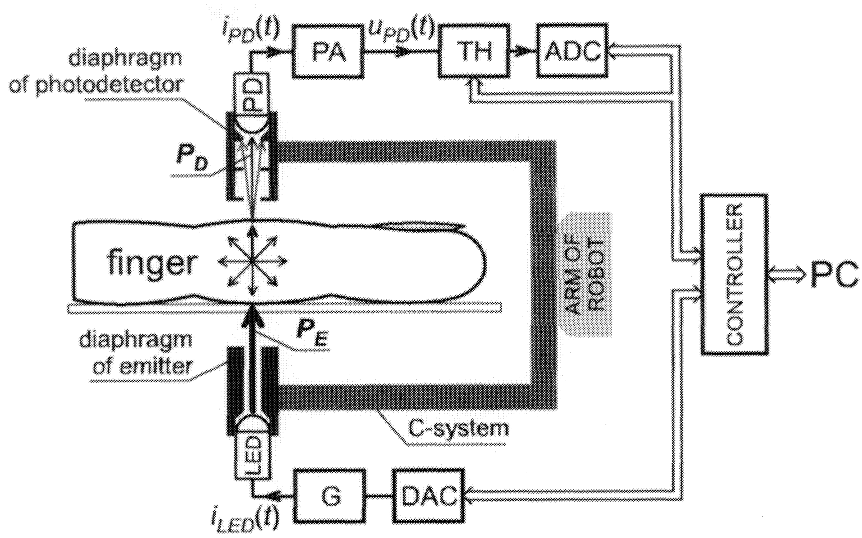
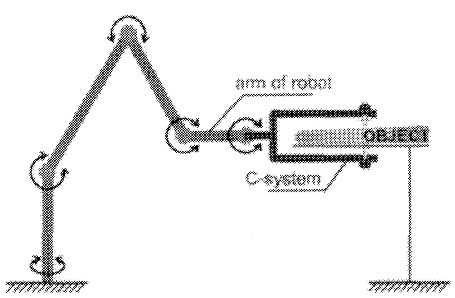
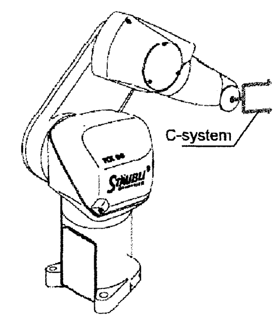


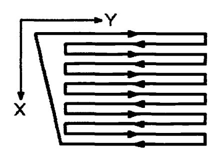
Figure 13. Impulse transillumination system of a finger: PD - photodiode (as photodetector), PA - amplifier and converter of photocurrent $i_{PD}(t)$, TH - track and hold, ADC - analog-to-digital converter, LED - photoemitter, G - source of current pulses $i_{LED}(t)$, DAC - digital-to-analog converter, P_E - radiation illuminating the object (a finger), P_D - power of radiation at photodiode PD.



(a) Kinematics of transillumination system



(b) View of arm robot RC60 with C-system

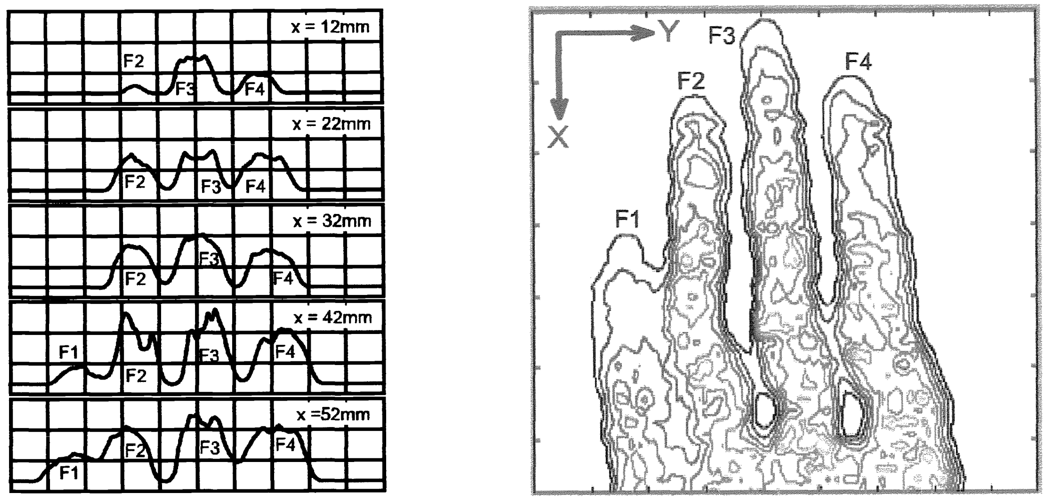


(c) Trajectory of C-system

Figure 14. Overview of transillumination system of a finger.

5. CONCLUSIONS

The transillumination of biological objects is a diagnostic technique under current intensive research. It concentrates on development of effective transillumination of thick layers of tissues and on building efficient and stable algorithms representing anatomic and functional properties. It seems reasonable to test transillumination techniques not yet described in any reference literature. Now, optical transillumination is mainly used in monitoring blood oxygenation, hemorrhage detection, brain imaging, Alzheimer disease diagnostics, mammography, rheumatism and joint inflammable condition monitoring. The finger transillumination test results show that effective transillumination is possible even in a simple system and indicate that the further development of the developed measuring system is reasonable. Upon the test results analysis the necessity arises to configure the optical part so that a better resolution can be obtained with ability of effective transillumination of objects optically thicker.



(a) Specification of the U_M signal dependency on the y location for selected cross-sections with x coordinate

(b) Transilllumination image of left hand fingers

Figure 15. Results of optical finger's transillumination.

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