Journal of Biomedical Optics 6(1), 90–96 (January 2001)

Optical measurement of cardiac rhythm using a personal computer with telediagnosis possibilities

Francisco Pérez-Ocón
Facultad de Ciencias
Departamento de Óptica
Universidad de Granada
18071 Granada, Spain

Antonio Abarca
Universidad de Jaen
Departamento de Electrónica
Avd. Madrid 35
Jaen 23071, Spain

Jesús Abril
Philips
Sistemas Médicos
C/ Manuel de Falla 18
Jaen 23007, Spain

Enrique Hita
Juan Luis Nieves
Universidad de Granada
Departamento de Óptica
Facultad de Ciencias
18071 Granada, Spain

Abstract. A system that enables the automatic measurement of cardiac rhythm and the quantity of oxygen in the blood has been designed, constructed, and patented. Equipped with the appropriate software, this system registers this information and represents it numerically, in the form of a graph, which can then be printed as a detailed record of cardiac rhythm. This system aids in the determination of cardiac pathologies, and also enables the information to be sent to medical professionals to perform telediagnosis. The apparatus is based on the measurement (sampling) of noninvasive medical parameters. The apparatus is intended to cover a broad range of requirements and needs, as can be used by medical professionals (to detect pathologies related to the pumping and circulation of blood in the body) as well as by lay people who might wish to monitor or gain information concerning their cardiac rhythm and the general functioning of their heart. Thus, the system is designed to be clear and concise in its information as well as easy to use, especially for people unrelated to the medical profession. The way to constructing this system is explained in detail.
[DOI: 10.1117/1.1331560]

Keywords: optical sensor; cardiac rhythm; transducer.

Paper JBO-007101 received May 21, 1999; revised manuscript received June 15, 2000; accepted for publication Oct. 10, 2000.

1 Introduction

The aim of the present study was to design and construct a system capable of monitoring cardiac rhythm and blood–oxygen levels using a personal computer (Patent No. P9801354 of our University and developed for us). Data were collected by optical methods, in such a way that the variable monitored was the absorption by the blood of the luminous radiation produced by a light emitter diode (LED) which emits long wavelengths.[1]

The functioning of the apparatus, based on measuring (sampling) noninvasive medical parameters,[1] was intended to cover a broad range of requirements and needs, since it could be used by medical professionals (to detect pathologies related to the pumping and circulation of blood in the body) as well as by lay people who might wish to monitor or gain information concerning their cardiac rhythm and the general functioning of their heart. Thus, the system was designed to be clear and concise in its information as well as easy to use, especially for people unrelated to the medical profession. Finally, the device was intended to be economical.

The steady increase in communication, optical engineering, and the need for rapid, accurate diagnoses makes these types of sensors and transducers a growing necessity. New technologies make it possible to monitor an individual's health without requiring visits to the doctor's office or the hospital, providing greater patient comfort, and reducing health-care costs. These technologies allow the transmission of information, in real time, of the cardiac-rhythm measurements (also given in real time).[2] In addition, for added comfort, the operation of the device does not require a medical professional. In cardiovascular patients, the cardiac parameters can be monitored in real time simply by turning on the system and connecting the computer with a medical network capable of diagnosing the results. Such communication is feasible with present-day telecommunications.[3]

The functioning of the device is based on a LED coupled with a light dependent resistor (LDR).[4] That is, the former generates a beam of light and the latter registers the variations in the beam passing through the blood vessels (of the thumb). In addition, a series of amplifiers and filters[5] are used to modify the signal to the data-acquisition system (DAS).[6] In this system, the analogic values provided by the sensor are converted to digital values, which on being transmitted to the personal computer can be represented on the screen or be recorded and represented in a graph.

Given the characteristics of the program, Visual Basic was chosen as the appropriate programming language, since it is oriented to objects and has a series of visual tools to facilitate user operation from within the program WINDOWS.

2 Description of the Device

2.1 Acquisition Functions and Signal Distribution

Figure 1 shows the general structure of a measure and control DAS. The different functions are as follows.

Juan Luis Nieves is a member of SPIE. Address correspondence to Francisco Pérez-Ocón. E-mail: fperez@ugr.es

1083-3668/2001/$15.00 © 2001 SPIE

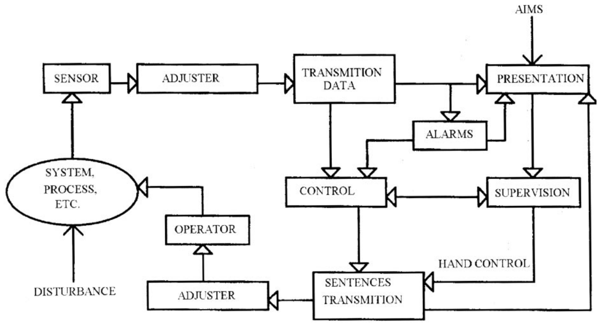

Fig. 1 Scheme of the general structure of a DAS.

2.1.1 *Transduction*

The first element of the DAS is the one that measures the optical magnitude of the input. The element of measurement is an input transducer, which converts the optical signal to an electric one.[7,8] As the energy converted by the transducer is small, the output must be modified to adapt it to the subsequent stages. The basic parameters of this sensor are: margin or field of measurement, sensitivity, resolution, and exactitude.[9]

2.1.2 *Digital–Analogic Converter (DAC)*

The output of this sensor is an analogic signal (continuous with regard to strength and time) and it must be converted to digital (binary: continues in time, but only with two levels of voltage), since the processing elements and many of the presentation elements require digital input. This quantization and codification are performed by DAC.

The analog to digital conversion is not instantaneous. If during this time the amplitude of the analogic input signal changes, the result of the conversion corresponds to some of the values taken by the input during the duration of the conversion.[6] So that this uncertainty in the amplitude is less than the discrimination permitted by the DAC (value of the less-significant bit), the maximum velocity of the change of the input dV/dt must satisfy the following condition:

$$\frac{dV}{dt} \leqslant \frac{M}{2^n t_c}, \tag{1}$$

where M is the range of voltage at the input of the DAC, n is the number of bits, and t_c is the time between conversions.

2.1.3 *Signal Modification*

For making use of the dynamic margin of the output of the DAC (2^n values corresponding to a margin of voltages of M input), the margin of amplitudes of the signal must coincide with that of the input to the converter M. For this, the output of the sensor must be amplified, avoiding the saturation of the amplifier. At the same time, the output of the sensor must be made compatible with the input of the DAC.[9]

3 General Conditions

3.1 Electronic and Electrical Components

All the components necessary to construct electronic circuits should be adjusted as closely as possible to the values determined in the design and calculation, with respect to their nominal values, current, and maximum power admissible.

3.1.1 *Resistances*

All the resistances used (apart from the exceptions mentioned above) are metal coated, and thus offer better electrical properties than those of carbon; they have great stability, low level of noise, low tolerance (±1%), low coefficient of temperature, and high functioning temperature. Having reduced ranges of power and current, except in the cases indicated, the carbon resistances are the most adequate. The maximum current of all of these should never be less than that calculated. Another advantage is that these rarely cost more than other resistances on the market.

3.1.2 *Variable Resistances*

It is recommended that these be cermet coated and multiturn adjustable, as this type offers greater precision. The type of adjustment is vertical because of its greater facility of access in case of having to readjust some of them after mounting. The tolerance of the variable resistances used is ±10%.

3.1.3 *Condensers*

The nominal current for the condensers should exceed at least 10% of the value of the working current. The condensers used are of MKC plastic (polycarbonate), except in the cases in which ceramics or electrolyte is indicated. The plastic condensers are characterized above all for their small size and for having dielectrics of excellent properties (highly resistant insulation and high functioning temperature). The electrolytes used are of aluminum.

3.1.4 *Integrated Circuits*

All the integrated circuits are mounted on a breadboard socket, rather than soldered directly over the circuit plate, in order to permit quick and easy changes if necessary. In the integrated circuits CA3140 used in the amplifiers, the design should include the condenser to screen out other frequencies.

3.1.5 *Sensor*

The sensor detector of beats must be compact to fit the size of the thumb without being so tight as to cut off the normal flow of blood and thereby provide inaccurate data. The sensor should be covered by a black cover to exclude all light (like a camera obscure), to avoid measurement errors due to the interference of illumination exterior to the system.

3.1.6 *Connectors*

The connectors used are screws or a type used especially for circuitry. The wires used are copper, 1.5 mm in diameter. These should not be longer than required.

3.1.7 *Connections*

The terminals which might remain exposed should be protected or covered with a thermoretractile cover to avoid interference, electrical failures, or other undesired effects.

The device is mounted in a plastic box large enough to accommodate the plate of the DAS and the power supply.

Given the DAS used and the optical sensor, it is not necessary to use additional security systems, but the state of the exciter–sensor (LED/LDR) should be checked periodically to verify their correct functioning and their correct connection to the acquisition module.

4 Materials

The minimum requirements of the computer include a computer PC386, 4 MByte RAM, operative system WINDOWS 3.X, 2 MByte free in hard disk and a graphic card VGA.

5 Biophysical Measurements

5.1 Pulse and Oxygen Measurer

The number of pulses or heartbeats per minute is the first and one of the most characteristic parameters in cardiovascular analysis.[10] For this, we use a simple optical method based on detecting the variation of the light that passes through a finger or the thumb when the density of the internal medium increases due to blood accumulation, or simply when pulsation occurs without occlusion. The transducer consists of a high-intensity luminescent diode (LED), which sends light through the surface of the skin[11] to the other side of the thumb where a LDR indicates the changes in the light received. On placing this LDR on a connection circuit, the value of the resistance varies and therefore the current flowing through the LDR, and thus we can detect the pulses.[4] The diode photoresistance is placed in contact with the skin and encapsulated in a small thimble well covered to avoid environmental interference. In applications of continued monitoring, it is advisable to use the optics method described by virtue of its great simplicity.

In view of all the requirements discussed above, we shall now describe the device capable of measuring the rhythm of blood being pumped by the heart, that is, cardiac rhythm. Our device has an added advantage over those which measure electrocardiograms (ECGs). By simply applying the device to a subject's finger it is capable of measuring the equivalent of ECGs in response to variations in light. The nervous impulses that reach the heart are transformed into mechanical impulses, which are what push the blood around the body. At the same time these mechanical impulses give rise to different pulses of blood within the blood vessels and these are precisely what our device is designed to measure, different pulses of blood, which are direct translation nervous impulses. The curve obtained by our device is equivalent to the graph produced by an ECG. It can also discover in real time the relative variation of oxygen in the blood. The device is small, portable, and does not need the presence of a medical practitioner to carry out the readings.

6 Design and Calculation

The starting point for the design of the circuit is, as stated above, a high-luminosity LED with sufficient emission to pass through the thumb and reach a LDR situated on the opposite side. The light that falls on the resistance is not constant or uniform like that emitted by the LED, but rather is modulated by the movement of the blood being pumped through the blood vessels. Therefore, on one end of the sensor, a variable voltage is generated according to the rhythm of the heart pumping; that is, cardiac rhythm.

The output signal of the LDR is applied at the input of a low-pass filter having a cutoff frequency of about 3 Hz.[5] This frequency was chosen because the margin of functioning of the heart can vary between 40 and 180 pulses/min as extreme values, therefore reaching frequencies of roughly between 0.5 and 3 Hz. In this way, noise and foreign signals that could cause fluctuations unrelated to cardiac rhythm are eliminated. As the signal obtained from the filter is quite weak, amplification is necessary, using a high amplifying stage (variable-gain amplifier). Even when the pulse is extremely low, this step is capable of amplifying the signal to measure it. At the end of this stage, the signal obtained has a DC (direct current) level of several volts. Below, this signal is passed through a rester to eliminate this continuous level,[5] as represented in Figure 2.

Fig. 2 Block diagram of the cardiac-rhythm detector. The sensor transduces the heart beat into an electrical signal. This is passed through a low-pass filter and then to an amplifier. The last stage is a rester circuit from which the output represents the cardiac rhythm.

6.1 Sensor

A sensor is composed of a photoresistance opposite a high-radiance LED, between which a thumb is inserted in order to be measured for cardiac rhythm. A diagram of the experimental device is shown in Figure 3. The LED and LDR are mounted on the same support, so that after insertion the thumb remains sufficiently snug and optically isolated from the exterior for good detection of the light from the LED varying according to the blood circulation.

For limiting the intensity of the LED, a resistance in series is connected to the LED. Likewise, the photoresistance goes in series with a resistance having the same function. The sensor is connected to the filter by means of a coupling condenser, providing continuous insulation of the amplifier with respect to the input, thereby ensuring that the DC component of the input signal does not interfere with the functioning of the amplifier.

Because the LED is one of high radiance and the detector is very highly sensitive, the patient can move without any loss of precision in the sensor. Furthermore the thimble is made of

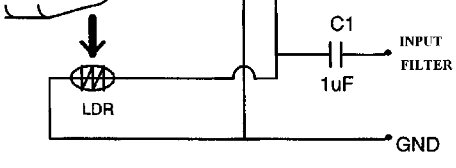

Fig. 3 Scheme of the pulse detector (sensor) indicating the position of the finger or thumb.

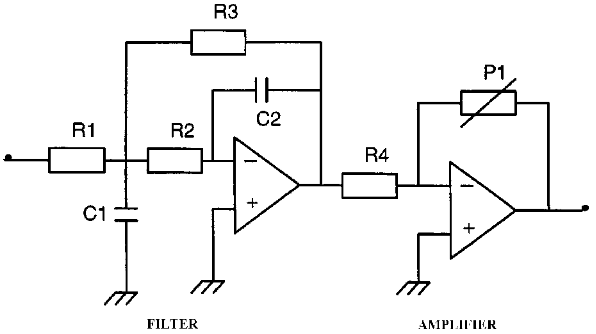

Fig. 4 Detail of the low-pass filter of 3 Hz and the subsequent high gain amplifier. The filter eliminates the middle and high frequencies which introduce noise into the signal and the amplifier increases the level of this signal, so that we can work with this later.

silicone and so adjusts perfectly to the shape of the finger. Although it is recommended to use the thumb, any other finger or even a toe will do.

6.2 LPF of 3 Hz and High-Gain Amplifier

For the overall design of the filter and amplifier, we used an operational commercial double amplifier with an input field effect transistor (FET), type TL082. This amplifier was chosen because it has certain conditions that make it apt for this particular design, for example, it has very high input impedance due to a joint field effect transistor (JFET) input stage, and a very low noise level within the economic range of operational amplifiers. In addition, it has low energy consumption, low harmonic distortion, and short-circuit protection.

The filter on which the design is based is an operational amplifier combined with resistance-capacitance (*RC*) dipoles,[5] as shown in Figure 4. The function of the transference of this filter is

$$\frac{V_s}{V_c}=-\frac{K}{R^2C_1C_2p^2+RC_2\left(1+K+\frac{1}{K}\right)p+1}, \tag{2}$$

where the resistances are indicated in Figure 4. For a gain unit $K=1$, the previous expression becomes

$$\frac{V_s}{V_c}=-\frac{1}{R^2C_1C_2p^2+3RC_2p+1}. \tag{3}$$

Thus, the expression for the cutoff frequency of the filter is

$$\nu_c=\frac{1}{R\sqrt{C_1C_2}}. \tag{4}$$

The high-gain amplifier was designed introducing a variable resistance P_1 as the feedback to adjust the gain to the value desired, in this case a gain margin ranging from 0 to 600. In Figure 5 the circuit is represented in more detail.

We introduced two zener diodes in a series, DZ_1 and DZ_2, to stabilize the power supply voltage. In addition, we achieved a reference voltage to apply to the positive input of each operational, as shown in Figure 5.

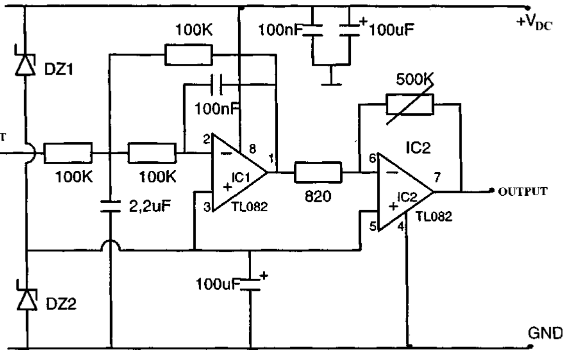

Fig. 5 Scheme of the low-pass filter of 3 Hz circuit and the stage of the high-gain amplifier (detail).

6.3 Rester Circuit

The rester circuit is comprised of a subtract circuit (DAC) based on two operational amplifiers CA3140, which reduce the level of the continuous amplifier signal to the desired level, and prepare it to enter the DAC. This subtracted circuit is shown in Figure 6. With P_1, we fixed the reference current which we wished to direct to the signal.

7 System of Communication with a Personal Computer

The modules can be connected both in series and parallel, while paying attention to direction, since each type permits a maximum of established directions. The computer and the modules communicate by pathways established in assembler language and these handle the protocol of communication. The user needs no knowledge of the internal process of these functions, and has only to follow the instructions for making calls to these. The functions will return the information requested or will perform the operation required.[12]

Only an analogic input with an acceptable number of bits of resolution is necessary to cover the needs with a single module. Due to their very low energy consumption, the modules do not generally require an external power supply to function, since they take power directly from the computer port where they are connected.

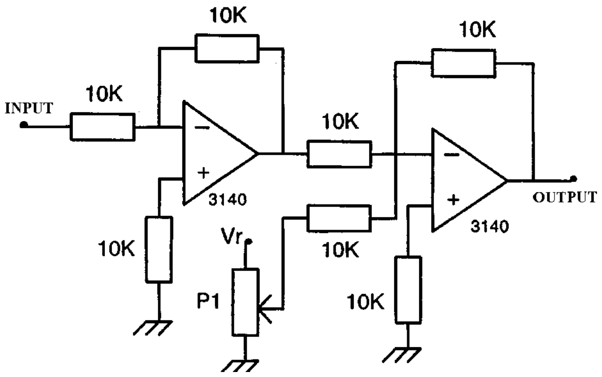

Fig. 6 Voltage circuit rester. At this stage, the dc current level which would contaminate the final signal is reduced. The output of this circuit is the value of the cardiac rhythm.

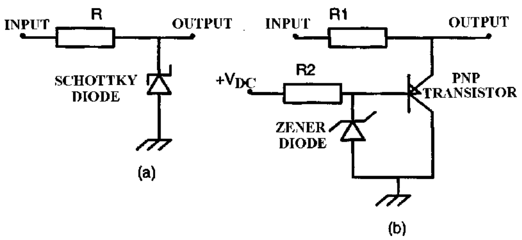

Fig. 7 Scheme of the protection circuit in the system module connected to the PC and the PC connected to the DAS. The output is protected from (a) negative voltages, (b) overvoltages.

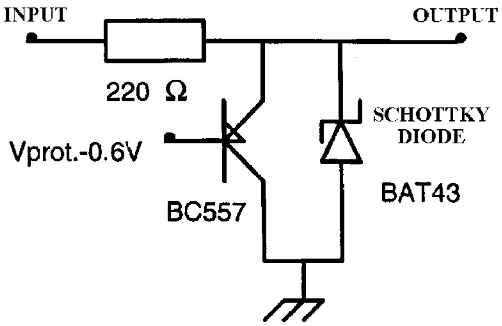

Fig. 9 Active protection by means of a transistor and a Schottky diode in the interfaces of the LipSoft AD12 module.

No module admits negative current as input. A simple inversely polarized Schottky or germanium diode would offer adequate protection, as shown in Figure 7(a). It is advisable as a protective measure to use a resistance to limit the possible current that could circulate through this diode.

In no case should the input levels exceed the maximum ranges for the input: analogic or digital. For a simple measure of protection a zener diode of an appropriate value is offered. This type of protection is not, however, advisable for analogic input, since it introduces a major error in the measurement signal. More appropriate protection is usually active, as shown in Figure 7(b).

7.1 Characteristics of the LipSoft Module AD12

This module enables the acquisition and control of analogic signals. It has eight input channels in simple or differential mode. The range of the signal at its entry is from 0 to 4.095 V, which is equivalent to a resolution of 1 mV. It contains a unipolar DAC channel of 12 bits of resolution. The range of the signal at the exit is from 0 to 4.095 V. It includes at its exit connector the inquiry-interruption line. This module has two lines to select the three directions that it attends; that is, it can connect up to three modules at the same Centronics port so that this remains available and can at the same time connect the printer. It is intended for highly precise monitoring and controlling of analogic signals. Its 12 bits of resolution enable it to record and control with precision the changes in the magnitudes measured.

To use the module with bipolar signals, the voltage levels must be changed to the range of the work of the module. The best design was the connection of a precision operational amplifier together with a stable reference. For optimal precision and resolution in the measurement, it is advisable to adapt the signals previously at the analogic entries using voltage splitters or amplifiers, so that it falls as closely as possible within the range of the measurement of the modules. A diagram of the module is shown in Figure 8.

The module does not generally require an external power supply. In certain models, where the signal levels of the printer port (Centronics) are very weak, it would be necessary to add an auxiliary input, though, for being of extremely low consumption (<4 mA) the specifications of the power supply are quite basic (5 V±5%, 5 mA). The ground (GND) line (0 V) is used as a negative voltage (power supply) terminal and is also connected to the terminal of least voltage for the analogic input/output, and therefore it is useful to have a good design in the GND to avoid measurement errors due to potential ground interference.

7.1.1 *Interface Characteristics*

Interface modules are board circuits that contain a set of circuits, connectors, and visualizers for easy interconnection between LipSoft modules and the outside world. All the lines of a given LipSoft module are available in each specific interface. The interfaces serve as an intermediate stage for signal modification (see Figures 9 and 10).

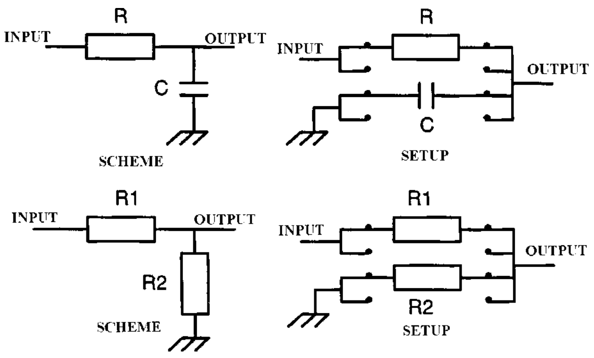

Fig. 8 Setup of the filter and the attenuator using a splitter setup in the Lipsoft AD12 module. In the first part (on the left) we show a scheme of the general device and in the second part (on the right) is the filters setup.

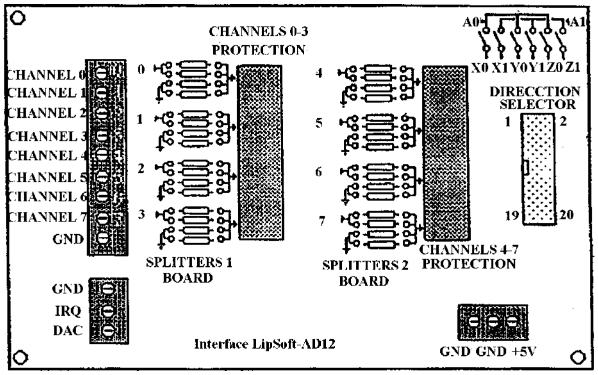

Fig. 10 Interface card in the LipSoft AD12 module, indicating the points where each component is placed in the card.

7.2 Software

The software enables the analysis of the number of heartbeats per minute of an individual, also allowing a representation in time of the pulses transmitted by the heart. The menu shown on the computer screen provides for all types of operations, such as quitting the program, printing the results (previously setting the printer), representing the results graphically (at any time), adjusting the sampling conditions (number of samplings and period), the color of the graphics, and the submenu of help.

At the same time, the screen not only shows the simulation of the heartbeats in real time for as long as the pulse counter is active but also shows the equivalent of the ECG curve, although measured in the patient's finger, together with the relative variation of oxygen in the blood.

A display that appears on the screen gives a running value of pulses per minute detected by the counter. The value is renewed every 10 s by means of an algorithm that uses the current and preceding reading as data in order to reduce the dispersion of the data due to any movement by the patient or disturbance outside the system.

Due to the characteristics of the program developed within our laboratory, we chose Visual Basic, as it is oriented to objects and possesses a series of tools that facilitate the handling of the program in a window format. All the software for the instrument was designed for this purpose by us in our laboratory.

8 Results and Conclusions

Subjects were submitted to a series of experimental measurements to test the reliability of the apparatus, while the measurements were being taken simultaneously by a different method tested by medical practitioners. Using our device and an ECG we checked the cardiac rhythm of healthy patients both at rest and exercising on a treadmill to test the efficiency of our method when the patient was moving, and whether there might be poor contact between the light emitter, the receiver, and the skin. The results turned out the same, from which we can conclude that there is no problem if physical contact with the emitter and receiver is broken slightly. We also made measurements on patients suffering from tachycardia and bradycardia, both with our device and an electrocardiogram. Once again the results were identical.

We carried out further comparative tests first by adjusting the device perfectly to the patient's thumb and then separating the emitter and receiver from the thumb until the signal disappeared from the computer screen. When each of the components was separated from the patient's thumb by somewhat less than 1 mm the result continued to be just as accurate as when they were well adjusted. As we have mentioned above, this is due not only to the high radiance of the LED and the equally high sensitivity of the receiver, but also to the filtration of the electrical signal and its variable amplification. All these are essential to the correct functioning of our device in the presence of a slight lack of adjustment on the patient's thumb.

Apart from these tests just described, our device has also been thoroughly tested at the Granada University teaching hospital (Hospital Clínico, Granada, Spain) under the supervision of a team of medical practitioners. Measurements were made with patients suffering from various pathologies using our device and other commercial apparatus. The results given by the commercial pulsimeters were less sensitive than those of our device. As far as the ECG is concerned, all the patients were subject to simultaneous checks with our device and ECG and the curves produced by our device turned out to be the same as the ECG results for both healthy patients and those with cardiopathic disorders. We show as an example in Figure 11 the graph obtained from a healthy patient, where the similarity between the curve given by a normal electrocardiogram and our device is quite clear. The interval of time between the sharpest peaks in the graph indicate cardiac rhythm. Thus the advantages offered by the simplicity and mobility of our device, bearing in mind the equivalence between the results given by our device and a traditional electrocardiogram, are manifest.

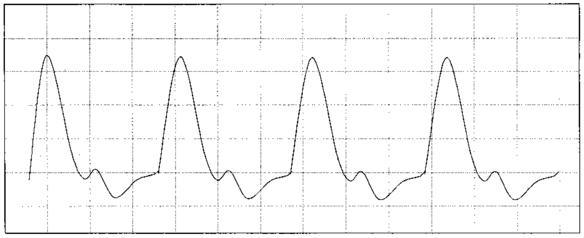

Fig. 11 Graph showing the equivalence of the curves obtained with an electrocardiogram and our device.

Measurements were also made of relative changes in blood–oxygen levels using our device and another commercial one for reference. The results were also entirely satisfactory. The height of the peaks diminishes concomitantly with a decrease in oxygen levels due to the opacity of the blood. Thus, when patients were connected to reference devices at the same time as ours we were able to demonstrate with our device that, while still measuring cardiac rhythm satisfactorily, we could also see whether blood–oxygen levels increased or decreased relatively, simply by observing the relative difference in the height of the peaks recorded.

Using light instead of pressure or electrical variations, the system eliminates noise without the need to add any type of filter. In addition, the data of the subjects were sent by Internet to remote points and received with the delay due to the web but not to the device. This device in an ambulance, connected by radio to the hospital, enables monitoring of the patients during the journey, and the hospital can receive physiological data before the patient's arrival.

References

1. J. M. Poblet, ''Serie Mundo Electrónico,'' *Introducción a La Bioingeniería*, B. Editores, Ed., Marcombo, Barcelona (1988).
2. Ch. Chunag-Chien, Y. Shou-Jeng, and L. Ruey-Chien, ''Data acquisition and validation analysis for Finapres signals,'' *Chin. J. Med. Biol. Eng.* **15**, 47–58 (1996).
3. A. Dittmar, ''Non invasive and minimal invasive sensor for measurements on the human body,'' in *Proc. First European School on Sensor (ESS'94). Sensors for Domestic Application*, pp. 148–155, Leece, Italy (Sept. 1994).
4. F. Bergtold, *Fotoconductores*, G. Gili, Ed., Barcelona (1980).
5. P. Bildstein, *Filtros Activos*, Paraninfo, Ed., Madrid (1983).

6. R. P. Areny, *Adquisición y Distribución de Señales*, Marcombo, Ed., Barcelona (1993).
7. M. De la Fuente, M. De la Casa, and J. M. Cano, *Transductores y acondicionadores de señal*, Cámara Oficial de comercio e industria de Jaén, Jaen (1993).
8. R. P. Areny, *Transductores y Acondicionadores de Señal*, Marcombo, Ed., Barcelona (1989).
9. R. P. Areny, *Sensores y Acondicionadores de Señal*, Marcombo, Ed., Barcelona (1994).
10. J. B. West, *Bases Fisiológicas de la Práctica Médica*, Médica, Ed., Panamericana (1993).
11. W. Hennig, *Fotoelectrónica*, Marcombo, Ed., Barcelona (1976).
12. A. M. System, ''Lipsoft Electronics,'' *Manual para Usuarios Lipsoft*, Jaén (1996).