3.1 INTRODUCTION TO PHOTOPLETHYSMOGRAPHY

Plethysmo-Graphy is a technique of measuring the volume changes in any part of the body that result from the pulsation of blood occurring with each heartbeat. These measurements are useful in the diagnosis of arterial obstructions and pulse wave velocity measurements, which may lead to determine the heart rate. Photoplethysmography (PPG) is the electro-optic technique of measuring the cardiovascular pulse wave found throughout the human body. The pulse wave is caused by the periodic pulsations of arterial blood volume and is measured by the changing optical absorption, which this induces.

The first paper on PPG dates back to 1936 when Molitor and Kniazak [3] recorded peripheral circulatory changes in animals. Hertzmann [4] presented several papers on PPG and coined the term Photoplethysmography. Hertzmann’s instrumentation comprised mainly of a tungsten arc lamp and a photomultiplier tube. Due to the wide band spectra of the source, Hertzmann could not obtain a reliable signal. With the advent of semiconductor technology, the last three decades has seen enormous development in the PPG instrumentation. A major part of activities in development of PPG systems today is directed towards measurement of the AC signal component which is caused by the pulse pressure wave driven by the heart beat. Analysis of the form and amplitude of the signal is used to analyze Raynauld’s disease, measure blood pressure in distal arteries and to quantify the perfusion quality. The major application
of PPG is the Pulse-Oximeter, which measures the relative optical absorption of Hemoglobin and Oxy-hemoglobin to obtain an in vivo measure of the arterial oxygen saturation.

PPG offers several advantages over other in vivo optical methods like Laser Doppler Flow Metry (LDF). PPG uses inexpensive optical sensors, which are rugged, and needs little maintenance. Since it consumes very less power and can be powered by a battery pack, it is an ideal ambulatory device. The PPG signal contains a rich source of information related to the cardio pulmonary system. In recent years, multi-wavelength application of arterial PPG has given the physician to analyze blood components non-invasively. A range of clinically relevant parameters like heart rate [5], respiratory rate [6], respiratory induced intensity variations (RIIV) [7] ventilatory volumes; autonomic dysfunction [8] can be obtained from the PPG signal.

Apart from Doppler Ultrasound, PPG is the most popular noninvasive method for assessing peripheral vascular hemodynamics. The history of PPG goes back over 50 years. After groundwork by Cartwright, Mathes, Hanzlik et al. And Molitor et al. Hertzman[5][6][7] found a relationship between the intensity of backscattered light and blood volume in the skin in 1938. His instrument consisted of the three essential components still found in modern systems: A light source, a light Detector, and a registration unit. He called the device which he used to measure arterial pulse volumes a Photoelectric Plethysmographic and wrote about his findings ([7], p.336): “The Volume pulse of the skin as an indicator of the state of the skin circulation at rest” and “Amplitude of volume pulse as a measure of the blood supply of the skin”.

Fig 3.1 Infrared Source and Detector Mounted on the Skin

During the next 40 years PPG systems were used for registration of arterial pulsations in the skin. In the 70’s it was discovered that PPG was also useful for the examination of the peripheral vein muscle pump after standardized exercise and that these measurements correlated well with the invasive vein pressure measurements. Since that time, several analog PPG devices have been developed.

However, due to technical difficulties in calibration, the use of PPG was limited to measurement of time-related hemodynamic parameters for a long time. It was only in the past few years that Blazek’s and Schultz-Ehrenburg’s group used modern computer technology to develop self-calibrating Photoplethysmography leading to new applications. This resulted in the development of quantitative Photoplethysmography, allowing measurement not only of the time-related parameters but also of the amplitude.

PPG has several advantages:

1. It uses simple inexpensive optical devices for sensing that need little maintenance.
2. This device is compact and is portable.
Hence it can be used in all types of environments. The simplest PPG sensor consists of an infrared LED and a photo detector placed in a small plastic housing (fig.3.1). The sensor is applied to the skin by means of a double-faced adhesive ring. The sensor can be either of transmitting type or reflecting type. The PPG sensor head can be modified by using an optical fiber to transmit and receive the light. With this modification, simultaneous measurements of PPG signal with MRI, ECG, EEG probes can be done without any electromagnetic interference problems.

3.2. OPTIC SENSOR SYSTEM

A PPG optic sensor system consists of sensor head and related circuitry, signal conditioning circuit, and hardware interface as shown in the figure 3.7. Before we deal with the sensor system, let us take a look at the optical properties of the skin wherein the basis of the principle of operation lies.

3.2.1. Optical properties of the skin

The interaction of electromagnetic radiation with the human tissue is well studied. It is seen that the skin acts as a scattering media in the wavelength region of 550-1100nm. The detailed Monte Carlo simulation of Optimum photon path shows an emitter-detector separation of 5-7mm. Also the penetration of light increases with increase of wavelength. Blood being a mixture shows multiple absorption peaks pertaining to different constituents in the wavelength region of 300-500nm. No such specific absorption is seen in the IR region. The IR region is thus termed as Isobestic wavelength region for blood. Most PPG device used IR emitter in 800-950nm region.
Figure 3.2 shows the different layers and vascular structure of the skin and their characteristics

1) *Stratum corneum & Epidermis* (*<200μm*)
   
   This layer largely absorbs the light and does not modify the signal in any significant way. This has important implications. Skin color, pigmentations are due to this layer. Thus all these factors do not affect the PPG signal.

2) *Dermis* (*1-3mm*)
   
   The dermis largely contains arterioles, veinules and capillaries. The bulk of the PPG signal is back scattered from this region.

3) *Subcutaneous Tissue* (*>3mm*)
   
   This layer contains bigger arteries and veins. Since, much of the back-scattered light is from the dermis, and hence this layer has little effect on the PPG signal in reflection type sensors.

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*Figure 3.2: Skin / Vessel topography*
3.3 BASIC PRINCIPLE BEHIND PPG:

The basic principle behind the measurement of blood volumetric changes in the skin by means of PPG is the fact that hemoglobin in the blood absorbs infrared light many times stronger than the remaining skin tissues. It is known that in the range of invisible infrared light around 900nm there is a particularly favorable “measurement window” for optical sensing. Only a small proportion of the entering light is absorbed by the epidermis.

There is also a large difference between the reflection of the bloodless skin and the reflection from the vessels filled with blood. In bloodless skin 60% of the light is reflected back whereas in the skin with blood, 6% is reflected back (Fig 3.3). Since the full blood vessels reflected approximately 10 times less light than the skin tissue without blood, they appear as dark lines against a relatively light background.
As the blood pressure in the skin vessels decreases, the surface area of the vessels will reduce. This increases the average reflection in the measuring window, so it will be recorded as an increase in the PPG signal. The optoelectronic measuring principle of the PPG thus depends on detecting the changes in reflection of the sub-epidermal layers of skin during and after a defined movement or occlusion routine, which causes variations in the volume of the vessel plexuses in the skin. As the optical radiation is introduced into tissue, part of the photons will be reflected directly by the skin surface, another fraction will be distributed in the tissue by absorption or scattering, while the remaining photons will travel into the tissue either straight through or with a number of collisions.

*Fig 3.3 Optical Characteristics of Biological tissue in the visible and infrared range.*
PPG uses low levels of infrared light to detect small changes in blood volume content in these regions. It gives a voltage signal, which is proportional to the amount of blood present in the blood vessels. This method gives only a relative measurement of the blood volumetric changes and it cannot quantify the amount of blood. However, it can reflect the dynamics of the blood volumetric changes exceedingly well.

The PPG signal mainly consists of 3 components:

1. Arterial blood volumetric changes, which largely reflects the heart’s activity.
2. Venous blood volume changes, which is a slow signal that has a modulatory effect on the PPG signal.
3. A DC component due to the optical property of the biological tissue.

### 3.4 PPG HARDWARE:

The PPG transducer has an infrared LED, which is placed, on the temples of a subject, one could monitor and register the arterial blood volumetric changes in the near skin vessels leading to the left and right lobes of the brain in the cerebral cortex. Depending upon the volume of blood flow present in the underlying capillaries, a certain amount of infrared

![Fig 3.4 Photoplethysmograph Sensor and Measuring window under the Sensor.](image)
radiation is absorbed; while the remaining infrared radiation is picked up by the phototransistor. The output of the phototransistor is a current proportion to the amount of radiation received; hence when there is an increase in blood flow in capillaries there will be a dip in current output. This is fed to current to voltage converter, which inverts current to voltage. This signal has a DC offset proportional to ambient light; the signal of interest is superimposed on this DC offset and this is of a few mill volts. This DC offset must be removed otherwise it would cause amplifier saturation. This is done by applying the voltage equal to DC offset to noninverting terminals of OpAmp current to voltage converter this voltage is obtained by connecting a potential difference between the two supply terminals and giving output to noninverting terminal. The output of current to voltage converter is fed to active low pass filter of cut off frequency 15Hz to eliminate supply noise. This is the output to signal capture device.

3.5 DESIGN METHOD of PPG:

The measurement system consists of a light source (usually Infra-red), a detector (positioned in the reflection or transmission mode) and a signal recovery/processor/display system. Infrared light is predominantly used since it is relatively well absorbed in blood and weakly absorbed in tissue; blood volume changes are therefore observed with reasonable contrast. The PPG measurement is entirely non-invasive and can be applied to any blood bearing tissue. Since light is highly scattered in tissue, a detector positioned on the surface of the skin can measure reflections from a range of depths and those reflections are variously absorbed depending on whether the light encounters weakly or highly absorbing tissue(fig.3.5).
Fig 3.5. Arrangement for obtaining PPG.

The detector at the surface will register any changes in blood volume since increasing (or decreasing) volume will cause more (or less) absorption. The effect will be averaged over many arteries and veins. In the absence of any blood volume changes, the signal level will be determined by the tissue type, skin type; probe positioning, static blood volume content and the geometry and sensitivity of the sensor. PPG systems differentiate between light absorption due to blood volume and that of other fluid and tissue constituents by observation that arterial blood flow pulsates while tissue absorption remains static. As the illuminated vascular bed pulsates, it alters the optical path length and therefore modulates the light absorption throughout the cardiac cycle. Non-pulsating fluids and tissues do not modulate the light but have a fixed level of absorption (assuming there is no animal movement).

The result of this absorption modulation is that any light reflected from the pulsating vascular bed contains an AC component, which is proportional to and synchronous with the animals’ plethysmographic signal. It is this modulated component which is known as the Photoplethysmography (PPG) signal. The amount of reflected light is roughly proportional to the amount of transmitted light, implying that either may be used as a measure of the optical absorption. A transmission mode
PPG device uses the transmitted light to estimate the absorption, while a reflection mode PPG uses the reflected light.

Figure 3.6 shows the block diagram of the PPG device. It consists of the following blocks.

1) Sensor head and related circuitry
2) Signal conditioning circuit
3) Hardware interface.

3.5.1) Sensor Head and related circuitry:

This block consists of a unipolar constant current source (to drive the IR led), the sensor head and photo detector circuit.
i) **Sensor head:**

Most PPG sensor heads comprise of a pair of led and photodiode. In some cases, the PPG head houses 1-2 leds and a number of photodiodes. This is mainly to improve the signal to noise ratio (SNR). In this sensor head, two modified designs have been evaluated to increase the SNR of the PPG signal. We assume that the illuminated and detected volume in the skin approximates to a sphere. To fully obtain the back-scattered light we arrange the photo detectors as shown (Fig 3.7).

![Fig 3.7 Simulation of photon distribution in tissue under a classical PPG sensor](image)

ii) **Unipolar constant current source:**

The pulsed unipolar constant current source is designed to deliver a maximum current of 200mA, at 125Hz pulsing frequency.

iii) **Photo detector circuit:**

The photo detector circuit consists of a current to voltage (I-V) converter and DC offset circuit to suitably bias the photo-detectors. The photo detectors were individually biased and were connected to the I-V converter.
3.5.2. Signal Conditioning Circuits.

3.5.2.1 Emitter Circuitry:

Figure 3.8. shows the emitter circuitry consists of an astable multivibrator, switching transistor, pulsed constant current source and an IRLED.

![Fig 3.8 Current Source and Emitter Circuitry](image)

i) Astable Multivibrator:

Also called a free running oscillator, the principle of generation of square wave output is to force an op-amp to operate in the saturation region. A fraction of the output is feedback to the non-inverting input terminal. The potential divider connected in the feedback path in the non-inverting terminal influences this fraction. The output is also feedback to the (-) input terminal after integrating by means of a low-pass RC combination. Whenever input at the inverting input terminal just exceeds Reference voltage, switching takes place resulting in a square wave output.
ii) **Constant Current Source (LM 317):**

The constant current source is constructed using a voltage regulator IC LM317 that is a 3 pin IC. Pin 1 is used for adjustment. Pin 2 gives out the constant current required and power supply 5V is given to pin 3. Changing the resistance connected between pin 1 and 2 can vary the value of current. The constant current obtained is fed to the collector of the switching transistor. The transistor 2N2222 is used in the circuit diagram as a switch that switches ON and OFF the current pulse from LM317 with respect to a zero volt or five volt at the base-emitter junction.

iii) **Transmitter (IR LED)**

The transmitter, in this case, is an infrared LED. The infrared LED, as the name suggests, radiates the infrared rays corresponding to the current at the LED. The wavelength of the infrared radiation, in this case, should be of the order 940 nm. The significance of this wavelength can be explained with the help of the diagram shown. As we note, at 940 nm, the absorption coefficient of the epidermal layer is the least, reflecting the maximum possible radiation. Also evident is the fact that at this wavelength the difference between the reflection coefficient blood-filled tissue and the bloodless tissue is the maximum. For this reason at this wavelength the least change in blood volume is detected and is converted to the variation in amplitude.

For the best performance of the PPG, two pairs of IR LED-Photo transistor combinations that can be used for the required wavelength. The 32-78 pair has a diameter of 3 mm and is very sensitive to the variation in
blood volume but it easily saturates on the slightest disturbance. This is the most widely used sensor combination. On the other hand, the TIL 38-81 combination is relatively less sensitive to the blood volume changes but more stable due to greater base-emitter resistance of the phototransistor. For the optimal performance of the sensor, the centre-to-centre distance between the IRLED & the transistor should be 3 mm. For this purpose the sensor heads have been designed with sufficient insulation and provision for external connection.

Obtaining a PPG involves the generation and transmission of a current pulse, which is then received and conditioned. The astable multivibrator generate the square wave with amplitude 13 V peak to peak and with frequency ranging from 125-250 Hz according to the resistance value at which 5K potentiometer at negative feedback is set. The negative part of the wave is removed by shunting the output by a 5V, 1/2-watt Zener diode. This is actually done to limit the amplitude from 0-5V, so that the base-emitter junction of the transistor acting, as a switch is not reverse biased. To achieve the signal, a constant current from the voltage regulator LM317 is fed to the collector of 2N2222 transistor, which acts as a switch. The driving signal for the transistor is a square pulse obtained from an astable multivibrator.

The square pulse fed to the base of the transistor, pulses the constant current at its collector to the IRLED (TIL 38), acting as a transmitter. Since a square wave is obtained from an astable multivibrator and not a pulse, a 5V Zener diode is introduced at its output to convert the 13V square to a pulse of amplitude 4.8 V. The pulsed unipolar current source was designed for a maximum current of 200mA, at 125Hz pulsing frequency.
3.5.2.2 Detector Circuitry

The detector circuitry (fig.3.9) comprises of the phototransistor and two stages of operating amplifiers in the inverting mode to get the required PPG signal.

![Fig 3.9 Detector Circuitry](image)

**i) Photo Detector:**

Phototransistor used is either TIL78 or TIL81 in combination with TIL32 and TIL38 respectively. The current signal received at base-emitter junction gives rise to the potential across the junction. This causes the collector emitter junction to draw corresponding current from the power
supply. The base emitter resistance influences the stability of the sensor. The more the resistance, the more the stability. The lesser the resistance, the easier the saturation of the sensor.

The current pulse transmitted as Infrared rays from the LED gets back scattered from the skin carrying the amplitude variations corresponding to the change in the pressure exerted by the blood on the walls of the capillaries. This change is due to change in volume of blood. Effectively, the amplitude variation represents the blood volume changes. This infrared ray is sensed by the Phototransistor at its base. The output current from the collector is fed to the inverting terminal of an Operational Amplifier (IC741). A potential divider is constructed at the non-inverting terminal using a trim pot. This is varied between the supply voltages to obtain the desired amplified output. The signal is again passed through a non-inverting amplifier to obtain the PPG signal (fig.3.10).

![Fig 3.10 Filter, Buffer and Amplifier Circuitry](image)

The signal obtained at the amplifier output is noise ridden. In order to retrieve the highly sensitive PPG, the signal is fed into the second order Butterworth low pass filter with a cutoff frequency of 5-7 Hz. The low pass filter comprises of a passive part followed by an active part. This cascading ensures better rejection of high frequency components, especially the
pulsing frequency. The low pass filter averages the signal there by minimizing the noise and unwanted components. The output of the active filter is given to a buffer for impedance matching.

3.5.3 **Hardware Interface:**

The hardware interface consists of a 12-bit ADC with 8 analog input channels. The interface also has a programmable timer circuitry to change the sampling frequency. The interface is connected to the Parallel port in the PC. Diadem software (version 7.0) is used to acquire the data from the PPG device, store it and display it in real time mode.

3.6 **The Problem of Artifact in PPG:**

Artifact is the term given to unwanted noise superimposed onto the PPG signal. It can be induced by anything, which causes a dynamic change in the light received by the receiver head. Any variation in the optical coupling between the sensor head and the subject or physiological changes which dynamically alter the transmitted light give rise to what is commonly termed as motion artifact. In fact a simple subject movement may give rise to many of these effects, producing a complex motion artifact. For example, a subject raising or lowering their hand whilst attached to a finger probe will dynamically alter the pressure their finger exerts on the probe, which alters the optical coupling, whilst simultaneously causing a change in venous blood, which will affect light transmission through the tissue.

![Fig. 3.11 A typical PPG signal Free of any artifacts.](image-url)
Ambient light can also cause artifact by coupling to the probe receiver, either directly or by transmission through tissue. Whilst it is theoretically straightforward to remove ambient artifact, practical limitations mean that sufficiently bright or high frequency artificial light sources can still cause artifact. The normal PPG signal which is free from artifacts is shown in the figure 3.11.