Acousto-optic Design to Measure Glucose Level for Diabetic Patients Non-invasively

Lina Nasseer Bachache*1, Jamal A Hasan1, Auns Qusai Al-Neami1

1Al-Nahrain University, College of Engineering, Biomedical Engineering Department, Baghdad, Iraq

Emails: lina_nasseer@yahoo.com jamalabduljabar@eng.nahrainuniv.edu.iq uns_alneami@eng.nahrainuniv.edu.iq

Abstract. Due to increasing numbers of diabetic patient and the dangerous of life threatening some cases that need a continuous monitoring of the glucose level. Recently the demand for a non-invasive system is raised. This study aims to design an optimized noninvasively acousto-optic monitoring glucose system device to limit the possibility of secondary risk that raised from infection of invasive blood sample or from glucose fluctuation due to fewer number of glucose checking. There is a great demand for painless, glucose sensitive and commercial equipment. The current design methodology depends on the liaison between the penetrated electromagnetic wave through tissue and glucose level based on acousto-optic interaction technique. We can exceed the complication of acousto-optic design for biological tissue testing practically, the complication are with light and sound penetration, heat generation, and others. This work study both of Raman-Nath and Bragg interaction methods of acousto-optic technique with their advantages and disadvantages, with the possibility to reach the optimization in sensing blood glucose.

Keywords: Non-invasive glucose; Diabetic; Acousto-optic; Infrared laser; Microwave.

1. Introduction

Recently diabetes mellitus (DM) is communal disorder in most parts of the world mainly the Middle East [1]. DM are group of disease where the patient body is incompetent to control the glucose level over a prolonged time due to poor insulin concentration or existence of resistant factor that counteract the action of insulin [2]. Too much sugar in patients’ blood produced serious health problems and sometime fatal cases. Glucose level is vital because it's major source of energy for brain, muscles and other tissues [3]. Patients with DM are considered to be at increased threat of infection, but the hazard is difficult to quantify [4]. By increase number of corona virus disease 2019 (COVID_19) patients and with increase number of diabetic patients that suffering fromCOVID-19 infection, it is very important to recognize their cases complication and it’s relation with glucose level variation [5]. At the last several
decades a large quantity of different biosensors types have been studied to provide information about the patient glucose level. In 2005 Seungjun and Vivekanand demonstrate a method to measuring glucose levels trans-dermally by using combination of the ultrasound array and electrochemical sensor that consist of ampere-metric electrodes and glucose oxidase hydrogel, they using ultrasound generated by a flex-tensional transducer class V that uses very low frequency (1-100) kilohertz. The glucose measurement results after twenty minutes by measuring the glucose diffusion rate from the hydrogel to the skin using the electrochemical biosensor [6]. In 1999 Malin and Stephen study the relation between the blood glucose and reflectance of near infrared at wavelength between (1050-2450) nm with strict calibration and signal conditions, the detected light is related to the amount of scattered and absorbed light and also related to glucose concentration in blood [7]. In 2012 Kottmann and J. Rey. implemented a mid-infrared photoacoustic in-vitro device to noninvasively measure glucose in deep epidermal layers, they using quantum-cascade laser (9132-9900) nanometre to monitor epidermal skin glucose, after characterized the skin by a high water content the photoacoustic cell measure the generated ultrasound related to the change in light absorbance or related to the relative humidity toward non-invasively measuring glucose concentration of diabetes patients [8]. Klonoff and David in 1999 study several non-invasive technologies, one of them is the detection of far-infrared that emets from human tissue, this light are within (5000-12000) nanometre wavelength for 37 degree body temperature, some of the infrared light energy are absorbed by blood glucose, that absorption make a possible measurement of emets far-infrared related to glucose level [9]. In 2008 R. J. Buford and E. C. Green study a microwave sensor for measuring blood glucose level non-invasively. They track the maximum amplitude measurement for different frequencies (10 megahertz to 2 gigahertz), the maximum amplitude is related to glucose concentration in the patient finger blood [10]. In 2014 A. Srivastava and M. K. Chowdhury Measured serum blood glucose by using amplitude modulated ultrasound with infra-red optical technique in normal and diabetic volunteers. Modulated ultrasound within 40 kilo-hertz produce a signature for specific molecular vibrations such as glucose in the area of 940 nanometre light propagation. The infrared and ultrasound standing wave are interacted in the patient tissue and some of lights are transmitted from tissue and detected by photodetector, then the photo detector peak values is processed by Fast Fourier Transform domain, this signal is compared to the signal obtained from normal human, and result a glucose correlation to the peak detected signal [11]. In 2014 Teklu Alem and Declercq study biological tissue imaging by acousto-optic technique and Bragg regime. This technique utilized the interaction of light at 10mW He-Ne laser and ultrasound of 30 mega-hertz and 100 watt to image the sample in acoustical fields optically. Limitation is based on strong acoustic impedance gaps that produce poor image quality and lost in details of physical tissue structures, the biological sample must immerse in tank of water, this technique is sensitive to elasticity and density variations of the tissue sample [12]. The non-invasive monitoring of blood glucose several times a day is very important in diagnosis and therapy of common diabetes patients to achieve an optimum metabolism control by choosing the best drug strategy for diabetic glucose management [13]. All the previous studies are falling with important challenges and produce limited accuracy, expensive, need long measurement time or hard measurement procedure. We study the interaction of electromagnetic wave and the elastic sound wave in the human tissue and design several optimal acousto-optic devices with the ability of detection the glucose concentration. The acousto-optic interaction in human tissue to detect glucose level is very useful but with great challenges due to acoustic anisotropy influence of tissue on the light diffraction, ultrasound and light penetration in the tissue is restricted, the acousto-optic interaction area is limited, the generated heat also limited the power of the laser and ultrasound, while the light wavelength that effected by glucose level is very limited. The current design approaches depends on the relationship between the penetrated electromagnetic wave through tissue sample and glucose level based on acousto-optic technique. The designed systems are with both Bragg and Raman-Nath methods. Acousto-optic technique is hypothetically harmless to biological cells and sensitive to the variation of density and elasticity of the finger tissue that changed with glucose concentration.
2. Acousto-optic interaction

Acousto-optic interaction are built on the elasto-optic effect, which is the optical belongings changes as a response of the applying ultrasound. The acoustic signal is practical into the tissue by means of a piezoelectric transducer, and acoustic elastic wave produces regions of compression and rarefaction. When an optical electromagnetic beam passes through the tissue sample it may be modulated or deflected, and it is frequency shifted. The refraction index of medium is changed due to medium strain. The type of the acousto-optic interaction is resolute by the light and sound wavelength and the interaction geometry and the optical and acoustic properties of the interaction sample material. Human tissue are anisotropic medium that change the optical beam polarization, and can result in either multiple (Raman-Nath regime) or single diffracted optical beams (Bragg regime). The Bragg regime is much more efficient but harder in implementation [14].

2.1. Raman-Nath regime.

Is a well-known type of acousto optic interaction where the fallen laser beam is incident with normal angle to the fallen acoustic sound beam and produce several output fringes (...-2, -1, 0, 1, 2 ...). Figure 1 demonstrated Raman-Nath regime and its several diffraction orders [14]. Raman-Nath interaction condition is in the case where L is sufficiently short as equation (1), where L is the interaction length, \( \lambda \) is the wavelength of acoustic wave, and \( \lambda_0 \) is the wavelength of electromagnetic light wave [15].

\[
L \ll \frac{\Lambda^2}{\lambda_0}
\]  

(1)

2.2. Bragg regime.

At one specific incidence angle, just two fringes generated, one diffraction fringe and one transmitted un-diffracted fringe. Figure 2 demonstrated Bragg regime and its one diffraction order [14]. Bragg interaction condition is in the case where L is sufficiently long as equation (2), Bragg angle (\( \theta_B \)) is the angle enclose between the incident electromagnetic wave and the vibrating ultrasound plain, which calculated from equation (3) [15].

\[
L \gg \frac{\Lambda^2}{\lambda_0}
\]  

(2)

\[
\sin \theta_B = \frac{\lambda_0}{2 \Lambda}
\]

(3)

When the light speed in space (c) is \( 3 \times 10^8 \), and due to the relation of light frequency (\( f_0 \)) and light wavelength (\( \lambda_0 \)) with light speed in free space described by equation (4), where the light frequency(\( f_0 \)) is related to radian light frequency (\( \omega_0 \)) in equation (5) [15].

\[
c = f_0 \cdot \lambda_0
\]

(4)

\[
\omega_0 = 2\pi f_0
\]

(5)
Figure 1. Raman-Nath acousto optic interaction [14].

Figure 2. Bragg acousto optic interaction [14].
By applying the conservation of energy law to the upshifted Bragg interaction shown in figure 3, to calculate the frequency of the scattered light from the incident light and incident sound this is described by equation (6), where $\omega_{+1}$, $\omega_{0}$ are diffracted and incident light radian frequency respectively and the $\Omega$ is the incident sound radian frequency [15].

$$\omega_{+1} = \omega_{0} + \Omega$$

(6)

Figure 3. Upshifted Bragg interaction [15].

3. Human tissue properties

3.1. Anisotropy.

Means the property of a material that exhibit different properties in different directions. Human tissue is optical anisotropy medium with many refraction indices, this property is useful for noninvasive derivation of the optical properties of tissue toward identifying specific component in the tissue [16].

3.2. Optical properties.

The human tissue covered with skin that consist of several layers. Epidermis layer of human skin tissue is the light-absorbing layer, where melain pigments are existent for ultraviolet protection. Conversely, at near-infrared wavelengths, the transmittance of light is (90 – 95) percent through the stratum corneum and epidermis liberated from absorption of skin pigmentation. In the dermis layer, light scattering is most important, being mainly responsible for light absorption of wavelengths less than 600 nanometer. Between 1520 nm and 1850 nm, scattering and absorptions by water and fat are predominate. Between (2000 – 2500) nm, absorption is dominates, primary with protein and secondary by water and fat. Outside these thresholds, a sharp decrease in the (600 -1300) nm region being called the “optical window” of the skin that shown in figure (4) [17].
3.3. *In vivo* glucose spectroscopic properties

In principle, blood glucose or serum glucose can be good quantified at specific bands that are (2000 nm – 2500 nm), (1400 nm – 1800 nm), or (950 nm – 1250 nm). MIR glucose characteristic frequencies in the MIR are 8.68 µm, 9.017 µm, 9.259 µm, and 9.66 µm. Only the peak of 9.66 µm is limited to glucose by the other context. For example, both the 7.326 µm and 9.259 µm peaks are identified in albumin, hemoglobin, while the 9.017 µm peak is identified only by hemoglobin. Therefore to detect glucose at 9.017 µm must be done with just interstitial fluid that is free from the hemoglobin effect. At other wavelengths glucose may masked by the large peak of other tissue components, such as a strong at 8.620 µm the glucose characteristic is masked by the urea peak [17].

4. **System design**

4.1. *First system: design acousto-optic interaction using 1 gigahertz ultrasound and 980nm laser.*

Assume the average speed of sound in human tissue is near 1540 m/s [18], and the sound and light interacted through finger with interaction length (L) of more than 10mm or 10000 µm, $\lambda_0 = 980$ nm.

\[
\Lambda = \frac{\text{sound speed in tissue}}{\text{sound frequency}} = \frac{1540}{1 \times 10^9} = 1.54\mu m
\]

Using Raman–Nath or Bragg conditions we obtain

\[
\frac{A^2}{\lambda_0} = 2.42\mu m
\]

(7)

By checking Bragg condition of equation (7) with equation (1) and equation (2), we obtained that the interaction will be achieved by Bragg regime, and by applying equation (3) to calculated Bragg angle, will equal to 18.55°, and by using both of equation (4) and (5), then:

$\omega_a = \omega_{ac} = 1923 \times 10^{12}$, and the distance between the first and zeros fringe is $2L \sin (\theta_B) = 6.36$mm.
The acousto-optic system interaction will be illustrated by figure (5) and proposed system configuration will illustrated in figure (6).

**Figure 5.** The acousto-optic interaction of the first system.

**Figure 6.** The first system design and the position of system component on patient’s finger at right and left side view, where a: is the ultrasound thin film of PVDF transducer, b: is the laser light, c is the photodetectors and $\theta_B$ is Bragg angle.

4.2. Second system: acousto-optic interaction using 20 megahertz ultrasound and 980nm laser.

Assume the average speed of sound in human tissue is near 1540 m/s [18], and the sound and light interacted through patient arm, with interaction length (L) of more than 30mm or 3 cm, the laser placed at the inner surface of arm, while the photodetector placed on the outer surface of the arm, both of the laser and photodetector placed at the area between radius bone and ulnar bone. The ultrasound placed beside the hand, $\lambda_0 = 980 \, nm$.

$$\Lambda = \frac{\text{sound speed in tissue}}{\text{sound frequency}} = \frac{1540}{20\times10^6} = 77\mu\text{m}$$

Using Raman-Nath or Bragg conditions

$$\frac{\lambda^2}{\lambda_0} = 6.05\,mm$$

By checking Bragg condition of equation (8) with equation (1) and equation (2), we obtained that the interaction will be achieved by Bragg regime, and by applying equation (3) to calculated Bragg angle, will equal to 0.36°, and by using both of equation (4) and (5), then:
\( \omega_0 = \omega_{11} = 1923 \times 10^{12} \), the distance between the first and zeros fringe is \( 2L \sin (\theta_B) = 0.377 \mu m \)

The acousto-optic system interaction will illustrated by figure (7) and proposed system configuration will illustrated in figure (8).

![Figure 7. The acousto-optic interaction of the second system.](image)

![Figure 8. The second system design and the position of system component on patient's arm at front and back view, where a: is the ultrasound thin film of PVDF transducer, b: is the laser light, c is the photodetector.](image)

4.3. **Third system: Acousto-optic interaction using 1megahertz ultrasound and 970nm laser.**

Assume the average speed of sound in human tissue is near 1540 m/s [18], and the sound and light interacted through finger with interaction length \( L \) of more than 10mm or 10000 \( \mu m \), \( \lambda_0 = 970 \text{ nm} \).

\[
\Lambda = \frac{\text{sound speed in tissue}}{\text{sound frequency}} = \frac{1540}{1 \times 10^8} = 1.54\text{mm}
\]

Using Raman-Nath or Bragg conditions

\[
\frac{\Lambda^2}{\lambda_0} = 2.4m
\]

(9)
By checking Raman-Nath or Bragg condition of equation (9) with equation (1) and equation (2), we obtained that the interaction will be achieved by Raman-Nath regime, where the light and sound are normal to each other’s, the system acousto-optic interaction will illustrated by figure (9) and proposed system configuration will illustrated in figure (10).

Figure 9. The acousto-optic interaction of the third system.

Figure 10. The Third system design and the position of system component on patient’s finger at right and left side view, where a: is the ultrasound thin film of PVDF transducer, b: is the laser light, c is the photodetector.

4.4. Forth system: electromagnetic-acoustic interaction using 100 Kilohertz ultrasound and 10 gigahertz microwave.

Assume the average speed of sound in human tissue is near 1540 m/s [18], and the sound and microwave interacted through patient finger, with interaction length (L) of more than 30mm or 3 cm, the microwave antenna sender placed at the inner surface of arm, while the microwave antenna receiver placed on the outer surface of the arm. The ultrasound placed beside the hand.

\[
\lambda_0 = \frac{3 \times 10^8}{10 \times 10^9} = 30 mm
\]

\[
\Lambda = \frac{\text{sound speed in tissue}}{\text{sound frequency}} \frac{1540}{100 \times 10^3} = 15.4 mm
\]

Using Raman-Nath or Bragg conditions

\[
\frac{\Lambda^2}{\Lambda_0} = 7.9 mm
\]
By checking Bragg condition of equation (10) with equation (1) and equation (2), we obtained that the interaction will be achieved by Bragg regime, and by applying equation (3) to calculated Bragg angle, will equal to 76.9⁰, and by using both of equation (4) and (5), then:

\[ \omega_o = \omega_o = 62.8 \times 10^9, \text{ and the distance between the first and zeros fringe is } 2L \sin (\theta_B) = 58.4 \text{mm} \]

The acousto-optic system interaction will be illustrated by figure (11) and proposed system configuration will illustrated in figure (12).

![Figure 11. The acousto-optic interaction of the forth system.](image1)

![Figure 12. The Forth system design and the position of system component on patient’s hand at front and back view, where a: is the ultrasound thin film of PVDF transducer, b: is the microwave sender, c is the microwave receiver.](image2)
5. Simulation results

We prevail the limitation of selection the optimal electromagnetic spectrum that must be used in the acousto-optic proposed system, by intersecting three important properties, there are the penetration depth, good glucose response and falling in a harmless band of electromagnetic spectrum. Blood Glucose has a good response in specific bands of electromagnetic spectrum. 980nm infrared laser and 30 mm (10 gigahertz) microwaves are both belong to the harmless spectrum of electromagnetic wave, have good properties of penetration in human tissue, and have a good glucose response.

5.1. 980nm infrared laser in acousto-optic system interacted through the human tissue.

When we plot equation (1) and equation (2), we found that the interaction could be designed in the Bragg regime if the used ultrasound is with 20 megahertz or more. Figure (13) demonstrated the relation between the interaction length and the ultrasound frequency, and show that when the ultrasound are less than 20 megahertz the interaction area must be more than 3cm to achieve Bragg regime, therefore the acousto-optic system must interacted on the patient arm. To apply acousto-optic system using Bragg regime on the patient finger, the ultrasound frequency must be within 1 gigahertz. The angle between fringes can be calculated using equation (3), when the system ultrasound frequency is equal or more than 20 megahertz then the angle must called Bragg angle due to the inquired of Bragg condition, while when the ultrasound frequency is less than 20 megahertz then the calculated angle must be the angle between fringes to achieve Raman-Nath regime. Figure (14) illustrated the relation between ultrasound frequency and the angles of acousto-optic interaction.

![Figure 13. The relation between the interaction length and the ultrasound frequency for 980 nm laser.](image-url)
5.2. (10 gigahertz) microwaves in acousto-optic system interacted through the human tissue.

When we plot the relation between the ultrasound frequency and the acousto-optic interaction angle, we found that the functioning angle should be near 100 megahertz ultrasound frequency, which will manifested in figure (15). So the acousto-optic interaction angle will called Bragg angle in this case. The interaction length at the ultrasound frequencies near the 100 kilohertz are very small that will achieve the acousto-optic interaction by Bragg regime, which will illustrated by figure (16).
Figure 15. The relation between ultrasound frequency and the acousto-optic interaction angle for 10 gigahertz microwave.

Figure 16. The relation between the interaction length and the ultrasound frequency for 10 gigahertz microwave.
6. Result of the implemented design
We implemented our third design. The simple design block diagram of the implemented system is manifested in figure (17). 980 nm IR laser of 10 milli-watt power is chosen as near infrared light emitter that has a good glucose response and good penetration depth, while GY-906 is also selected as sensitive near infrared detector, while Arduino UNO is selected as microcontroller for data processing and displaying glucose level. 1 megahertz low cost and low power ultrasound has a very good penetration properties.

![Figure 17. The block diagram of implemented system](image)

This low cost painless system is established for measuring the blood glucose magnitude using acousto-optic non-invasive monitoring system. Microcontroller is fixed to display glucose magnitude rapidly. The acquired glucose measurements are compared to commercial invasive glucometer instantly and from the same body part (finger). Figure 12 is demonstrated the comparison of the measuring blood glucose values of the five diabetic patient and five normal persons, concerning two methods the first one is our acousto-optic non-invasive system and the second reference commercial invasive method, for 100 samples, from 1 to 50 samples are obtained from the five diabetic patients in different times in the days and nights, while from 51 to 100 samples are taken from five normal persons, all the volunteers are between 18 to 50 years old.

![Figure 18. The measurements of implemented system.](image)
7. Discussion

Acousto-optic interaction of electromagnetic light wave or microwave with an ultrasound elastic wave in order to produce a novel free risk system that can extract a vital information noninvasively, especially glucose level information can be extracted from the patient blood without taking blood sample by using acousto-optic system with several challenges, the first limit is the spectroscopic response of glucose in specific ranges of electromagnetic microwave and light, the second limit is the penetration of the electromagnetic and sound waves at the glucose response ranges. The other limits are the heat generated from the applied waves must not exceed the allowable values, the non-homogeneity of the human tissue, and the complication of angle implementation between the sound and the electromagnetic waves and the interaction length. We discuss a comparison between the designed four systems that can emulate patient glucose with different advantages and limitations that will be summarized in table 1.

| Table 1. Acousto-optic systems for measuring glucose level. |
|---------------------------------|----------------|----------------|---------------------------------|----------------|
| Type of interaction             | Wavelength of electromagnetic | Frequency of ultrasound wave | System advantages | System challenges          |
| First system                    | Bragg regime               | 980 nm          | 1 GHz                          | 1-Detect all the penetrated light. |
|                                 |                            |                 |                                | 2-The detection place on the finger. |
|                                 |                            |                 |                                | 3-The complication of angle implementation. |
|                                 |                            |                 |                                | 1-The detection place on the hand not the finger. |
| Second system                   | Bragg regime               | 980 nm          | 20 MHz                         | 1-Detect all the penetrated light. |
|                                 |                            |                 |                                | 2-The simplest of implementation. |
|                                 |                            |                 |                                | 1-The detection place on the hand not the finger. |
| Third system                    | Raman-Nath regime          | 980 nm          | 1 MHz                          | 1-The detection place on the finger. |
|                                 |                            |                 |                                | 2-The simplest of implementation. |
|                                 |                            |                 |                                | 3-The low cost of components. |
|                                 |                            |                 |                                | 1-The cost of using two detectors. |
|                                 |                            |                 |                                | 2-The high cost of ultrasound. |
|                                 |                            |                 |                                | 3-The complication of angle implementation. |
| Forth system                    | Bragg regime               | 15.4 mm         | 100 KHz                        | 1-Detect all the penetrated microwave. |
|                                 |                            |                 |                                | 2-The complication of angle implementation. |
|                                 |                            |                 |                                | 3-The low cost of components. |

8. Conclusion

Four novel acousto-optic glucose monitoring proposed systems are designed and we implement our optimized third system to measure this important vital factor which is the blood glucose value, the optimized implemented system shows an excellent relationship concerning the invasive commercial glucometer values and the new designed acousto-optic system measurements. The results illustrates the simplicity of using both of ultrasound and near infrared laser in Raman-Nath regime for measuring the blood glucose non-invasively. The ultrasound mechanical waves are used to enhance the glucose system sensitivity by enhancing the electromagnetic light penetration through the patient finger.
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