Design for Biosecurity

Prof. Mainak Das

Department of Design

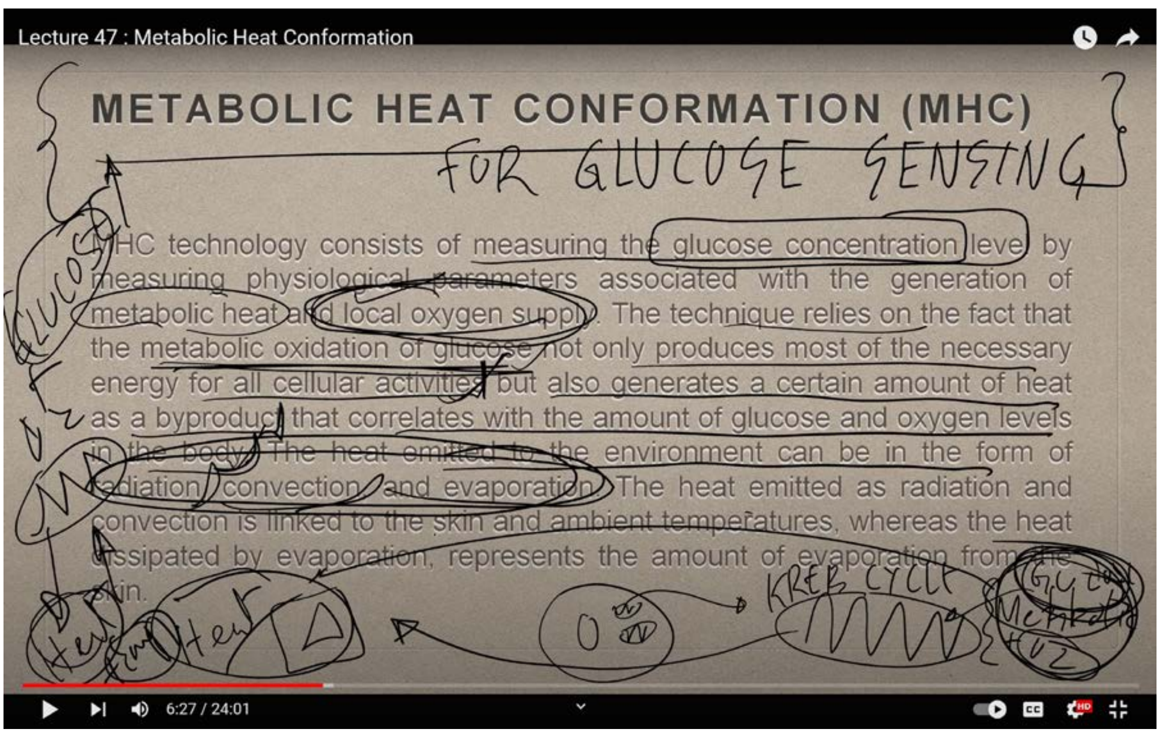
Indian Institute of Technology, Kanpur

Lecture 47

Metabolic Heat Conformation

Welcome back to the class. In our last session, we wrapped up our discussion on thermal emission spectroscopy and explored how biosensor technology is advancing, particularly in the design of integrated suits. These suits will be equipped with a wide array of sensors embedded in the fabric, marking a significant leap in technical textiles. This technology is especially crucial for the military, army, navy, and air force, where real-time monitoring of soldiers' physiological parameters during warfare or crisis situations is imperative. These developments point toward a future where these sensor-integrated garments will allow continuous health and performance monitoring of individuals in high-stress environments.

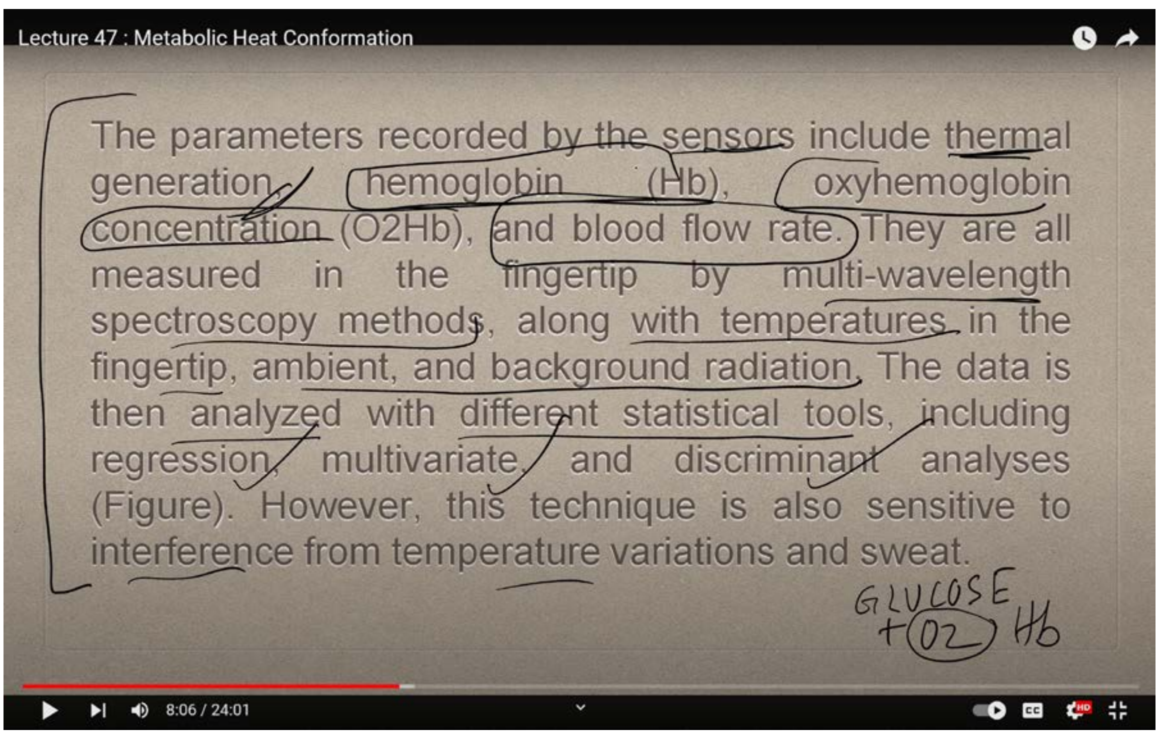
(Refer Slide Time: 06:27)



Today, we’re going to dive deeper into a related topic: Metabolic Heat Conformation (MHC) for glucose sensing. As the term implies, MHC is based on the principle that metabolic activities within the body generate heat, which can be measured to infer glucose levels.

Now, let’s break down the fundamentals of metabolism. Metabolism consists of two interconnected processes, anabolism and catabolism. Catabolism involves breaking down larger molecules into smaller ones, releasing energy that the body uses for various functions. Anabolism, on the other hand, is the process of synthesizing larger molecules from smaller ones for storage. During catabolism, as the body breaks down molecules to generate energy, a measurable increase in body temperature occurs, directly linked to metabolic activity.

(Refer Slide Time: 08:06)

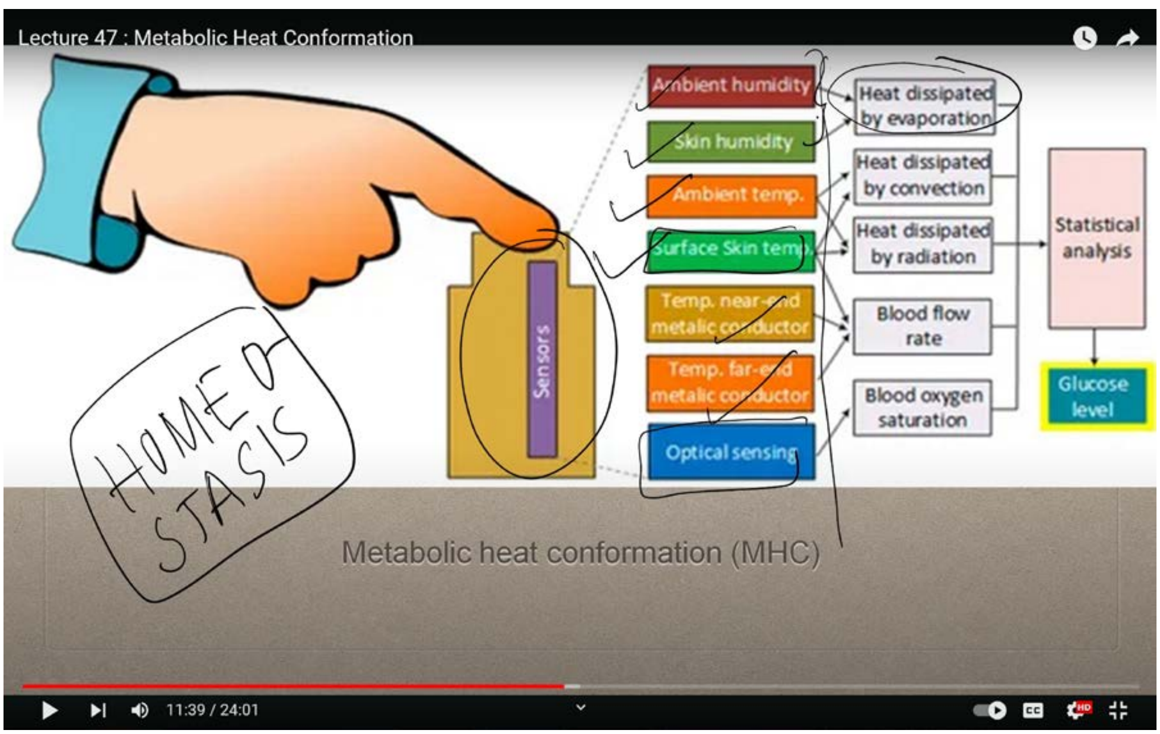


This catabolic process primarily occurs in the mitochondria, often referred to as the "powerhouse" of the cell. Mitochondria are present in trillions across the body’s cells and are crucial in regulating our body's energy dynamics. During cellular metabolism, mitochondria consume oxygen, which is intricately tied to energy production. Consequently, there is a direct correlation between oxygen consumption and metabolic heat generation.

MHC technology capitalizes on this relationship by measuring glucose concentration through physiological parameters associated with metabolic heat generation and local oxygen supply. Essentially, as metabolic processes unfold within the mitochondria, the heat generated and oxygen used serve as indicators of glucose levels in the body. So, when we monitor metabolic heat and local oxygen availability at specific sites, we can infer glucose concentration levels with considerable accuracy.

In essence, MHC technology offers a promising avenue for non-invasive glucose sensing by leveraging the body's natural metabolic processes to provide real-time data on glucose concentrations.

(Refer Slide Time: 11:39)



The technique hinges on a fundamental principle: the metabolic oxidation of glucose not only produces the majority of the necessary energy for cellular activities but also generates a significant amount of heat as a byproduct. This heat is closely correlated with the levels of glucose and oxygen present in the body. Specifically, when glucose is metabolized in the presence of oxygen through the Krebs cycle, it yields a considerable amount of heat, which is directly proportional to the quantity of glucose available.

To simplify, consider the reaction occurring within the mitochondria: glucose plus oxygen produces heat and energy. Here, glucose and oxygen serve as the reactants, while heat and energy are the products. Thus, the amount of reactants is directly proportional to the heat and energy generated; this holds true for both glucose and oxygen. Consequently, one can theoretically back-calculate the amount of glucose consumed based on the heat produced. In essence, this technique relies on the metabolic oxidation of glucose to produce energy while simultaneously generating heat that correlates with glucose and oxygen levels in the body.

The heat emitted during this process can manifest in several forms: radiation, convection, and evaporation. Radiation and convection relate to the skin and ambient temperature, while evaporation represents the moisture lost from the skin. These metabolic heat conformations are essential for understanding the physiological processes involved.

Sensors record several key parameters, including thermal generation, hemoglobin concentration, oxyhemoglobin concentration, and blood flow rate, all of which are measured at the fingertip using multi-wavelength spectroscopy. Additionally, the temperature of the fingertip, along with ambient and background radiation, is monitored. The collected data is then analyzed using various statistical tools, including regression and multivariate analysis.

However, it’s important to note that this technique is sensitive to temperature variations and can be affected by sweat interference. Before I delve into the specifics illustrated in the upcoming figure, I want to highlight one more crucial parameter: oxygen transport. Hemoglobin serves as the oxygen carrier in the blood, and thus, both hemoglobin and oxyhemoglobin concentrations are measured.

To clarify, hemoglobin can exist in two forms: unbound (standalone) or saturated with oxygen (oxyhemoglobin). Hemoglobin possesses four distinct sites where oxygen can bind, allowing for varying degrees of saturation. Additionally, monitoring blood flow rate is critical, particularly when metabolism is occurring following food intake, as it reflects the body's physiological state during these metabolic processes.

Automatically, this increase in metabolic activity leads to a faster metabolism, resulting in an elevated blood flow rate. By examining the blood flow rate, one can determine the amount of oxygen being transported to the site and the efficiency of oxygen transfer by the hemoglobin molecules. It's crucial to establish a baseline hemoglobin level for the individual; for instance, one person may have a hemoglobin level of 16, another 13, and yet another 9, each reflecting different oxygen-carrying capacities. Once you know the blood flow rate, you can back-calculate to assess how much hemoglobin is reaching the tissues, how much of it is saturated with oxygen, and how much remains unsaturated.

This information allows you to understand precisely how much oxygen is reaching the site, which reacts with glucose to generate energy, along with the accompanying heat, just as I illustrated in the previous slide. All these measurements are conducted at the fingertips using a multi-wavelength spectroscopy method, which also captures fingertip temperature. Temperature is a critical factor as it indicates how much heat is being generated, in addition to monitoring ambient and background radiation. The collected data is subsequently analyzed using a variety of statistical tools, including regression analysis, multivariate analysis, and discriminant analysis.

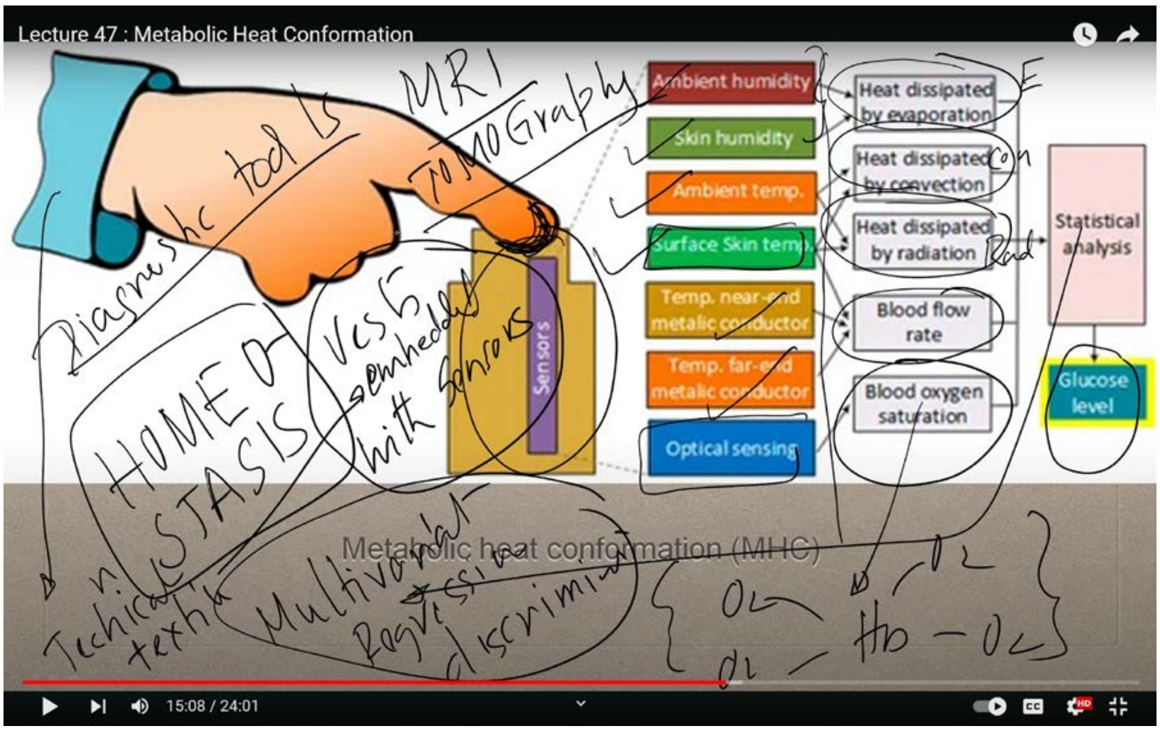
Now, if you look at the accompanying figure, it illustrates our multi-wavelength spectroscopic sensor. This sensor records ambient humidity, skin humidity, and surrounding humidity levels. Understanding skin humidity is essential, as individuals sweat at varying rates; thus, knowing how much moisture is present on the skin, specifically on the fingertip, provides valuable context for the data collected.

Next, we consider ambient temperature, which represents the temperature of the environment around us. For example, if I am in a room with a temperature of approximately 24 degrees Celsius, it’s essential to note how this compares to the skin surface temperature.

A thermometer must indicate the body temperature relative to the surroundings, as this will influence how much metabolism the body must perform to maintain homeostasis, the delicate balance of physiological parameters.

Additionally, the temperature readings near the end of the metabolic conductor and at its far end, along with optical sensing, are vital parameters that need to be measured. This data will assist in calculating the heat dissipated through evaporation. Understanding these parameters will help differentiate between heat lost through convection versus that lost through radiation.

(Refer Slide Time: 15:08)



To clarify, when discussing heat emitted as radiation, remember that convection is linked to skin and ambient temperature, while heat dissipated by evaporation signifies the moisture lost from the skin. It's imperative to account for all three forms of heat generation, heat dissipated by evaporation, convection, and radiation.

Next, we'll address blood flow rate and blood oxygen saturation, which essentially reflects the number of hemoglobin molecules available. To effectively analyze these components, you will need to employ a series of mathematical tools. This is where mathematics plays a pivotal role in modern sensing technologies, necessitating the use of regression analysis, multivariate analysis, and discriminant analysis to extract meaningful insights from the data.

These three analytical tools, regression, multivariate analysis, and discriminant analysis, are primarily employed in glucose level detection, but many other tools are also available. Among these, multivariate regression and discriminant analysis play crucial roles in extracting glucose levels from complex data. This technology represents a significant part of the future, as researchers are increasingly integrating such advancements with various devices, particularly MRI and tomography equipment. These integrations are becoming indispensable for a wide array of diagnostic tools utilized in the biomedical field for strategic applications.

Moreover, to enhance sensitivity, gels are being applied to the skin's surface to achieve better recordings of physiological data. In our last class, I mentioned the exciting developments occurring in technical textiles, especially the design of vests embedded with sensors tailored for various strategic applications. These sensor-embedded vests are being developed not only for sports but also for workers operating in hazardous environments, particularly during epidemics where they must navigate tricky and extremely susceptible conditions. Such innovations are becoming increasingly common.

Now, let’s shift our focus to our next technology: photoacoustic spectroscopy. When we discuss acoustics, we're fundamentally referring to sound; however, photoacoustic spectroscopy intertwines both light and sound. Here, we are addressing two distinct types of radiation: light, which encompasses various forms of waves, including electromagnetic radiation, and acoustic sound waves, which are mechanical in nature.

The technology capitalizes on the principles of ultrasound but utilizes short laser pulses at wavelengths specifically absorbed by targeted molecules within a fluid. This absorption results in microscopic localized heating, which depends on the specific heat capacity of the tissue being examined. The absorbed heat prompts a volumetric expansion of the medium, consequently generating ultrasound waves that can be detected by an acoustic or pressure sensor.

By monitoring the peak-to-peak variations of the detected signal, it becomes possible to correlate these changes with glucose levels in the blood. Thus, this method utilizes two different types of waves: on one side, we have the light in the form of laser pulses, and on the other, we have mechanical vibrations. This dual-wave approach is why it’s aptly named photoacoustic spectroscopy. For non-invasive glucose detection, the two primary forms of excitation are pulsed and continuous waveforms, each contributing to this innovative method of analysis.

In pulse mode, the laser pulses have durations on the order of nanoseconds and a pulse repetition rate of a few kilohertz. This rapid pulsing results in fast and adiabatic thermal expansion of the sample, generating a wide spectrum of acoustic frequencies. Essentially, what happens is that you deliver a pulse, creating numerous vibrations within the fluid. These vibrations produce a pressure wave, which is what you measure. The characteristics of the pressure waves will vary depending on the type of particles present in the liquid, leading to the generation of a wide array of acoustic frequencies alongside various acoustic noises within the broad bandwidth of the detectors or transducers.

Conversely, when employing continuous pulse excitation, a modulated continuous wave is used, producing a single acoustic frequency in the detected spectrum. This method offers a higher signal-to-noise ratio, particularly when utilized in a lock-in detection configuration.

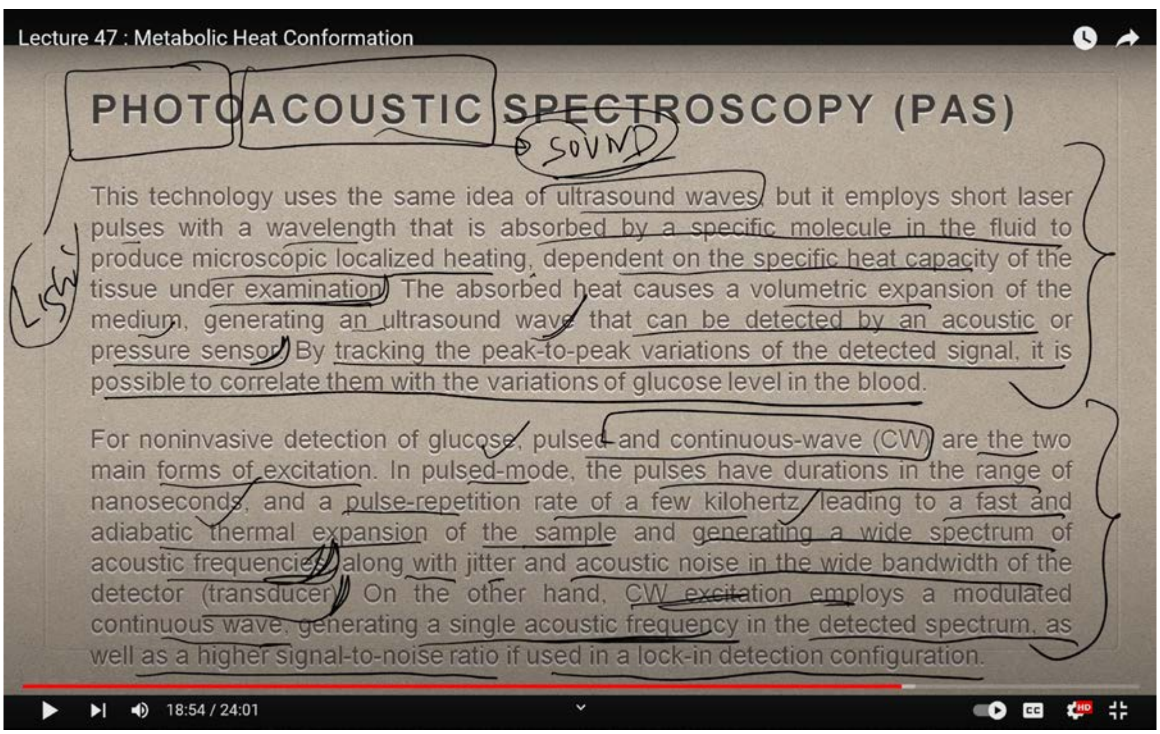
These different configurations are crucial, but the most vital concept to grasp is the integration of two distinct types of waves: radiation and mechanical waves for molecular detection. This integration presents an exciting avenue for advancing sensing technologies.

In this setup, you can visualize the components involved: the piezoelectric transducer generates the ultrasound waves, while the laser provides the photo aspect of the process. When the laser beam strikes the acoustic resonator, it creates a specific signal based on the variation of waves generated by the interaction of photons with the ultrasound. This signal is what you measure.

If you refer to the accompanying figure, you can see the fundamental configuration of pulse sensing. The light emitted from the laser interacts with the sample, generating ultrasound waves as we previously discussed. We have already covered how these generated ultrasonic waves propagate through the acoustic resonator, also referred to as a cell, and ultimately reach the detector, which typically consists of piezoelectric transducers like microphones.

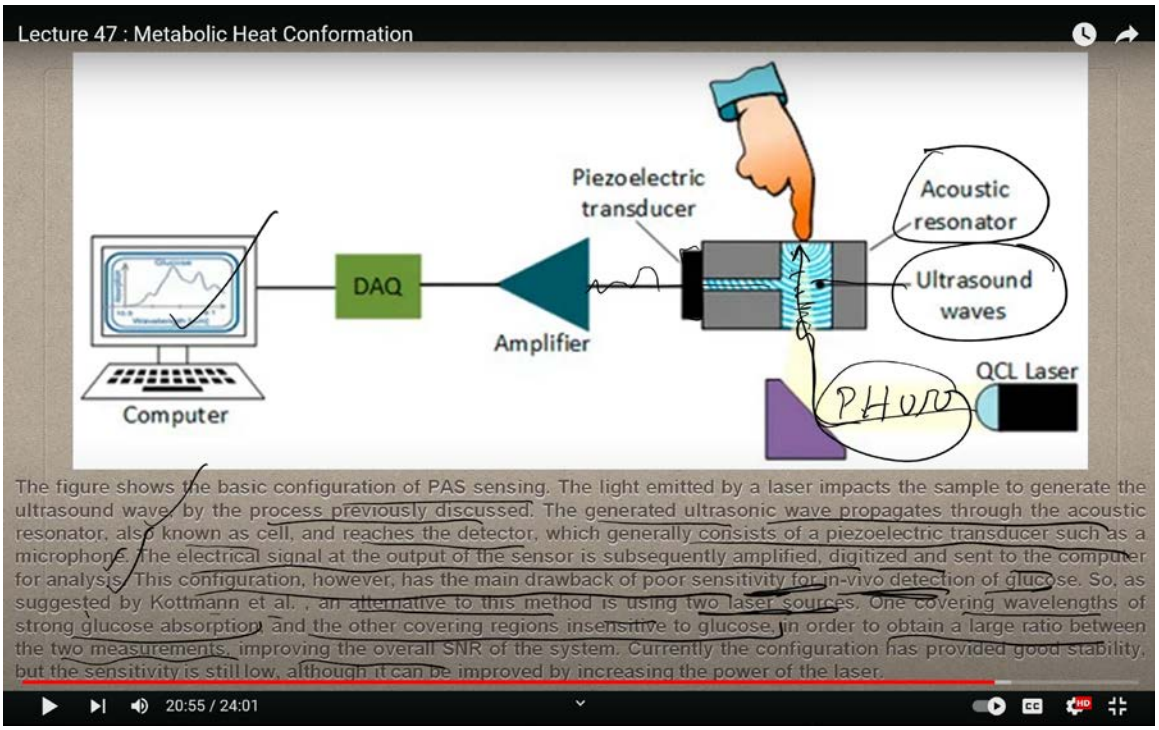
The electrical signal produced at the output of the sensor is then amplified, digitized, and sent to a computer for analysis. However, this configuration faces significant drawbacks, such as poor sensitivity and challenges related to in vivo detection of glucose, as highlighted by Cotman et al.

(Refer Slide Time: 18:54)



An alternative approach involves using two laser sources: one targeting the wavelength of strong glucose absorption and the other focused on regions that are insensitive to glucose oxidation. Essentially, this technique aims to derive a measurement from a less sensitive laser compared to a more sensitive one, creating a substantial ratio between the two measurements. This strategy enhances the overall signal-to-noise ratio (SNR) of the system, significantly improving the accuracy and reliability of the glucose detection process.

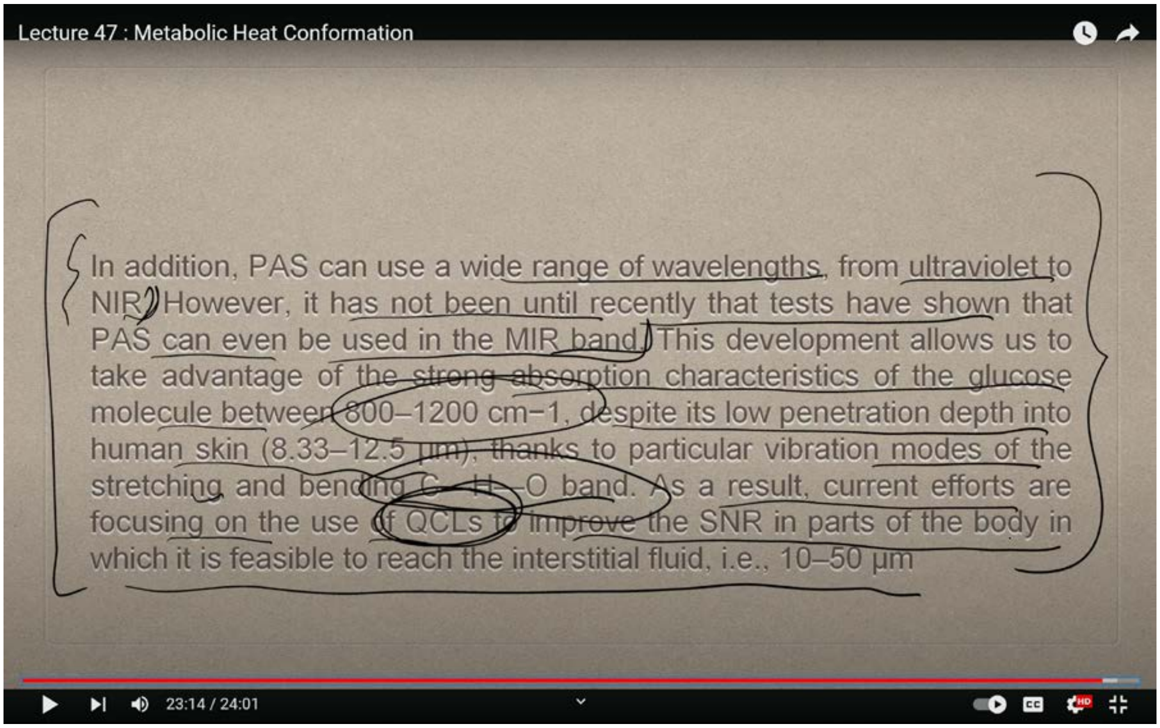
(Refer Slide Time: 20:55)



The signal-to-noise ratio (SNR) is indeed a critical aspect. Currently, the configuration has demonstrated good stability; however, the sensitivity remains low. One way to enhance this sensitivity is by increasing the power of the laser. This overview encapsulates the pass-based technology we have discussed.

Furthermore, photoacoustic spectroscopy (PAS) can operate across a broad range of wavelengths, from ultraviolet to near-infrared (NIR). Interestingly, it has only been in recent years that tests have confirmed the feasibility of using PAS in the mid-infrared (MIR) bands. This advancement enables us to leverage the strong absorption characteristics of glucose molecules within the range of 800 to 1200 centimeters, despite the low penetration depth into human skin, which measures around 8.33 to 12.5 micrometers. This capability arises from the specific vibrational modes associated with the stretching and bending of the CHO (carbon-hydrogen-oxygen) band.

(Refer Slide Time: 23:14)



Consequently, current research efforts are focusing on utilizing quantum cascade lasers (QCLs) to improve the signal-to-noise ratio of measurements taken from interstitial fluid at depths of 10 to 50 micrometers. In summary, these represent the fundamental principles of photoacoustic spectroscopy and its recent developments.

It is essential to recognize that this entire field is progressively transitioning towards integrating multiple sensors into textiles, effectively embedding them within the body through these materials. The future lies in flexible electronics, advanced technical textiles, innovative sensor technologies, data management algorithms, and optimization strategies, all of which are converging to shape the next generation of integrated sensor technology.

With that, I will conclude today's class. In our next session, we will explore electromagnetic sensing. This discussion will serve as a stepping stone towards concluding our focus on glucose sensing, after which we will delve into the evolution of various types of electrodes and the development of electrochemical sensors. Thank you!