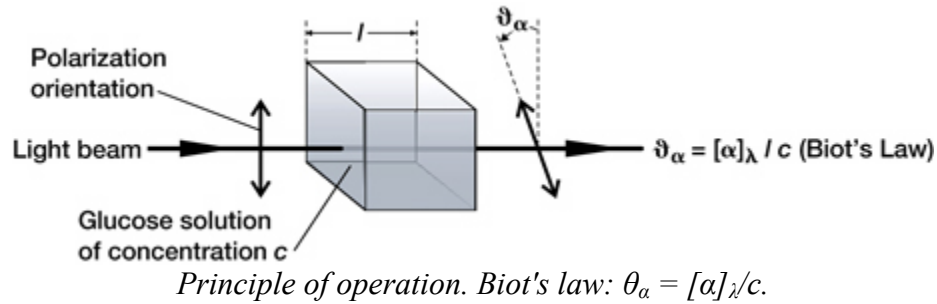


# Calibration Experiments Conducted for Noninvasive Blood Glucose Sensing Through the Eye

There are more than 16 million diabetics in the United States and more than 100 million worldwide. Diabetes can lead to severe complications over time such as blindness, renal and cardiovascular diseases, and peripheral neuropathy in the limbs. Poor blood circulation in diabetics can lead to gangrene and the subsequent amputation of extremities. In addition, this pathology is the fourth leading cause of death in the United States. The most effective way to manage diabetes is frequent blood glucose monitoring performed by the patients themselves. However, because of pain, inconvenience, and the fear of developing infections from finger-prick blood tests or implants, many patients monitor their blood glucose levels less frequently than is recommended by their physicians. Therefore, a noninvasive, painless, and convenient method to monitor blood glucose would greatly benefit diabetics.

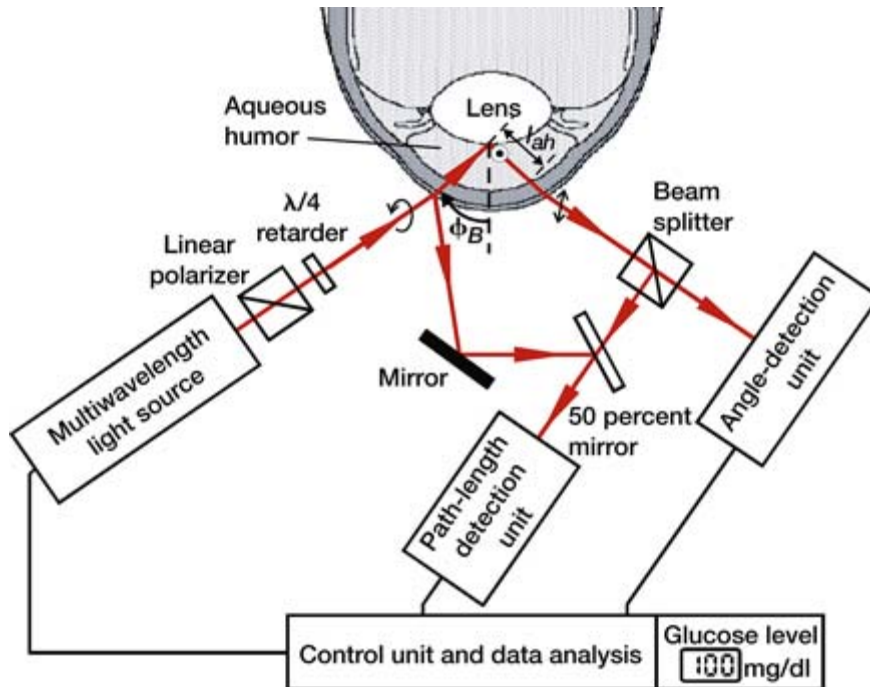
Likewise, detecting, preventing, and treating the untoward effects of prolonged space travel (e.g., a human mission to Mars) in real-time requires the development of noninvasive diagnostic technologies that are compact and powerful. As a "window to the body," the eye offers the opportunity to use light in various forms to detect ocular and systemic abnormalities long before clinical symptoms appear and to help develop preventative and therapeutic countermeasures early. The noninvasive feature of these technologies permits frequent repetition of tests, enabling an evaluation of the response to therapy.

Certain molecules (e.g., glucose) possess chiral properties: they will rotate a plane of polarized light to the right (clockwise). The rate of rotation is directly proportional to the amount of glucose present in a solution. The aqueous humor of the eye exhibits low scattering properties, and its glucose concentration closely matches blood glucose levels. A glucose molecule rotates the plane of polarization of incident polarized light by an angle  $\theta_\alpha$  that is proportional to the path length  $l$  and the concentration  $c$  in the sample. The substance-specific proportionality factor  $[\alpha]_\lambda$  denotes the optical rotatory power, which is a function of the wavelength  $\lambda$ . By knowing this quantity at the wavelength and optical path length  $l$  used and by observing the polarization rotation  $\theta_\alpha$ , one can calculate the glucose concentration  $c$ .



The preferred test site for the polarimetric measurement of glucose concentration in the human body is the aqueous humor of the eye: the clear fluid between the cornea and crystalline lens in the eye's anterior chamber. This fluid is an ultra-filtrate of blood containing most of the molecules found in serum, including glucose, at concentrations that are reflective of serum levels in the human body. Therefore, the aqueous humor can act as an exceptional optical window to measure the glucose levels of diabetics without contact.

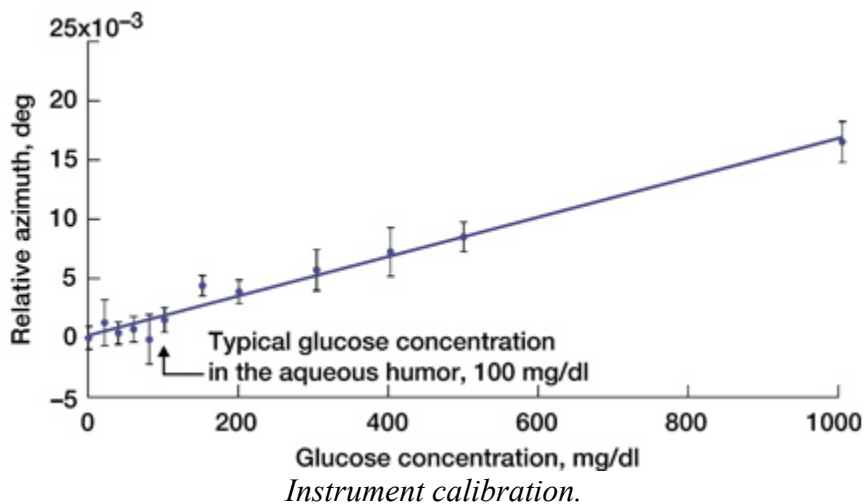
In our experimental setup, the aqueous humor is optically accessed with a circularly polarized light beam reflected at the Brewster's angle  $\varphi_B$  off the eye lens. On its way out of the eye, the resulting reflected linearly polarized light constitutes the measured quantity for the sensor. The application of a multiwavelength light source permits spectrally resolved signal detection by the angle-detection unit so that the device can benefit from the specific wavelength dependence of the optical rotatory power of glucose. Therefore, the influence of optically active confounders<sup>1</sup> and of changes in the polarization state induced by the geometry of the setup are mostly eliminated. For simultaneous measurement of the optical path length inside the aqueous humor, a path-length detection unit was built on the basis of low-coherence interferometry.



*Schematic diagram of the apparatus  $I_{ah}$ , reflected optical path length.*

Long description. This diagram shows light from a multiwavelength light source passing through a linear polarizer and a one-fourth wavelength retarder through the aqueous humor to the lens of the eye. It returns to the control unit for data analysis (glucose concentration) via a beam splitter and an angle-detection unit and via mirrors and a path-length detection unit.

Preliminary proof-of-concept calibration experiments using aqueous glucose samples were conducted at the NASA Glenn Research Center. The results showed good linearity (correlation coefficient,  $r = 0.986$ ) and high sensitivity (angle of rotation,  $\sigma = 1.38$  millidegrees corresponding to a glucose concentration,  $c$ , of 77 mg/dl). Efforts are underway to further improve the sensitivity and repeatability and to reduce the size and cost of the sensor. The ultimate goal is a portable, easy-to-use, reliable measurement device for daily patient medical care and better diabetes management.



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<sup>1</sup>Molecules other than glucose (e.g., albumins).

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## **Reference**

1. Ansari, Rafat R.; Böckle, Stefan; and Rovati, Luigi: New Optical Scheme for a Polarimetric-Based Glucose Sensor. *J. Biomed. Opt.*, vol. 9, no. 1, 2004, pp. 103-115.

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