Biomedical Optics & Medical Imaging

A New Eye in Law Enforcement

Photonics technology enables accurate, noninvasive alcohol testing.

By Benjamin Ver Steeg and Trent Ridder

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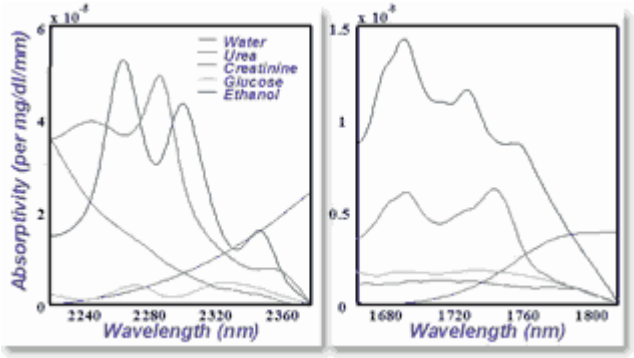
Although alcohol testing is typically associated with drunk driving, it also plays significant roles in probation monitoring, workplace safety, and emergency medicine. Blood, breath, and saliva alcohol measurement methods are currently used to varying degrees in these environments. These measurement techniques suffer from two key limitations, however: They require the handling of a bodily fluid, which gives rise to biohazard concerns, and they require some degree of direct subject supervision from a test administrator (e.g., a police officer). These limitations have restricted testing to those applications in which oversight is readily available.

A recent advance in optical testing methods promises to overcome these limitations by simultaneously offering improved subject safety and the ability to conduct completely unsupervised testing. Our team has developed a touch-based alcohol monitoring technology that uses near-infrared (NIR) reflectance spectroscopy to noninvasively measure alcohol through a subject's skin. This creates a rapid, easy-to-use method for determining alcohol concentration in a variety of environments.

Making the Calculations

Much has been written about the complexity of applying noninvasive measurements to people. Structural physiological variations such as the size, orientation, and density of collagen fibers result in significant person-to-person differences in the optical scattering properties of skin. Concentrations of physiological compounds also vary across individuals and in the presence of diseases such as diabetes. From the standpoint of developing a noninvasive alcohol monitor, these variations result in spectral noise that must be properly accounted for in the design of the measurement system (see oemagazine, September 2003, p.18). The focus of this article is on the key aspects of the technology that enable noninvasive alcohol monitoring in challenging environments well-removed from the laboratory.

Our system uses NIR spectroscopy to measure analytes in tissue. The specific molecular structure of a chemical compound determines the wavelengths of light it absorbs. NIR spectroscopic methods use these unique spectral absorption signatures to selectively detect the presence of the analytes of interest.



NIR spectral fingerprints exist for a variety of analytes.

Quantitative NIR spectroscopic applications rely on the Beer-Lambert Law (commonly referred to as Beer's Law), which relates analyte (alcohol) concentration to absorption magnitude. Multiple absorbers with overlapping spectral signatures complicate the measurement, but the use of multiple wavelengths allows quantification of analytes with nonidentical absorption spectra. Consider the application of Beer's Law to a two-analyte system using absorption data captured at two wavelengths, λ_1 and λ_2. We can describe the system by

$$A_{\lambda_1} = \varepsilon_{\alpha\lambda_1} bc_\alpha + \varepsilon_{\beta\lambda_1} bc_\beta \quad [1]$$

$$A_{\lambda_2} = \varepsilon_{\alpha\lambda_2} bc_\alpha + \varepsilon_{\beta\lambda_2} bc_\beta \quad [2]$$

where ${}^A\lambda_1$ and ${}^A\lambda_2$ are the measured absorptions at wavelengths λ_1 and λ_2, c_a and $c_ß$ are the concentrations of analytes a and ß, b is the path length of light through the sample, and the epsilon terms (e) are the absorptivities of analytes a and ß at wavelengths λ_1 and λ_2. Because and are measured quantities and the absorptivities are known via literature or analyte calibration curves, the only unknowns are the analyte concentrations. We have a system of two equations and two unknowns, so we can use simple algebra to directly determine the concentrations of both analytes despite the fact that both analytes contribute to the absorption at each wavelength. This type of approach has been successfully implemented in process-control monitors using only three to four wavelengths of light.

A noninvasive alcohol monitor that measures tissue, however, presents a much more complex problem due to the hundreds of species present in human skin. The resulting system of equations would be immense and would require several hundred wavelengths of light as well as direct knowledge of the absorptivity values for all analytes at all wavelengths. These complications make a direct solution for alcohol concentration in skin impractical.

Custom, compact FTIR makes noninvasive alcohol measurements commercially viable.

Indirect multivariate calibrations such as partial-least-squares regression (PLS) are the methods of choice for such situations.[1] With indirect methods, the effects of interferents (absorbing species other than alcohol) are modeled using calibration spectra that contain sufficient variability of each source of spectral variation. The purpose of the PLS algorithm is to generate a calibration that is selective for the analyte of interest without explicitly modeling interfering absorbers. Essentially, the output of the PLS algorithm consists of a set of spectral weights (one per wavelength, **b** in equation 3 below), called the regression vector, that minimizes analyte measurement error in a calibration data set in a least-squares sense. We obtain subsequent alcohol concentrations *c* by calculating the vector dot product of the regression vector **b** and each measured absorbance spectrum **x**. Other inverse approaches are functionally similar to PLS, yet differ in how **b** is determined.

$$c = \mathbf{x}^{\mathrm{T}}\mathbf{b} \qquad [3]$$

The signal-to-noise ratio (SNR) of the spectroscopic signal is an obvious consideration for measurements in such a complex system. Since noise can arise from fundamental sources (for example, shot noise) as well as nonfundamental sources (for example, vibrational and environmental effects), photon throughput and instrument stability are important figures of merit that contribute to the accuracy of the alcohol measurement. Indeed, these parameters drove many of our optomechanical design decisions.

Theory into Practice

The alcohol monitor consists of illumination, tissue probe, interferometer, and detector subsystems optimized to provide high SNR and stability in a robust package suitable for a wide variety of environments. Illumination is provided by a ceramic filament operating at a color temperature of 1200°C with a lifetime exceeding 10,000 hours. The relatively low color temperature of the filament allows for efficient generation of light in the region of interest without the need for color-shaping filters. The light is delivered to, and collected from, the tissue using an optical probe composed of high-numerical-aperture fused-silica fibers arranged such that illumination and collection fibers are separated by approximately 500 μm center-to-center. This geometric arrangement enables the instrument to preferentially interrogate alcohol-containing regions of tissue while rejecting the

undesirable light that reflects off the surface of the skin. The collected light is then delivered to the interferometer subsystem.

The first generation of our noninvasive alcohol monitor uses a Fourier transform spectrometer (FTS) because of the inherent throughput and wavelength-axis stability advantages relative to dispersive spectrometers. Our FTS system uses a custom, scanning Michelson interferometer with cube-corner retro-reflectors to encode spectral information as a time-varying signal. This interferometer consists of a 50/50 beamsplitter, a fixed retro-reflector, and a scanning retro-reflector (see figure 1). By moving the scanning retro-reflector, the two beam paths are phase shifted relative to each other, producing sinusoidal intensity variations at the detector that have frequencies proportional to the wavelengths of incoming light. The optical resolution of our interferometer (proportional to the maximum distance traveled by the scanning retro-reflector) is fixed at 32 cm^{-1}, which provides sufficient resolving power for alcohol measurements in tissue. The fixed 32 cm^{-1} resolution allows a large (15-mm) input-aperture diameter, and its associated high photon throughput, while simplifying the optomechanical design, thereby yielding a compact and economical instrument.

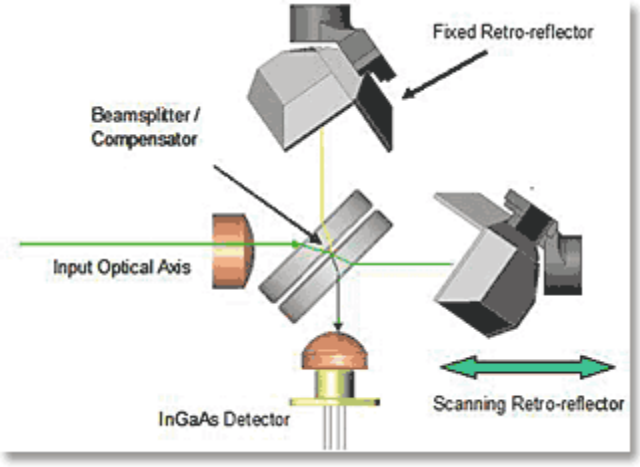


Figure 1*. Our Fourier transform spectrometer (FTS) is based on a Michelson configuration. Moving the scanning retro-reflector phase shifts the two beam paths relative to each other, producing sinusoidal intensity variations at the detector that have frequencies proportional to the wavelengths of incoming light.*

We achieve optical scanning with a barrel flexure constructed from a single piece of machined aluminum mounted on a voice coil actuator. The barrel-mount design pushes the first off-axis resonant mode above 1 kHz, providing significant reduction in vibration sensitivity in virtually all practical commercial environments. The design preserves radial symmetry along the optical axis of the instrument, eliminating the need for low coefficient of thermal expansion materials and achieving an alignment thermal stability of 0.3% change in modulation efficiency per degree centigrade. The final,

optical detection stage is provided by a thermoelectrically cooled, single-element extended indium-gallium-arsenide detector operating at 15°C.

Experimental Results

We measured 10 volunteer subjects over a period of five days in order to assess the noninvasive monitor's performance relative to blood and breath alcohol measurements (see figure 2).[2] Upon arrival, subjects were administered doses of alcohol based on subject weight and gender. Shortly after alcohol consumption, we acquired repeated cycles of breath, capillary blood, and noninvasive alcohol measurements, accruing nearly 200 sets of measurements (approximately 20 sets per subject). As can be seen from the results, the noninvasive monitor performance was comparable in accuracy and precision to those of an evidentiary breath monitor.

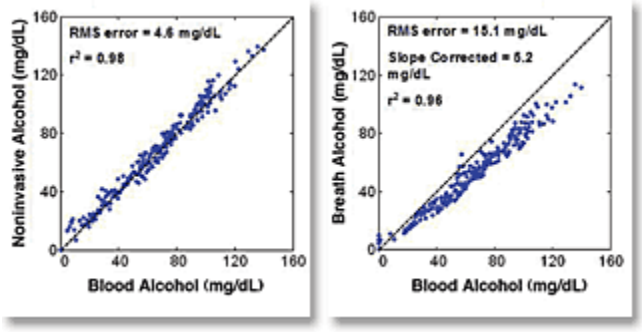
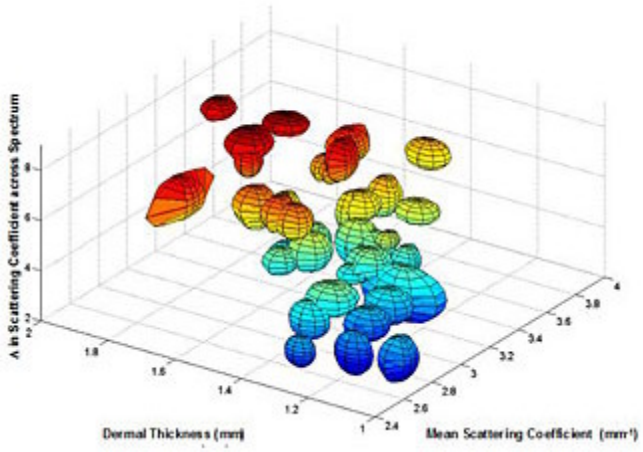


Figure 2. *Data taken from a 10-subject study shows good agreement between noninvasive (left) and breath-based (right) instruments. Dotted lines indicate unity slope. The slope error in the breath measurements is real and is related to the well-known blood-breath partition coefficient that relates breath alcohol concentration to blood alcohol concentration. Note that 80 mg/dL (0.08%) is the legal limit in the United States.* [4]

Although the complexity of tissue represents a challenge for accurate alcohol measurements, it provides a wealth of structural and chemical information that is unique for each subject. As such, the NIR spectral measurement inherently contains information that can be used to differentiate between subjects. A visual representation of multiple physiological properties demonstrates the intersubject resolving power of the NIR measurements. It is clear that with only three properties, each subject resides in a unique region of 3-D space. This example can be easily extended to include additional properties, which results in a demonstrated biometric performance comparable to commercially available fingerprint readers.[3]



Visual representation of noninvasive biometric signal using three physiological properties shows the uniqueness of each measurement. Each ellipsoid encompasses the properties extracted from multiple noninvasive measurements (typically 10 to 15) obtained from a single subject.

The integral biometric signal of the noninvasive technology has significant advantages for alcohol monitoring applications in which an individual or small group of individuals needs to be monitored in an unsupervised setting. One example of such an application is in home arrest situations in which a convicted offender must remain alcohol free. Most existing alcohol testing methods require direct supervision in order to confirm that the offender is the one performing the test. There is a strong desire to automate this kind of remote testing by eliminating the need for supervision. The NIR spectroscopic approach offers a promising solution for unsupervised alcohol monitoring because the alcohol and biometric signals are obtained from the same NIR measurement. As a result, the NIR technique offers the potential for alcohol testing in several law enforcement and corrections environments that have been difficult to address with existing technologies. **oe**

References

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Benjamin Ver Steeg, Trent Ridder

Benjamin Ver Steeg is the director of engineering and Trent Ridder is the chief technical officer at TruTouch Technologies Inc., Albuquerque NM.

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