

Evanescent Wave Catheter: New Phototechnology in Anaesthesia and Intensive Care

Matsuyuki Doi
Department of Anesthesiology and Intensive Care
Hamamatsu University School of Medicine, Hamamatsu, Japan

1. Introduction

Technology using light, photonics or phototechnology, is becoming commonplace in medicine. However, the use of phototechnology in anaesthesia and intensive care is limited. Although an intravenous fibre-optic catheter is clinically available and has great potential in our field, it is not used except in estimating oxyhaemoglobin. This limited usage results from two factors.

The first of these is the narrow range of available wavelengths. Three wavelength regions are used in medicine, ultraviolet (< 400 nm), visible light (400 – 750 nm), and near infrared (750 – 2000 nm). Ultraviolet light is widely used in in-vitro spectroscopy to estimate concentrations of biological substances such as DNA (260 nm) and peptides (280 nm). However, ultraviolet light is not applicable to in vivo spectrometry because it damages DNA. In the visible light region, only red light (650 – 750 nm) is used because haemoglobin and myoglobin almost totally absorb visible light at wavelengths shorter than 650 nm. Water strongly absorbs near-infrared light at wavelengths longer than 1200 nm. Therefore, available wavelengths are limited to those between 650 and 1200 nm for in vivo spectrometry.

The second factor is calibration technique. Relative concentrations of two substances are easily estimated, and almost all clinically available instruments are designed to determine ratios of two components; the fibre-optic oximeter determines the ratio of oxyhaemoglobin fraction and deoxyhaemoglobin, and the pulse dye densitometer determines the relative concentration of indocyanine green against a known haemoglobin concentration. Quantifying the absolute concentration of a substance, however, requires complex methodology that requires a fixed light path length and constant incident light intensity.

I am going to propose the evanescent wave catheter as a candidate for overcoming these obstacles.

2. Evanescent waves

Snell's law (Equation 1) is the simple formula used to calculate the refraction of light passing through an interface between two media with different refractive indices.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \text{ (Equation 1)}$$

where n_1 and n_2 are the refractive indices on either side of the interface.

When $n_1 > n_2$, the refracted angle θ_2 is larger than the incident angle θ_1 . As the angle of incidence is increased, the refracted wave eventually becomes parallel to the interface (i.e., $\sin \theta_2 = 1$) at one particular angle of incidence. This incident angle θ_1 is called the critical angle. At or beyond the critical angle, all of the light is internally reflected. This phenomenon is called total internal reflection (TIR). Even though 100% of the incident light is reflected, an electromagnetic field vector is propagated across the interface in the form of evanescent waves. The evanescent waves may be imagined as escaping from the interface then immediately coming back again. Unless the evanescent waves interact with certain materials, the evanescent energy is not absorbed.

Evanescent waves are formed at the surface of the interface at which TIR occurs. "Evanescent" means "tending to vanish". The intensity of evanescent waves decays exponentially with distance from the interface at which they are formed. The depth of penetration is defined as the distance at which the amplitude of the evanescent wave has decayed to $1/e$, approximately 36% of the initial intensity. The distance of the evanescent wave field is very short, less than half the wavelength, e.g., around 100 nm for green light (500 nm). This very thin band is the strongest point of the evanescent wave. Owing to its limited range, an evanescent wave can interact selectively with molecules at or near the interface without any interference from molecules in the bulk.

3. In vitro techniques

At present, evanescent waves are mostly used in in-vitro instruments. These are divided into two categories, fluorescence microscopes and chemical sensors in the laboratory.

1) Total internal reflection fluorescence microscopy

Evanescent waves produced by total internal reflection are employed as the excitation light in a fluorescence microscope. Total internal reflection fluorescence microscopy is a powerful optical technique. The evanescent waves enable extremely thin sectioning with excellent signal-to-noise ratios. The distance of the evanescent field is about 100 nm, and only fluorescent molecules within the band are excited. Unwanted background and out-of-focus fluorescence signals are dramatically reduced with this technique. Total internal reflection fluorescence microscopy is often employed in studying the movement of a single molecule, and thus this is called nanophotonics.

2) Evanescent wave chemical sensor

Evanescent wave chemical sensors have become increasingly widely used analytical tools in biomedical applications. The main advantage of these sensors is their ability to provide rapid and sensitive analyte detection in real time at low cost. Evanescent wave chemical sensors are categorised into two groups, immunosensors and absorbance sensors.

(1) Immunosensors. When antibodies are used to recognise corresponding antigens, the term “immunosensor” is used. Due to the extremely high equilibrium association constant of immunoreactions, these systems have the potential to be highly sensitive. The antibodies are usually immobilised on the surface of the optical pathway or within the evanescent field. There are several techniques for quantifying the immunoreactions, one of the most widely used of which is two-site immunometric or sandwich architecture with fluorescent tracer antibodies. As the evanescent field is very thin, the evanescent waves selectively excite the fluorescent tracer. The fluorescence emissions tunnel their way back into the same optical fibre. As the fluorescence always has a longer wavelength than the excitation light, it is easily distinguishable.

(2) Absorbance sensors. Evanescent wave absorbance spectrometry is also called attenuated total reflection spectroscopy, and is a well-established technique for chemical analysis. The detection principle is based on absorption of the evanescent wave by substances in contact with the fibre surface. Evanescent wave absorption spectroscopy offers several advantages compared with standard absorption spectroscopy. It is often difficult to perform an accurate standard absorption measurement of highly absorbing or scattering media, whereas evanescent wave spectroscopy is applicable to such samples.

4. In vivo techniques

There is a very small number of projects aimed at developing in vivo sensors using evanescent waves.

1) Evanescent wave catheter for attenuated total reflectance spectrometry

Infrared spectroscopy in the wavelength range from 2 to 25 μm has been used to study the composition of materials in vitro. An infrared spectrum consists of absorption peaks of the frequencies of vibrations between the bonds of the atoms making up a material. Therefore, the spectrum represents a material-specific “fingerprint”. The attenuated total reflectance (ATR) method is ideal for measuring the infrared spectra of biomedical materials. Unlike the transmission technique, ATR spectroscopy can be used for the analysis of thick or strongly absorbing samples, such as tissue. Hooper et al (1) developed an ATR evanescent wave catheter to identify atherosclerotic plaques in blood vessels. The catheter consists of an optic tip and two hollow glass waveguides for input and output infrared waves. The optic tip is cone-shaped, with a 45° angle, and is made of zinc sulphide, with a high refractive index of 2.25. This catheter provides infrared evanescent waves from 2 to 10 μm . ATR spectra obtained from the catheter can distinguish adipose tissue from blood, muscle, and aorta.

2) Fibre-optic evanescent fluorosensor

We have investigated the development of a fibre-optic catheter to detect fluorescence in blood. As many drugs (e.g., propofol, antibiotics) and substances in blood (e.g., bilirubin, vitamins) fluoresce, we expected to be able to quantify blood concentrations of various substances using the fibre-optic catheter very readily. However, a very narrow range of wavelengths is available for excitation because haemoglobin in red blood cells totally absorbs visible light at wavelengths shorter than

650 nm. In order to overcome this constraint, we launched a project to develop a fibre-optic evanescent wave catheter to detect fluorescence. We designed five prototype catheters which produce evanescent waves at their tips and collect fluorescence efficiently. From mathematical simulation it is estimated that 1/600 of the power of the input light is available as evanescent waves to excite fluorescent substances, and that 30% of the fluorescence is collected as emission light into the fibre-optic wave guide. The following investigations are required to complete this project. (1) As the power of the emitted light is very small compared with that of the input light, high power laser diodes are a suitable light source. A laser diode of specific wavelength for each analyte should be prepared. An optical pathway must be designed so that the high power laser wave is focused into the optic fibre. (2) Separating emission light from strong input light is another difficult task. Not only are a dichroic mirror and optical filters required, but digital signal processing is also needed. (3) As the power of the emitted light is extremely small, the photodetector should be highly sensitive, and a photomultiplier may be employed.

5. Future vision

Although evanescent wave sensors have been widely used in vitro, their clinical application in vivo is still under investigation. However, evanescent waves have the potential to bring about significant advances in phototechnology in anaesthesia and intensive care. Biochemical analysis and pharmacokinetic studies could be achieved without blood sampling in the near future.

Reference

(1) Hooper BA, Maheshwari A, Curry AC. Alter TM: Catheter for diagnosis and therapy with infrared evanescent waves. *Applied Optics* 42: 3205, 2003