FIBREOPTIC SENSORS IN CLINICAL MEASUREMENT

I. H. YELLOWLEES

Measurement systems utilizing optical fibres are now becoming available for use in many different fields. Applications in clinical measurement are often cited in the scientific journals, as the small size and electrical safety of these optical devices make them potentially suitable for in vivo use within the blood stream and other body cavities [9, 13, 16, 20].

Many of the systems for clinical use are still at an experimental stage, and little information has filtered through to the clinical journals. This review outlines the basic principles of optical fibre sensors, and describes briefly how some of the variables of interest to the anaesthetist can be measured. A glossary of terms that may be unfamiliar to clinicians but are standard within this field is included as an Appendix.

OPTICAL FIBRES

Optical fibres are made of glass or plastic. A core section is encased in a cladding of material of lower refractive index, the whole having a diameter of about 0.1–0.2 mm. The principle of operation is shown in figure 1. Light from a bulb, laser or other device is directed into the fibre (the incident light), and is prevented from leaving the core by total internal reflection at the interface between the core and the cladding. The light is thus guided along the length of the fibre.

Some losses of light do occur, as a result of manufacturing tolerances and molecular interactions, but this is not usually a problem with the short lengths of fibre used in biosensors.

Optical fibre sensors may be classified into two broad groups according to the function of the fibres:

1. The fibres may be used solely to transmit light to or from a remote location. In this arrangement, the fibres are analogous to wires carrying electrical data signals to and from the measurement site. Such an arrangement is termed an "extrinsic" system, and most of the sensors for biomedical use are of this type (fig. 2). (An ECG may be considered an extrinsic device, as the wires carry the small voltages generated by myocardial activity to a distant recorder.)

2. If the variable to be measured may be made to interfere directly with the fibre to change its light-guiding properties, the fibre becomes an integral part of the system, rather than only a means of transmitting data. This arrangement is termed an "intrinsic" system (fig. 3). (A more familiar example of this arrangement would be a resistance thermometer, in which changes in ambient temperature alter directly the electrical resistance of the wires.)

In order to use intrinsic or extrinsic sensors in measuring systems, changes in the variable to be measured must result in some change in the characteristics of the light travelling along the fibre [5, 11].

Intensity

Changes in the intensity of the light are easy to measure, but a reference signal must be provided to negate the effects of drift.

Wavelength

Changes in the wavelength of light (i.e. colour), are also easy to measure spectrophotometrically. Many chemical indicators are available which change their colour in response to a change in concentration of some variable such as H⁺ (pH). Haemoglobin saturation may be monitored in a similar way.

Changes in the intensity or colour of the light are the most common in biosensors.

KEY WORDS
Measurement techniques: fibreoptic sensors.

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One optical fibre enlarged

Beam of light

Core Cladding

FIG. 1. Optical fibre. The refractive index of the cladding is less than that of the core.

Incident light

Optical fibres

Silvered face (if required)

Reflected light

Reagent

FIG. 2. Extrinsic sensor. The optical fibres are used solely to guide the light which is modulated by an external, optically active material.

Polarization

If the light source emits polarized light, and the variable to be measured is able to change the angle of polarization, this change in angle may be converted to variations in intensity using a plain polarized filter. (Polaroid sun-glasses work in this way to reduce the intensity of the partially polarized light produced by reflection from a surface such as water.)

This is a very sensitive technique, but it is difficult to use outside the laboratory because the angle of polarization may change as a result of physical stresses on the fibre.

Phase

The phase of the light may be measured using an interferometer. This is another highly sensitive technique that is probably unsuitable for use outside the laboratory, because of the problems of stability and calibration.

SENSOR DESIGN

The term "sensor" rather than "transducer" is used to describe these devices, as it does not imply a specific mode of operation (see glossary). Many of these devices are not transducers because no net energy transfer is involved.

For intravascular use, it is often most convenient to arrange fibres carrying incident and returning light to lie parallel with each other within an outer wrap. Some sensor designs involve transmission of the light through a reagent, rather than reflection of the light from the face of the material. In such designs, the distal face may be silvered, so that the light is reflected back again through the reagent to the returning fibre (fig. 2). A detailed account of the various factors and problems involved in sensor design may be found in references [1] and [22].

Optical fibre

Incident light

Modulated light

Sensing zone

FIG. 3. Intrinsic sensor. Part of the cladding is replaced by a material the optical properties of which depend upon the surrounding medium.
Optical fibre carrying incident light

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Optical fibre carrying modulated light

**FIG. 4.** Pressure sensor. Extrinsic pressure sensor using a diaphragm and mirror to vary the proportion of incident light that is reflected into the returning fibre.

*Sensors for Chemicals*

These sensors are generally extrinsic. They may be classified into two types: those that utilize reversible chemical indicators, and those that utilize reagents which, when excited by light of a suitable wavelength, fluoresce to a degree dependent on the chemical composition of the surroundings. In both categories, the reagent is bonded onto the end of a pair of fibres, one of which illuminates the reagent while the other transmits the returning light back to a colour- or intensity-measuring system.

$PCO_2$ and $pH$ may be measured using a reversible indicator [6], whilst $PO_2$, volatile agents, $K^+$ and glucose may be measured using fluorescence techniques [10, 15, 18, 27].

The colour changes of haemoglobin may be monitored very simply, and flow-directed catheters with integral optical fibres are available to provide a continuous measurement of mixed venous oxygen saturation [14, 26].

Measurement of $PCO_2$ by infra-red absorption spectrophotometry is familiar to anaesthetists. Optical fibres may be used to guide the incident and returning infra-red light to and from the measurement site. No sampling tube is required, and the system functions as a mainstream type analyser, but without the usual bulky optics. Unfortunately, ordinary glass fibres do not transmit light in the infra-red region and special fibres (termed chalcogenide fibres) have to be used. At present, chalcogenide fibres are very expensive and fragile, and infra-red $PCO_2$ analysis using optical fibres is impractical [28].

*Sensors for Biological Compounds*

Sensors for biological compounds such as antibodies are now becoming available for laboratory use. Antibody-antigen reactions may be monitored optically by coating the antibody onto a fibre (often in place of part of the cladding, making an intrinsic sensor). Subsequent combination with the antigen changes the transmission properties and may thus be detected as a change in intensity [24].

Immunofluorescence techniques and luminescent enzymes may be used with optical fibres and have enabled highly specific extrinsic sensors to be made for many widely differing compounds, from ethanol to acetylcholine receptors [4, 19]. These techniques (generally known as immobilized enzyme systems) are already producing practical measurement systems for materials that previously required time-consuming laboratory assays.

*Sensors for Physical Variables*

**Temperature**

Temperature sensors are based on changes in fluorescence, absorption spectra or refractive index.

Some phosphor compounds fluoresce at an intensity dependent upon their temperature. Such
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FIG. 5. Pressure sensor. A differential pressure across the spiral wrap deforms the fibre and disrupts total internal reflection of light at the core-cladding boundary.

A compound may be bonded to the end of a pair of fibres to form an extrinsic sensor in a manner similar to the fluorsensors described above.

Many materials change their light absorption spectra with temperature and may be bonded onto the end of a pair of fibres. The intensity of reflected or transmitted light of certain wavelengths varies with this temperature [2].

A small section of the cladding at the end of a fibre may be replaced by a compound in which the refractive index changes with temperature. The degree of reflection at the core-cladding interface (and thus the intensity of the light guided) then becomes temperature dependent, and the whole forms an intrinsic sensor [21].

Pressure

Until recently most systems for measurement of pressure were extrinsic, using a diaphragm and mirror assembly. A typical arrangement is shown in figure 4. The proportion of light reflected from one fibre back into the other is dependent on the angle of the mirror and thus on the pressure difference across the diaphragm. This design has been assembled within a catheter for measurements in vivo [12].

Other methods of pressure measurement have been tried, including sensors based on the change in polarization or phase of light passing through a material under stress. With some of these sensors the fibres constitute the material under stress, thus forming an intrinsic sensor [7, 17]. Another intrinsic pressure sensor may be based on micro-bending (fig. 5). The fibre lies inside a spiral cover. When pressure is applied to the spiral the fibre is deformed as shown and the total internal reflection properties are disrupted.

Flow

Fibreoptic sensors for flow are based on the principle of Doppler shift used in acoustic flow measurement. The optical version uses a laser light source and can detect flow velocities from $10^{-6}$ to $10^6$ m s$^{-1}$ [23]. A spectrum analyser is used to detect the frequency shift. This forms an extrinsic sensor. At the present time, flow measurement systems based on this principle are not suitable for medical use, because of the requirement for a high degree of optical stability.

Flow may also be measured by exploiting the turbulence that occurs around a cylindrical object (fig. 6). A single fibre is placed across the flow, and small eddies are formed alternately on each side of the fibre (vortex shedding). Each eddy causes a small change in the pressure acting on the side of the fibre, causing it to vibrate laterally at a frequency dependent on the flow velocity. The vibrations result in a small loss of light from the core into the cladding, and the intensity of the light signal thus varies at the same frequency [5]. Sensors of this type may be suitable for use in anaesthetic breathing circuits.

A linear array of optical fibres mounted behind a variable orifice flowmeter may be used to
monitor the position of the float and hence the flow rate. This is a simple technique and is directly applicable to the measurement of fresh gas flow rates in anaesthetic machines.

Optical versions of presently well established indirect techniques such as indicator dilution cardiac output measurement have been tried successfully. The fibres may be inserted down the lumen of a flow-directed catheter and measure the change in ‘colour’ of the blood as the solution used as an indicator is injected \([8, 25]\).

**ADVANTAGES AND DISADVANTAGES OF FIBROPTIC SENSORS**

Typical sizes for some of the sensors described are shown in table I. These sensors are non-conducting, therefore there is no risk of microshock with in vivo probes (and thus no requirement for strict electrical isolation techniques) and no interference from surgical diathermy. Although single optic fibres are fragile, the small bundles usually used in these systems are reasonably robust. In addition, breakage of a few fibres in the bundle is not important in these applications, as the reference signal is affected in the same way as the data. (Breakage of fibres is a problem in endoscopes, as each broken fibre results in a ‘hole’ in the visual image.)

The further development of immobilized enzyme systems may produce sensors capable of measuring in vivo many of the substances now measured using laboratory assay techniques.

Response times for these sensors vary depending on the exact design of the sensor. Physical systems such as the mirror pressure sensor respond in a few milliseconds, whilst some of the chemical sensors may take several minutes to reach 90% response.

There are many technical problems yet to be solved, particularly those associated with biocompatibility and fibrin deposition for in vivo probes, before these sensors become available for widespread routine use \([3, 22]\).

**CONCLUSION**

Fibreoptic sensors for use in clinical measurement are now becoming available commercially. With these new sensors, it is becoming possible to measure, within the body, some chemical concentrations and physical variables of interest to the anaesthetist. These systems may eventually replace many laboratory techniques, but many problems remain before these sensors become reliable for in vivo use.

**APPENDIX**

**GLOSSARY**

*Sensor*: Device giving a signal for detection or measurement of a property to which it responds. In this context, the term sensor is taken to imply all components of the measurement

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Diameter (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure sensor utilizing a plastic under stress</td>
<td>3.7</td>
<td>8</td>
</tr>
<tr>
<td>Mirror system for pressure</td>
<td>5 (approx.)</td>
<td>10</td>
</tr>
<tr>
<td>Fluorescent and other “reagent” type sensors</td>
<td>&lt; 0.6</td>
<td>2</td>
</tr>
<tr>
<td>Thermochromic temperature sensor</td>
<td>1.5</td>
<td>10</td>
</tr>
<tr>
<td>Refractive index temperature sensor</td>
<td>0.8</td>
<td>8</td>
</tr>
<tr>
<td>LASER Doppler flow sensors</td>
<td>&lt; 0.4</td>
<td>Only the tip lies in the vessel</td>
</tr>
</tbody>
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REFERENCES


