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Novel oxygen-enhanced membrane assemblies for biosensors

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Abstract

Many chemical sensors and biosensors rely on chemical, biochemical and electrochemical reactions involving oxygen for the detection of the targeted substance. Due to the usually rapid consumption of oxygen by chemical, biochemical or electrochemical reactions and the low rate of oxygen dissolution, the test sample is often in a state of oxygen depletion during the test. This is particularly true if the rate of chemical, biochemical or electrochemical reactions is relatively high. With the drive to develop sensors having a faster response, i.e. shorter measuring cycle, oxygen depletion became a more serious problem. This research had been aimed at the development of oxygen-enhanced membrane assemblies suitable for use in sensors and other devices. Thus, oxygen-enhanced zeolite molecular sieves were included in the membrane assemblies. The oxygen was pre-adsorbed/entrapped on/into the zeolite. Results have shown that desirable levels of "oxygen-enhancement" were achieved, such that effective sensors could be developed.

Keywords: Membrane; Oxygen-enhancement; Biosensor; Medical diagnostic device; Cholesterol sensor

1. Introduction

Many chemical sensors and biosensors are characterised by their obvious advantages of highly selective detection and rapid response. Detection using such sensors often involves chemical, biochemical or electrochemical reactions that require oxygen [1–4]. Thus, a sufficient supply of oxygen is essential to ensure accurate measurement using such sensors. Scheme 1 demonstrates the mechanism of a typical oxygen-dependent, medical diagnostic biosensor assembly, i.e. the blood cholesterol sensor [5–7].

However, during measurement using most chemical or biochemical sensors, a sufficient supply of oxygen is often difficult to ensure due to the fact that most of these sensors have to be immersed in the sample to be tested. Therefore, the only significant source of oxygen is the oxygen contained in the sample itself. The amount of oxygen dissolving into the sample, during the test process, is often inadequate bearing in mind the amount of oxygen required by the reactions. As a result, "oxygen depletion" has been experienced in many biosensor assemblies [8–12]. Fig. 1 demonstrates a typical reduction in the sensitivity of a cholesterol biosensor, where the response of the biosensor is indicated by the electrical current–time (I–t) integration. Thus, instead of the more desirable linear relationship, a curved relationship between the response of the biosensor and the concentration of the analyte was obtained.

There have been few reports on successful attempts to overcome such oxygen-depletion problems. In this paper are reported the strategies for the development of a membrane-based oxygen-enhancement assembly which could be incorporated into sensor systems. The protocol reported here could also be used in developing oxygen-enhanced membrane systems for applications in other devices or processes.

2. The concepts

It is clear that there is a demand for oxygen-enhancement strategies, particularly for sensor systems. Two aspects of the oxygen-enhancement strategies need to be addressed. First of all, materials having sufficient capacity for carrying adequate amount of oxygen need to be identified. Secondly, techniques have to be developed to attach the oxygen-enhanced materials to the targeted location.

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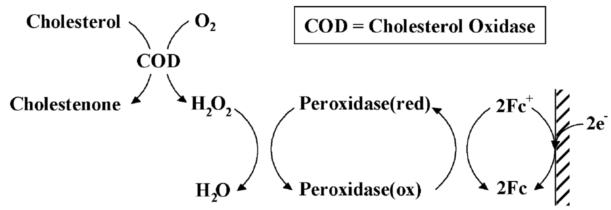


Scheme 1. Mechanism of an enzymatic cholesterol sensor.

2.1. The oxygen carrier materials

Various oxygen carriers, including perfluorocarbons, cobalt salen and zeolite molecular sieves, are available. Each of these is detailed as follows.

2.1.1. Perfluorochemicals

Perfluorochemicals are colourless, odourless, non-toxic and chemically inert organic compounds in which all the hydrogen atoms are substituted by fluorine atoms. The oxygen binding ability of perfluorocarbons had been reported by Mattiasson and Adlercreutz [13] and others [14–19].

Theoretically, for every hydrogen-containing organic compound there is a perfluoro analogue. Because there is little intermolecular attraction, molecular packing in perfluorochemicals is minimal. The loose packing of the molecules allows considerable space into which gas molecules can enter and leave. Thus, gases are readily soluble in many perfluorocarbons. In fact, the oxygen binding capability of the perfluorochemicals is of importance to medical research where the perfluorocarbons are used as substitute for blood. Perfluorocarbons having relatively long carboxyl chains are preferred for the purpose of oxygen entrapment.

2.1.2. Cobalt salen

Co(III) salen, otherwise known as *m*-peroxo bis-[*N*,*N*′-ethylene bis-(salicylideneiminato) cobalt(III)], can react with oxygen under particular conditions, yielding material–oxygen complexes. These oxygen-enhanced complexes deoxygenate under different conditions giving out oxygen easily [20–23].

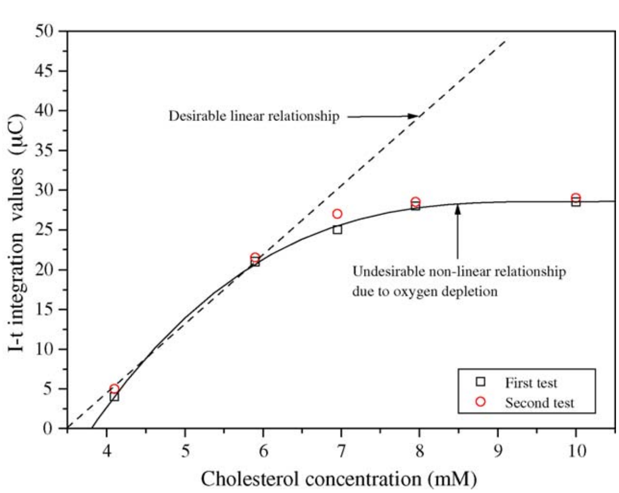
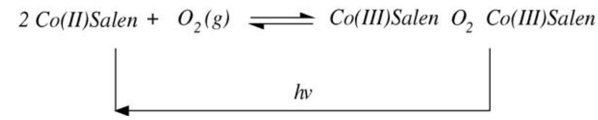


Fig. 1. Typical example of oxygen depletion in cholesterol biosensor.



Scheme 2. Thermal/photochemical equilibrium of oxygenation/deoxygenation of cobalt salen.

This involves the photochemical and thermal decomposition of *m*-peroxo bis-[*N*,*N*′-ethylene bis-(salicylideneiminato) cobalt(III)]. In the presence of *N*,*N*′-dimethylformamide, the *m*-peroxo complex of Co(III) undergoes a thermal equilibrium of oxygenation/deoxygenation at 25–60 °C following the reaction illustrated in Scheme 2, where salen denotes the ligand.

2.1.3. Zeolite

Zeolite has been used within polymer membrane for the purpose of increasing the long-term stability of biosensor assemblies [24]. Thus, zeolite particles within a zeolite–polydimethylsiloxane (PDMS) membrane crosslink with PDMS matrix. As a consequence, leaching of membrane components during the exposure to surfactants was prevented, thus prolonging the shelf-life of the biosensor–membrane assembly.

Zeolites have also been used in membrane assemblies for separation liquids and gases [25–27].

Many zeolite molecular sieves possess the ability to adsorb and release oxygen under different pressures. Therefore, zeolite molecular sieves become good candidates as oxygen carriers. The advantages of using molecular sieves as gas carriers, particularly oxygen carriers/enhancers are:

(i) There is a wide range of molecular sieves covering specific pore sizes. In fact, specific molecular sieves can be selected for carrying oxygen.
(ii) Most of the molecular sieves are strongly water-adsorptive when they are exposed to aqueous solutions. Therefore, the water included in the test sample can replace the oxygen adsorbed in the molecular sieve, thus releasing the oxygen into the test sample.

Zeolite molecular sieve type 4A was considered suitable for the intended oxygen-enhancement purpose. This was because zeolite molecular sieve 4A has cages with the diameters of the free apertures of about 4×10^{-2} μm that allow the oxygen molecules, whose size is about 3×10^{-2} μm in diameter, to diffuse in and out.

2.2. The carriers for oxygen-enhanced materials

As pointed out earlier, in order to fulfil the purpose of supplying oxygen to sensor systems, oxygen carriers need to be present in the vicinity of the location where chemical or biochemical reactions take place. It was considered that a more appropriate approach to achieving this would be to incorporate the oxygen carrier into polymeric membrane assemblies. In fact, many chemical sensors or biochemical sensors require polymeric membranes for separation of the interfering components from the test sample [28].