KINETICS OF ISOBARIC COUNTERDIFFUSION

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Isobaric inert gas counterdiffusion has been demonstrated to produce gas lesions in man (Lambertsen and Idicula, 1975) and lethal gas embolism in animals (Lambertsen, Cunnington and Cowley, 1975). Equations have been derived for the stable-state supersaturation pressures developing at interfaces during inert gas counterdiffusion (Graves et al., 1973). The present analysis is a mathematical treatment of the kinetics of the isobaric counterdiffusion of a pair of gases through a membrane consisting of two layers composed of substances with different diffusion coefficients and solubilities for each of the gases involved. The time to reach the stable supersaturation state due to isobaric counterdiffusion, even when circulatory transport and pulmonary washout times are included, is found to be at least an order of magnitude smaller than the time required for visible bubble formation and tissue distortion.

Introduction. Recently Lambertsen and Idicula (1975) identified a new gas bubble lesion disease in man, occurring at increased ambient pressures during the breathing of nitrogen or neon-oxygen mixtures while the individuals were surrounded with helium. Since no decrease of ambient pressure preceded the development of urticaria and skin lesions, and the circumstances led to dermal gas lesions at a stable ambient pressure, the phenomenon was designated the "isobaric inert gas counterdiffusion syndrome." This phenomenon has been found capable of inducing lethal venous gas embolization (Lambertsen, Cunnington and Cowley, 1975).

Analysis of this phenomenon in its stable-state form has been carried out by Graves et al. (1973). They substantiated the concept that counterdiffusion of gases through substances or membranes could lead to gas supersaturation, under isobaric conditions, at interfaces between substances having different physicochemical characteristics relating to gas solubility and diffusivity (Graves et al., 1973). It is therefore considered that such supersaturation, in the
presence of gas nuclei, leads to the observed formation and growth of bubbles in tissues, accounts for the gas lesions observed in man and the embolization observed in animals.

Development of the symptoms of urticaria and the actual appearance of cutaneous lesions occur only after a period of sustained counterdiffusion. This period may exceed one hour, even at the ambient pressures of 10 to nearly 40 atm where the phenomena were identified (Lambertsen and Idicula, 1975).

The purpose of this paper is to provide the means to examine mathematically the kinetics of isobaric gas counterdiffusion during transient, non-stable-state conditions. The analysis does not pertain to the development of actual lesions in an individual but to development of supersaturation at discrete membranes. The method permits prediction and quantitative comparison of the time courses for the development of supersaturation with gases of varying characteristics and for membranes of specifiable composition.

\[ \text{Interface} \]

\[ \text{Layer A} \]

\[ \text{Layer B} \]

\[ \Delta X_A \]

\[ \Delta X_B \]

\[ \text{Gas 1} \]

\[ \text{Gas 2} \]

Figure 1. Circumstances of isobaric gas counterdiffusion. The thickness of lipid layer A is $\Delta X_A$, that of aqueous layer B is $\Delta X_B$. At uniform ambient pressure gases diffusing in opposite directions through the layers of the composite membrane develop supersaturated states within the membrane, leading to bubble formation.

**Approach.** The analysis of kinetics for isobaric counterdiffusion extends directly from the stable-state analysis derived by Graves et al. (1973). Components of these analyses are illustrated in Figure 1. The example includes:

1. A lipid-containing membrane having adjacent layers of differing composition, interfacing with gas-permeable structures such as dermis or capillaries. In Figure 1 these adjacent layers are designated Layer A and Layer B.

2. Two different gases counterdiffusing through this two-layer system. These are designated Gas 1 and Gas 2.