

Editorial I

Fifty years after—reflections on 'The elimination of rebreathing in various semi-closed anaesthetic systems'

Soon after I joined the Anaesthetics Department of the University of Wales College of Medicine in Cardiff as an assistant lecturer in 1952, William Mushin, the founding Head of Department, drew out five 'semi-closed' breathing systems and asked me to see if I could work out what conditions were required to eliminate rebreathing in each one. I needed some means of distinguishing between the systems so I labelled them A, B, C, D, E (Fig. 1). The resulting analysis was published in the *British Journal of Anaesthesia* in 1954¹ in the September issue—exactly 50 years ago.

I regarded that paper as just a minor piece of theoretical work to keep me occupied while waiting for volunteers for my main experimental project.² Accordingly, I was astonished when, just one year later, at a meeting of the Anaesthetics Section of the Royal Society of Medicine on December 2 1955,³ I heard the systems being referred to as the 'Mapleson A', 'Mapleson B' and so on. Dr Bracken even 'found the nomenclature... particularly useful'. System A is known as the Magill attachment, although Sir Ivan Magill has stated that he 'never published a description' of the 'so-called "Magill attachment"'.⁴ So I here apologize, posthumously, to him—and to Dr Jackson Rees (whose modification⁵ of Ayre's T-piece⁶ is similar to System D) for not giving due acknowledgement at the time. However, for internal consistency, I will here continue to use A, B, C, D, E.

So how did I set about my task? I wanted a more general analysis than that of System A by Molyneux and Pask⁷ and the subsequent comment by Domaigne,⁸ so I just sat down with a pad of paper and worked things out from first principles. I set out five idealizing assumptions and then applied logic and algebra to deduce the minimum fresh-gas flow to eliminate rebreathing: System A, alveolar ventilation; Systems B and C, 'appreciably more than the alveolar ventilation' (applying an I/E ratio of 1/1.5 to the relevant equation implies approximately twice the alveolar ventilation); and Systems D and E, twice the total ventilation (assuming a short expiratory pause).

However, as a non-clinical tiro in anaesthetics, I was anxious not to recommend anything that might be harmful to the patient. Accordingly, I then examined in a qualitative fashion the likely effects, in each system, of deviations from

the assumptions. In Systems A, B and C, the main concern was the assumption of 'plug flow'—no longitudinal mixing of gases in the trachea, face mask or corrugated tube. Guessing at the degree of mixing that would necessarily occur led me to conclude that the fresh-gas flow required to 'almost completely eliminate rebreathing' would be total ventilation for System A, and twice the total ventilation for Systems B and C. Longitudinal mixing was largely irrelevant to Systems D and E and the only qualification was that the waveform of the inspiratory flow should not be too 'peaky'.

How have these conclusions stood the test of time? First, two limitations: (i) the analysis related solely to spontaneous ventilation; (ii) very little was said about the waveform of respiratory flow.

It was Sykes⁹ who first showed that System A was much less efficient during controlled ventilation than with spontaneous ventilation. It was Denys Waters who drew this to my attention, so we investigated all the systems except E, in theory and with a cross-over study in six patients, during manual controlled ventilation.¹⁰ We found that, although rebreathing occurred, with fresh-gas flow and total ventilation both set to just 8 litre min⁻¹, the mean end-expired carbon dioxide concentration was a creditable 5% (about 4.2% for B, C and D).

With regard to waveform, assumption 2 was, 'At the start of inspiration the flow into the lungs rises instantaneously to some value greater than the fresh-gas flow. No other assumption need be made as to the nature of the breathing pattern'. However, except for System A, I had to add caveats. For B and C, I stated, 'unless some assumption is made as to the form of the expiratory flow curve, T' is indeterminate', where T' is the time during which, with plug flow, only dead-space gas is expired. With System D, I acknowledged that the duration of the expiratory pause came into the equation for rebreathing but dismissed it as 'rarely more than a small fraction of the respiratory period'. At that time, I was not aware of the long expiratory pauses that can occur with heavy sedation.

Thus my equations might help the reader to work out the likely effects of unusual waveforms of respiratory flow but

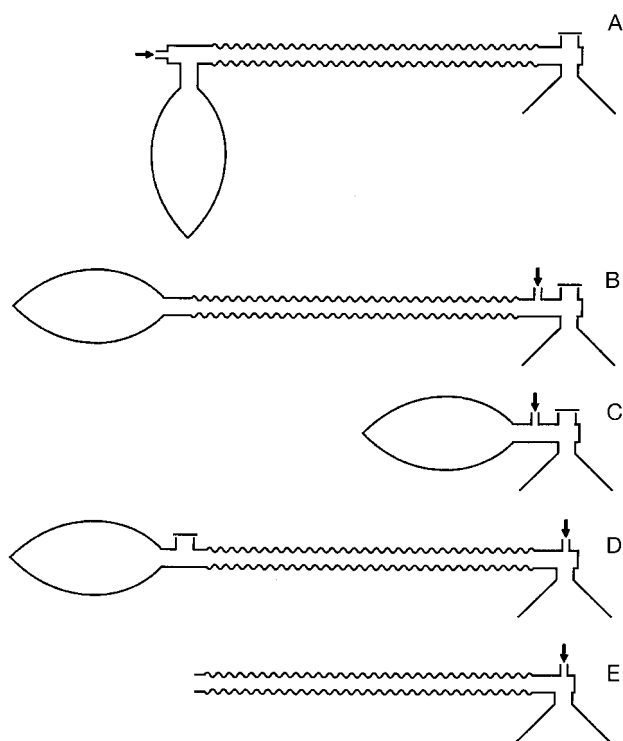


Fig 1 The five semi-closed anaesthetic breathing systems

did not explore them. Much the same could be said of Dorrington's extremely elegant graphical analysis.^{11 12} the reader can apply it to any waveform, and he acknowledges that a long expiratory pause with a slow respiratory frequency would improve the performance of System D and make it better than System C—but adds 'conditions which do not normally prevail during anaesthesia'. It fell to Cook¹³ to explore, with a painstaking mathematical analysis, how lengthening the expiratory pause for a given respiratory frequency and tidal volume has no effect on System A but makes System D more efficient, while System C becomes less efficient, ultimately less efficient than System D.

All these theoretical studies assume plug flow. Subject to that limitation, Dorrington's graphical method permits an 'exact' solution for any waveform that can be precisely specified. But that leaves the important effect of longitudinal mixing; I do not think anyone has tackled that theoretically. The first experimental analysis, by Woolmer and Lind,¹⁴ was published in the *British Journal of Anaesthesia* as the paper immediately preceding my theoretical analysis. The results from their cleverly designed lung model, which probably produced approximately sine-wave flow, can be interpreted as follows. In System A, with the fresh-gas flow equal to the alveolar ventilation, there was 8% rebreathing; 2.5% with it equal to the total ventilation. These figures suggest that the freehand curve that I added to my graph of percentage rebreathing against fresh-gas flow as a guess at the effect of longitudinal mixing was a little pessimistic: 12% and 5% instead of 8% and 2.5%.

It was a long wait for any detailed studies in human subjects and then two came along at once. On 6 January 1967, Kain and Nunn presented to the Section of Anaesthetics of the Royal Society of Medicine a study in anaesthetized patients breathing spontaneously through System A. On 31 March in the same year, Norman, Adams and Sykes presented a similar study in conscious subjects to the Anaesthetic Research Group (now Anaesthetic Research Society). Definitive versions of both studies^{15 16} found that, to induce rebreathing, the fresh-gas flow had to be reduced to less than 70% of the total ventilation, just about to less than the alveolar ventilation.

Onset of rebreathing depends very much on the definition used. Kain and Nunn's definition, slightly simplified, was: total ventilation increased by 10% or more, *or* end-expired carbon dioxide increased by 5 mm Hg (also about 10%) or more, *or* a bit of each. Norman, Adams and Sykes' definition was roughly similar. When rebreathing is defined in terms of the inspired concentration of carbon dioxide, its 'presence' depends very much on the exact definition of inspired concentration: if it is 'minimum carbon dioxide greater than 0.2%', rebreathing may not be detected until the fresh-gas flow has been reduced to 50% of the total ventilation; whereas if it is 'carbon dioxide zero throughout the inspiratory phase', or at least for that part of the inspired tidal volume that is destined to reach the alveoli, the answer may be 90% of total ventilation – even more in Woolmer and Lind's experimental study.¹⁴ Therefore, Kain and Nunn's practical clinical definition seems to imply that a fresh-gas flow equal to alveolar ventilation will cause no more than a clinically acceptable degree of rebreathing. It is on this basis that I have been accused of causing a great wastage of fresh gas by my cautious recommendation to use a flow at least equal to the total ventilation.

It was five breathing systems that Mushin drew for me; again it was Denys Waters who prompted me with 'What other systems are there?' It is an interesting exercise to draw on separate pieces of paper (or pieces of overhead transparency for teaching) the five components of Systems A–E: fresh-gas supply, bag, corrugated tube, expiratory valve and face mask or tracheal tube, and then manipulate them to see what systems can be constructed. It turns out that, apart from two absurdities with huge amounts of dead space, A–E are the only possible systems using one of each component.

So why did I later call the Jackson Rees' modification of Ayre's T-piece, System F?¹⁷ I now regret doing so because I think that it is better to regard System F as a variant of System D: a leak instead of a spill valve. Miller's 'preferential flow' system¹⁸ is a somewhat similar, but more sophisticated, modification of System A. To avoid pollution of the theatre atmosphere, Danish anaesthetists invented a complete set of modified Systems A–D: the 'Hafnia' systems¹⁹—Hafnia was the Roman name for Copenhagen. In each of these systems, the spill valve was replaced by a steady flow of suction which had to be matched to the fresh-gas flow. All the above systems are recognizably variants on the original A–D systems, even though performances may sometimes be different.

On the other hand, the Lack and the Bain Systems, which are coaxial Systems A and D respectively, behave very much as their progenitors but appear to be very different: both have the fresh-gas supply and the expiratory valve physically at the bag end of the system.

I am often credited with ‘classifying’ Systems A–E, but that is not so: I provided a nomenclature; it was Donald Miller²⁰ who classified them into afferent-reservoir systems, where the reservoir (bag or open-ended limb) branches off the afferent or inspiratory pathway (A, also B and C as originally drawn, see Figure 1) and efferent-reservoir systems, where the reservoir branches off the efferent or expiratory limb (D, also B and C if the positions of the fresh-gas flow and spill valve are interchanged).

If I were writing the paper today, would I use the same approach? I would certainly put any mathematics in an appendix. I learnt that lesson when I proudly showed my first major reprint in anaesthetics to a medical student whom I knew personally through our mutual interest in amateur theatre: he looked at the title page with curiosity, turned it over, said ‘Oh, maths’ and lost all interest. But for teaching, I have long used animated overhead transparencies so that the student can ‘see’ what is happening, and I am now incorporating these into teaching videos.

At the time of completing my analysis, the anaesthetic machines in the Cardiff Royal Infirmary had all been changed from System A to System B on the basis that, ‘If you want the patient to breathe fresh gas then surely you should put it in near the patient’. The first practical effect of my work in anaesthetics was that all the machines were changed back to System A.

It was very generous of Mushin to give me sole authorship of the paper: he posed the question and encouraged me to solve it, which some senior academics would see as justification for co-authorship. If it had been Mushin and Mapleson, or even Mapleson and Mushin, I wonder if the systems would have become known as the Mushin and Mapleson A and so on—it does not trip off the tongue so readily. Certainly I would not have become so well known in anaesthetics, or at least not for much longer.

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