SOME OBSERVATIONS ON NITROUS OXIDE CYLINDERS DURING EMPTYING

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SUMMARY
In an effort to correct misunderstandings and to establish the value of nitrous oxide pressure monitors on anaesthetic machines, the decrease of pressure within nitrous oxide cylinders has been studied under a variety of clinical conditions. Although the matter had been clarified by 1946, the teaching of several current anaesthetic textbooks is still fallacious since an almost linear fall in cylinder pressure under constant flow conditions has been demonstrated. In addition, premature failure of nitrous oxide cylinder pressure due to cooling of the liquid contents has been noted. The value of cylinder pressure monitors is discussed in the light of these findings.

Many anaesthetic machines in Britain are not equipped with pressure gauges for registering nitrous oxide (N₂O) cylinder pressure. Consequently, patients receiving anaesthetics in which N₂O is largely responsible for unconsciousness run the risk of awareness when the cylinder approaches exhaustion. The absence of pressure gauges appears to stem from a widely held misunderstanding concerning the pressure changes within N₂O cylinders during use. The present study was undertaken to clarify this situation and to investigate the feasibility of providing a warning device for use with N₂O cylinders.

It is well recognized that the relationship between a N₂O cylinder pressure and the contents hinges upon the fact that N₂O may be present in both liquid and gaseous phases at normal ambient temperature. Texts related to anaesthesia still mistakenly indicate that when a cylinder of N₂O is drained at a constant gas flow rate, the pressure within the cylinder is kept constant by vaporization of the liquid. When the last drop of liquid has evaporated, the pressure then falls linearly in a manner consistent with Boyle’s law. It was in 1946 that Macintosh and Mushin first indicated the fallacy of this teaching in an account of an experiment conducted upon a 900-l. cylinder which was emptied at a constant rate of 8 l./min. They found that the pressure in the cylinder decreased progressively throughout the period of emptying despite the presence of liquid N₂O. Furthermore, they demonstrated that, if liquid remained in the cylinder, the pressure would eventually increase again to its original level when the cylinder was allowed to rewarm after discontinuing the flow of gas. These authors pointed out that this is because of the effect of temperature upon the vapour pressure of liquid N₂O. Nevertheless, several authors have perpetuated the original erroneous interpretation (Minnitt and Gillies, 1948; Wylie and Churchill-Davidson, 1972; Lee and Atkinson, 1973). Hill (1972) makes the same assertion, even though he provides evidence which clearly supports the teaching of Macintosh and Mushin. Indeed, his contention can only be true for a cylinder emptied infinitely slowly. Macintosh and Mushin, on the other hand, had used a high flow with a small cylinder, thereby possibly exaggerating the effect of cooling. The experiments described below were designed to establish the relevance of their work to present-day clinical practice.

Experimental method.
Standard 900 and 1,800-l. pin index, N₂O cylinders (British Oxygen Co. Ltd) were connected to a suitable yoke on an anaesthetic machine. The cylinder pressure was recorded using a calibrated Bourdon pressure gauge (0-1000 Lb/sq.in.). A continuous record of pressure was made by connecting a low-torque rotation transducer to the needle spindle of the Bourdon gauge, the electrical output being continuously recorded on a potentiometric chart recorder. The cylinder was connected via a 60 Lb/sq.in. (42 KN/m²) reducing valve to a flowmeter and needle valve. This permitted flow of up to 10 l./min to be controlled. Weighed cylinders were allowed to come into thermal equilibrium with...
room air and were then emptied at a constant flow rate in an ambient temperature of between 20 and 23 °C until the pressure in the cylinders had decreased to 60 Lb/sq.in. Each cylinder was then turned off, warmed to room temperature in a water bath, and re-weighed to establish the amount of nitrous oxide remaining. It was then re-connected to the anaesthetic machine and allowed to run at the original gas flow once more until it was finally empty. In all, four 1800-l. cylinders and four 900-l. cylinders were tested, one of each being tested at flow rates of 2, 4, 8 and 10 l./min. In addition, the development of frost upon the cylinder walls was noted and recorded.

RESULTS

Cylinder pressure recordings.
The cylinder pressure tracings for 900-l. cylinders are summarized in figures 1 and 2 and those for 1800-l. cylinders in figures 3 and 4. The horizontal axis in figures 1 and 3 represents litres delivered. For comparison, time forms the horizontal axis in figures 2 and 4. The former correlation makes for more convenient comparison though, of course, the latter is more relevant clinically. In all cases, a progressive fall in pressure accompanied the release of gas from the cylinder at constant flow. The rate at which the pressure declined (i.e. the slope of the curve) was related to the flow rate. Flows of 10, 6, and 4 l./min from both 1800- and 900-l. cylinders lead to premature failure of the pressure and in these cases re-warming enabled a further volume of gas to be delivered. Only at a flow rate of 2 l./min did the cylinders not fail prematurely, and even at this flow, the moment of vaporization of the “last drop” of liquid N₂O was not clearly defined by a sharp change in slope.

The development of surface frost.
Frost developed on the outside surface of all the cylinders during the initial decompression. This was not related to the state of emptiness of the cylinders or to the duration of operation. Generally it developed below a demarcation line situated approximately half-way down the cylinder when the pressure within the cylinder reached approximately 300 Lb/sq.in. Once this line was established, the frost level did not fall more than 2 cm before the cylinder failed, though the thickness of the ice layer did increase.

When those cylinders which had failed prematurely were inverted immediately after disconnection from the yoke, a tinkling sound was audible and the neck of the cylinder immediately became extremely cold. Frost promptly formed on the neck in these circumstances (see figs. 5A, B). It was originally intended to allow cylinders to re-warm at ambient temperature whilst attached to the anaesthetic machine. However, it was found that re-warming was incomplete after 6 hours with the cylinder valve closed and re-warming in a water bath which had been brought to ambient temperature was undertaken.
FIG. 5. The effect of inversion of a frosted cylinder which contains residual liquid N₂O. (A) Cylinder immediately after removal from the anaesthetic machine; (b) 1 minute after inversion. Note the development of frost around the neck of the cylinder.

**DISCUSSION**

From the evidence it is clear that, under clinical circumstances, the pressure within N₂O cylinders does not remain constant. On the contrary, particularly at high flow rates, an almost linear decline in pressure occurs. This is the result of a progressive decrease in temperature within the cylinder. The relationship between the vapour pressure of nitrous oxide and temperature in the presence of liquid N₂O is indicated in figure 6 which is taken from data published by Couch and Kobe (1961). Using the vapour pressure curve, the change in temperature that occurred in the 1800-l. cylinder which had been emptied at 6 l./min has been extrapolated (fig. 7) and indicates that there is an increase in the rate of fall of temperature with time. The explanation for this depends upon several factors:

1. The latent heat of vaporization (which is the sole reason for heat consumption within the cylinder) increases as the temperature decreases. Thus, as the rate of vaporization is kept constant, so the rate of heat consumption increases.

2. The first source of heat for this increase in consumption is derived from the thermal inertia of the liquid N₂O itself. However, as the liquid evaporates, so this source of heat decreases resulting in a further acceleration in the rate of decline of temperature.
(3) As the cylinder cools it absorbs heat from its environment: the greater the temperature differential the more rapidly the heat is absorbed. This tends to limit the acceleration in decline of temperature and accounts for the difference in pattern between rapidly and slowly emptied cylinders.

(4) Ice formation on the cylinder wall further complicates the situation. Its formation can occur only after the temperature of the cylinder has decreased below zero degrees centigrade thus implying that the pressure within the cylinder has decreased below 300 lb per sq. inch in the presence of liquid N₂O. Thereafter, as ice forms, latent heat of formation of ice is delivered to the vaporizing N₂O. However, the increasing thickness of the ice and snow layer acts as an insulator which limits the further transfer of heat from the environment.

Warning of cylinder failure.

Failure of the N₂O gas flow during anaesthesia may have two consequences. In those anaesthetic techniques where it is of major significance in maintaining unconsciousness, as in neuroleptanaesthesia, temporary discontinuation of that gas might result in awareness. Of perhaps greater physiological significance is the influence of the total fresh gas flow rate upon the degree of re-breathing with some anaesthetic systems. Unnoticed failure of a N₂O cylinder could reduce the fresh gas flow by 70%. The hypercapnia, which would ensue if this situation was to pass unheeded, could lead to serious consequences.

Notwithstanding these considerations, a committee of the Ministry of Health set up to discuss warning devices and contents gauges for anaesthetic machines, did not consider it necessary to provide warning devices for N₂O cylinders (Hospital Technical Memorandum No. 15, 1965). In view of the fact that N₂O cylinder failure does sometimes temporarily pass unnoticed, and that this is occasionally associated with the hazards detailed above, it seems imprudent not to adopt some form of system which gives warning of the failure of gas delivery from a N₂O cylinder.

Though it is true that the pressure within a N₂O cylinder gives no indication of its total contents, this does not constitute an adequate indication for discarding pressure monitoring. In practice, these cylinders fail (i.e. achieve an internal pressure below that which is necessary to maintain a constant pressure to the needle valves) for two reasons: either because the liquid N₂O has become too cold; or because the cylinder is empty. In both instances, cylinder pressure will give the most reliable warning of failure.

The development of frost on a cylinder gives no indication of impending failure since it is purely temperature dependent and merely indicates, at the time of its development, that there is residual liquid N₂O present and that the pressure within the cylinder is below 300 Lb/sq.in. This situation may occur when a cylinder is still half full if high gas flow rates are employed. Alternatively, it may never develop at all if the emptying of the cylinder is interrupted by re-warming intervals. Although the simple test of inversion of a frosted failed N₂O cylinder will give some indication of whether liquid N₂O remains within it (fig 5A,B), the only reliable, convenient method of establishing the contents of a cylinder, is to compare its weight with the tare weight stamped on the neck of the pin index valve body, taking care to ensure that ice remaining on the cylinder wall does not falsify the readings.

Conventional N₂O cylinder pressure gauges are unsatisfactory for giving advance warning of failure for a number of reasons. Firstly, since N₂O cylinders may occasionally achieve temperatures in storage exceeding 65°C, pressures exceeding 2575 Lb/sq.in. might be encountered. Conventional gauges capable of withstanding such pressures are calibrated to 3000 Lb/sq.in. Under normal conditions of temperature such a gauge would be registering only quarter full-scale for a full cylinder, and the measurement of 70 or 80 Lb/sq.in. as an indication of impending cylinder failure is unlikely to be achieved with any degree of accuracy. Furthermore, such a system requires constant attention. It would appear that the most satisfactory warning system would be some form of pressure sensitive device introduced into the circuit and operating an audible alarm. Such a device sited between the cylinder and the reducing valve must be capable of withstanding pressures exceeding 2000 Lb/sq.in. and, possibly, temperatures as low as —60 or —70°C (depending on its precise location) yet be sufficiently sensitive to respond to a pressure difference of only a few Lb/sq.in. In addition, one would have to be provided for each cylinder yoke.

A pressure sensitive device operating at slightly below the reducing valve pressure and located between it and the flowmeter block, designed to operate some form of audible warning device and powered by the pressure remaining in the N₂O cylinder would constitute the most practicable sys-
tem. Such a device, the Ritchie Whistle, is available at moderate cost (Longworth Scientific Instruments Ltd), and is readily fitted to anaesthetic machines which are designed to operate at 35–60 Lb/sq.in.

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