REVIEW ARTICLE

LOW FLOW ANAESTHESIA

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ABSTRACT: Modern inhalational anaesthetic agents are metabolized to a small extent only and are largely exhaled unchanged. The use of closed system with carbon dioxide absorption units and comprehensive gas monitoring permits the exploitation of this to perform economical and safe 'low-flow anaesthesia'. Modern equipment permits the further reduction of the carrier gas flow to the ultimate degree of providing the patient's requirements. This article describes the principles of Low flow anaesthesia, its advantages & disadvantages.
KEYWORDS: Low flow anaesthesia, closed system anaesthesia, inhalational anaesthetics.

INTRODUCTION: Low flow anesthesia is defined to be an inhalation anesthetic technique via a rebreathing system in which the rebreathing fraction at least amounts to 50%, i.e. 50% of the exhaled gas volume is led back to the patient after carbon dioxide absorption in the next inspiration.[1]

It is carried out with a fresh gas flow rate which is significantly lower than the minute volume. When such low FGF are used, the anaesthetic gases must be conducted to the patient via semi closed or even closed rebreathing systems. The rebreathing fraction increases with the reduction of the FGF whereas the volume of excess gas decreases.

In Low Flow Anaesthesia the FGF rate is reduced to 1L/min, in Minimal Flow Anaesthesia to 0.5L/min & in metabolic flow to 0.25L/min[2].

UPTAKE OF OXYGEN, NITROUS OXIDE & INHALATIONAL AGENTS:

Oxygen Uptake: It corresponds to approximately BMR & during anesthesia oxygen consumption can be regarded as virtually constant. It can be calculated using Brody's formula[3]:

$$\mathbf{VO2 = 10 \times BW\ [kg]^{3/4}\ [mL/min]}$$

However, for clinical purposes, oxygen consumption can be calculated as:

$$\mathbf{VO2 = 3.5 \times BW\ [ml/min]}$$

Uptake of nitrous oxide: The uptake is high at the beginning of anaesthesia but it becomes less in the course of time with increased saturation of the tissue with gas. It is calculated using Severinghaus's formula[4]:

$\mathbf{VN_2O = 1000\ t^{-1/2}\ [ml/min],}$ where t is the time since induction.

Uptake of inhalational agents: During anesthesia the uptake of volatile agents decreases as a function of tissue saturation. Can be calculated using Lowe's formula[5]:

$$\mathbf{Van = f * MAC * \lambda_{B/G} * Q * t^{-1/2}\ ml/min}$$

f = factor that defines the inhalation concentration that is sufficient for unresponsive skin incision at ~MAC $_{1.3}$

$\lambda_{B/G}$ = blood/gas partition coefficient

Q = cardiac output

t = time

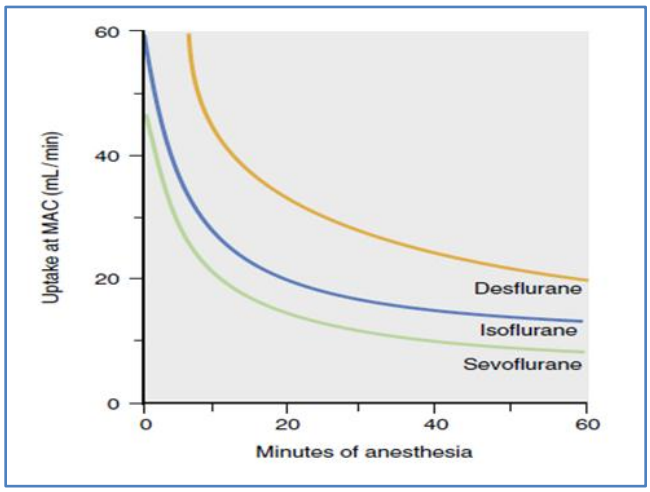

Fig. 1: Uptake of volatile anesthetic agents

CHARACTERISTICS OF LOW FRESH GAS FLOW TECHNIQUES: A gas flow in excess of the minute volume will provide readily predictable inspired gas concentrations, which will be more or less the same for any patient, using any breathing system, at any stage of the anesthetic and will be unaffected by agent uptake by the patient. However, as the carrier gas flow is reduced and rebreathing fraction is increased, gas uptake by the patient will affect the exhaled and the inspired gas mixture. Once the flow rate is reduced to near the patient's requirements, the fresh gas mixture will closely reflect the uptake of each of its components by the patient. These techniques are critically dependent on gas monitoring. This shift towards a quantitative concept of gas delivery is the fundamental defining feature of low-flow techniques[6].

TECHNICAL REQUIREMENTS:

1. Circle rebreathing system with CO_2 absorption
2. Accurate flow meters calibrated to flows down to 50 ml/min.
3. Gas tight breathing system. Recommended test leakage should be below 150 mL/min at 30 cm H_2O test pressure. These techniques are not applicable to mask anesthesia, but practicable with a well-fitting laryngeal mask.[6]
4. Calibrated Vaporizers capable of delivering high concentrations and that are accurate at low FGF are required.
5. The breathing system should have **minimal internal volume** and a minimum number of components and connections.

6. Continuous gas monitoring. The measurement of expiratory gas concentrations close to the Y-piece is of crucial importance. That information is essential in controlling the patient's alveolar gas concentrations.

MONITORS[1, 8, 9]

- Continuous measurement of oxygen concentration is mandatory.
- EtCO2 monitoring to ensure proper functioning of the absorber.
- Monitoring of end tidal anesthetic concentration.

SETTING OF THE ALARMS[9]

- The lower alarm of the inspiratory oxygen concentration should be set between 28% and 30%.
- Minute volume monitoring: lower alarm limit 0.5 L/min below nominal value
- Inspired volatile anesthetic concentration: Upper alarm limit for halothane, enflurane and isoflurane: 2.5 vol% sevoflurane: 3.5 vol% & desflurane: 8.0 vol%
- Disconnect alarm: lower alarm limit 5mbar below peak pressure

TECHNIQUES OF LOW FLOW ANESTHESIA: Premedication, pre-oxygenation and induction of sleep are performed according to the usual practice. Concerning adjustment of FGF anaesthesia can be divided into 3 phases:

1. Initiation of low flow anaesthesia.
2. Maintenance of low flow anaesthesia.
3. Recovery

INITIATION: Primary aim at the start of low flow anesthesia is to achieve an alveolar concentration of the anesthetic agent that is adequate for producing surgical anesthesia (approximately 1.3 MAC). The factors that can influence the buildup of alveolar concentration are classified into;

1) Factors governing the inhaled tension of the anesthetic.
2) Factors responsible for rise in alveolar tension.
3) Factors responsible for uptake from the lungs thus reducing the alveolar tension.

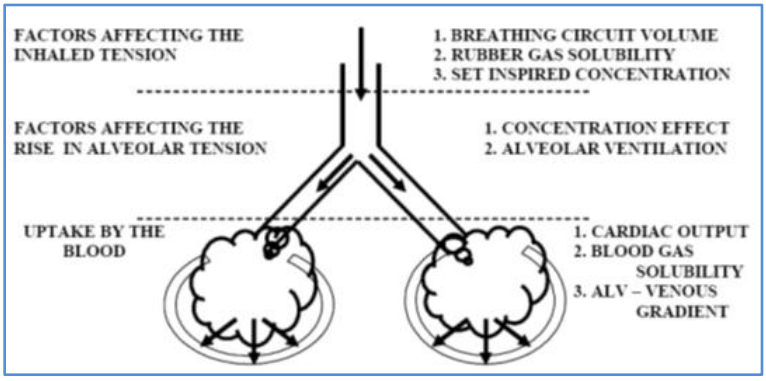

Fig. 2: Factors affecting the buildup of alveolar tension

Methods to achieve desired gas and agent concentration:

1. **Use of high flows for a short time/ loading:** This is the commonest and most effective technique of initiating closed circuit. By using high flows for a short time, the time constant is reduced thereby bringing the circuit concentration to the desired concentration rapidly. Often, a fresh gas flow of 10L of the desired gas concentration and 2 MAC agent concentration is used so that by the end of 3mins (three time constants) the circuit would be brought to the desired concentration. They also compensate for the large uptake seen at the start of the anesthesia. The advantages are the rapid achievement of desired concentration, prevention of unexpected raise in the agent concentration, better de nitrogenation & the ability to use the commonly available plenum vaporizers to achieve the desired concentration. The disadvantage is compromise on the economy of the gas utilization and the need for scavenging systems to prevent theatre pollution.

2. **Prefilled circuit:** The second method is utilizing a different circuit like Magill's for pre oxygenation. Simultaneously, the circle is fitted with a test lung and the entire circuit is filled with the gas mixture of the desired concentration. Following intubation, the patient is connected to the circuit thereby ensuring rapid achievement of the desired concentration in the circuit.

3. **Use of large doses of anesthetic agents:** Large amounts of anesthetic agent are added into the circuit so that the circuit volume + FRC rapidly achieve the desired concentration as well as compensate for the initial large anesthetic gas uptake. The patient is connected to the circuit, filled with oxygen (used for pre oxygenation), after intubation. FGF is started with metabolic flows of oxygen and a large amount of nitrous oxide in the range of 3-5L/min. Oxygen concentration in the circuit, which gradually falls, is continuously monitored and the nitrous oxide flow is reduced once the desired oxygen concentration is achieved (33 - 40%). The disadvantage is the potential for errors and hypoxia if the oxygen monitor were to malfunction. Hence this method is seldom used for N2O.

   This method is often used to build up the agent concentration in the circuit. It involves setting the VOC to deliver a large amount of the agent while using low to moderate flows so that the required amount of vapor is added into the circuit. The usual requirement of anesthetic agent is approximately 400 - 500 ml of vapor in the first 10 minutes i.e. 40 - 50 ml/min. Most of the vaporizers allow a maximal concentration of 5% to be delivered. At a setting 5% in the vaporizer, with a FGF of 1L/min, the required mass of 500 ml of vapor could be added to the circuit so that the alveolar concentration could be built up. The setting in the vaporizer can be brought down to 0.5 –0.8 % after 10 minutes and titrated according to the surgical needs.

4. **Injection techniques[10-14]:** An alternative method for administering the large amounts of the agents is by directly injecting the agent into the circuit. This is an old, time-tested method and is extremely reliable.

At 20° C, 1ml halothane yields 226ml of vapors & 1ml Isoflurane yields 196ml. The requirement of about 2ml of the agent is injected in small increments into the circuit. The high volatility coupled with the high temperature in the circle results in instantaneous vaporization of the agent. Anesthetic liquid can be injected directly into the expiratory limb. The injection is made using a small bore needle and a glass syringe. Placing a gauze piece or a wire mesh inside the T piece often helps in the vaporization of the liquid. The intermittent injections are often made in 0.2-0.5 ml aliquots manually. Doses should never exceed 1ml at a time. Doses exceeding 2 ml bolus invite disaster. Intermittent injections can often be easily substituted with a continuous infusion with the added advantage of doing away with the peaks and troughs associated with intermittent injections.

Accurate dose is calculated using the formula:

Priming dose (ml vapor) = Desired concentration x {(FRC + Circuit volume) + (Cardiac output x blood-gas coefficient)

THE MAINTENANCE OF LOW FLOW ANESTHESIA: This is the most important phase as financial savings result directly from this, since it is stretched over a period. It is characterized by:

1. Need for a steady alveolar concentration of respiratory gases.
2. Minimal uptake of the anesthetic agents by the body.
3. Need to small amounts of the anesthetic gases to match the uptake and providing oxygen for the basal metabolism should suffice. In Closed circuit anesthesia, this would be directly equal to the uptake. In low flow anesthesia, the amount of gas which is vented is also added to the circuit to maintain steady state anesthesia.

Oxygen and nitrous oxide flow during the maintenance phase: Oxygen is taken up from the lungs at a constant rate of about 4 ml/kg/min. There is a constant removal of O2 at a rate of 200 - 250 ml/min, whereas the insoluble gas N2O uptake is minimal. Hence, the gas that is partly vented and partly returning to the circuit will have more N2O and less of O2. Over a period of time, due to the mixing of fresh gas that has 66% N2O and the expired CO2 with much higher N2O, the percentage of N2O will go up and that of O2 will fall, sometimes dangerously to produce hypoxic mixtures. In the absence of oxygen analyzer, it is safe to use a high flow of 10 lit/min at the start, for a period of 3 minutes, followed by a flow of 400ml O2 and 600 ml N2O for the initial 20 minutes and a flow of 500ml O2 and 500ml N2O thereafter. This has been shown to maintain the oxygen concentration between 33 and 40 % at all times.

The Gothenburg Technique[15]: Initially high flows, oxygen at 1.5 L/min and nitrous oxide at 3.5 L/min had to be used for a period of six minutes after the induction of anesthesia and this constitutes the loading phase. This is followed by the maintenance phase in which the oxygen flow is reduced to about 4ml/kg and nitrous oxide flow adjusted to maintain a constant oxygen concentration in the circuit. The usual desired oxygen concentration is about 40%. The use of an oxygen analyzer is very important since the nitrous oxide added is directly based on its readings and hence any errors would be dangerous.

Maintenance with potent anesthetic agents: This is easily accomplished by dialing in the calculated concentration on the plenum vaporizer for the flow being used. In practice the actual dial setting often over estimates the actual output since the plenum vaporizer under delivers the agent at low flows. Hence, the dial setting is fine-tuned depending on the endpoints being achieved.

1. In Low Flow Anaesthesia the fresh gas enflurane concentration is increased to 3.0 Vol%, isoflurane to 2.0 Vol% and sevoflurane to 3.0 Vol%[1, 9]. Due to its specific pharmacokinetic properties, only the fresh gas desflurane concentration can be maintained unchanged[16]. Executing these standardized schemes, the expired anaesthetic concentrations will be maintained in the aspired range of 0.7 to 0.8 times the MAC.
2. During completely closed circuit anesthesia, the most popular method of adding agents into the circuit is by the injection technique. The dose to be added depends on the uptake model being used for the conduct of the closed circuit. The endpoint for adding the agent can be the achievement of the desired end tidal agent concentration, measured most accurately using an agent analyzer. The end point may also be based on the hemodynamic stability.[17]

The infusion rates of isoflurane (ml/hr) derived from the Lowe's theory of the uptake of anesthetic agent are as follows:

0 - 5min: 14 + 0.4 x body wt.
5 - 30min: 0.2 x initial rate.
30-60min: 0.12 x initial rate.
60-120min: 0.08 x initial rate.

For halothane infusion, it is suggested that the above rates be multiplied by 0.8 and for enflurane, multiplied by 1.6. These rates have been suggested to produce 1.3 MAC without the use of nitrous oxide. The infusion rates have to be halved if nitrous oxide is used.

The other salient points to be considered during the maintenance phase are the following:

a. Leaks must be meticulously sought for and prevented since they would decrease the efficacy of the system. Flows must be adjusted to compensate for the gas lost in the leaks.
b. Most of the gas monitors sample gases at the rate of 200 ml/min, which may be sometimes as high as half the FGF. Hence, care must be taken to return the sample back to the circuit to maximize the economy of FGF utilization.

TERMINATION OF LOW FLOW ANAESTHESIA: There are only two recognized methods of termination of the closed circuit. They are as follows:

i. Towards the end of the anesthesia, the circuit is opened and a high flow of gas is used to flush out the anesthetic agents, which accelerates the washout of the anesthetic agents. This has the obvious advantage of simplicity but would result in wastage of gases.

ii. The second method is the use of activated charcoal[14] which when heated to 220°C adsorbs the potent vapors almost completely. Towards the end of the anesthesia, the gas is directed through the activated charcoal canister. This results in rapid recovery and at the same time, reducing theatre pollution. Nitrous oxide, due to its low solubility is washed off towards the end by using 100% oxygen.

LOW FLOW ANAESTHESIA TECHNIQUES IN CLINICAL PRACTICE:

1. Low flow anaesthesia with an oxygen /nitrous oxide carrier gas mixture:

Premedication, pre-oxygenation, induction & intubation are performed according to the usual practice & patient is connected to rebreathing system.

Initial high flow phase

- Duration 10 to 15 (max. 20) minutes, depending on the anesthetic agent and the patient's constitution
- 1.4 L/min oxygen & 3.0 L/min nitrous oxide
- Vaporizer setting:
    - Halothane 1.0-1.3 vol%
    - Enflurane 2.0-2.5 vol%
    - Isoflurane 1.0-1.5 vol%,
    - Sevoflurane 2.0-2.5 vol%
    - Desflurane 4.0-6.0 vol%.

Reduction of the fresh gas flow rate: Stepwise reduction in the fresh gas flow rate, e.g. reducing the flow to 2 L/min after the initial 5minutes, to 1 L/min after 10 minutes and, finally, to 0.5 L/min after 15 minutes.

- 0.3-0.25 L/min oxygen
- 0.2-0.25 L/min nitrous oxide
- Vaporizer setting:
    - halothane 2.5-3.0 vol%
    - enflurane 3.0-3.5 vol%
    - isoflurane 2.0-2.5 vol%
    - sevoflurane 3.0-3.5 vol%
    - Desflurane: increase initial vaporizer setting by 1.0-1.5 vol% (i.e. 5.0-7.5 vol%).

Emergence and Recovery:

- Switch off the vaporizer 15-30min prior to the end of the surgical procedure.
- Maintain a fresh gas flow rate of 0.5 L/min
- Lead patient to spontaneous breathing by manual ventilation, SIMV or PS (ASB)
- Wash-out anesthetic gases with 5.0 L/min of pure oxygen 5-10 min prior to extubation
- Routine postoperative care.

2. Low Flow Anaesthesia without nitrous oxide:

- The loss of analgesic effect can be compensated by a moderate increase in the additive dose of opioids, while the reduction in hypnotic effect can be countered with an increase in the concentration of the inhaled anesthetic agent by only 0.2-0.25% of the MAC value of the respective agent used. For adults, the desired expiratory isoflurane concentration is 1.2%, for sevoflurane 2.2% and for desflurane 5%.
- Because only oxygen and the anesthetic agent are absorbed, total gas uptake is noticeably reduced and de-nitrogenation is no longer necessary.
- The initial phase of low flow anesthesia, when high fresh gas flow rates are used, can be kept much shorter. Its duration is solely determined by the wash-in characteristics of the inhalation anesthetic agent used.
- By eliminating nitrous oxide uptake, the breathing system filling is improved following the reduction of fresh gas flow– even down to 0.5 L/min, than in low flow anesthesia using a nitrous oxide/oxygen with very airtight, compact breathing systems, the conduction of non-quantitative anesthesia with closed systems is possible, where fresh gas flow can be reduced to patient oxygen uptake.
- At this low flow rate, however, the limits of the vaporizer's capability to emit sufficient amounts of agent into the fresh gas stream are reached, which, as a rule, are approximately 3 × MAC of the respective anesthetic agents. The new volatile anesthetics with reduced solubility, sevoflurane and desflurane, are much better suited for use with fresh gas flows corresponding to the rate of patient oxygen uptake.

ADVANTAGES[18]:

1. Economy: Significant savings can be achieved with lower flows of nitrous oxide and oxygen, but the greatest savings occurs with the potent volatile agents.[19-21] These are partly offset by increased absorbent usage, but this cost is small.

2. Reduced Operating Room Pollution: With lower flows, there will be less anesthetic agent put into the operating room. However, the use of low-flow techniques does not eliminate the need for scavenging, because high flows are still necessary at times. Since less volatile agent is used, vaporizers have to be filled less frequently so that exposure to anesthetic vapors during filling is decreased.

3. Reduced Environmental Pollution: Fluorocarbons and nitrous oxide attack the earth's ozone layer, and nitrous oxide contributes to the greenhouse effect.[22,23] With low flows, these ecological dangers are reduced.

4. Estimation of Anesthetic Agent Uptake and Oxygen Consumption: In a closed system without significant leaks, the fresh gas flow is matched by the patient's uptake of oxygen and anesthetic agents.[24,25] Changes in volume may be attributed principally to uptake of oxygen or nitrous oxide because the volume contributed by the potent inhalational agents is usually not significant.

5. Buffered Changes in Inspired Concentrations: The lower the fresh gas flow, the longer it takes for a change in concentration in the fresh gas flow to cause a comparable change in the inspired concentration.

6. Heat and Humidity Conservation: With lower gas flows, inspired humidity will be increased, and the rate of fall in body temperature reduced**.** The incidence of shivering is lowered.[26-28]

7. Less Danger of Barotrauma: High pressures in the breathing system take longer to develop with lower flows.

DISADVANTAGES:

1. More Attention Required: With closed system anesthesia, fresh gas flow into the system must be kept in balance with uptake. This requires frequent adjustments.

2. Inability to Quickly Alter Inspired Concentrations: The use of low fresh gas flows prevents the rapid changes in fresh gas concentration in the breathing system that occurs with high gas flows. As a result, it may be more difficult to control acute hemodynamic responses[29]**.** This is a significant disadvantage only if the user insists on using low flows at all times. The clinician who uses low flows should accept that when it is necessary to change inspired concentrations rapidly, higher flows should be used.

3. Danger of Hypercarbia: Hypercarbia resulting from exhausted absorbent, incompetent unidirectional valves or the absorber being left in the bypass position will be greater when low flows are used.

4. Accumulation of Undesirable Gases in the System: The accumulation of undesirable gases is most likely only a problem with closed-circuit anesthesia, because low flows provide a continuous system flush. With closed system anesthesia, flushing with high fresh gas flows once an hour will decrease the concentration of most of these substances. Alternately, a diverting gas monitor with the sample gas scavenged instead of being returned to the circle system can be used to remove small amounts of gas.

   a. Carbon Monoxide: Carbon monoxide from the interaction of desiccated absorbent and anesthetic agent was discussed earlier in this chapter. Since low-flow anesthesia tends to preserve the moisture content of the absorbent, it may protect against the production of carbon monoxide resulting from desiccated absorbent.[30] However, if desiccated absorbent is present, low flows tend to increase the amount of carbon monoxide present in the system. Carbon monoxide produced from the breakdown of hemoglobin or exhaled by smokers can accumulate in the closed circle system.[31, 32]

b. Acetone, Methane, Hydrogen, and Ethanol: Acetone, methane, and hydrogen accumulate during closed system anesthesia. However, dangerous levels are reached only after hours of closed system anesthesia. Methane can disturb infrared analyzers. The common intoxicant ethanol, can also accumulate.[33, 34]

c. Compound A: It is accepted that prolonged sevoflurane anesthesia with low fresh gas flows results in proteinuria, glycosuria, and enzymuria. However, this is not, and has not been shown to be, associated with any clinical manifestations, even when such a technique is applied to patients with pre-existing biochemical renal abnormalities. Furthermore, it occurs if isoflurane is used in place of sevoflurane and seems also to be independent of carrier gas flow rate.[35, 36]

Much of the laboratory work on renal toxicity was undertaken on rats, where compound A causes acute tubular necrosis at concentrations in excess of 250 ppm. It is now clear that these studies were invalid due to the marked differences between human and rat renal biochemistry. The generally held view is that compound A has a considerable margin of safety in humans at the concentrations typically found during low-flow sevoflurane anesthesia (around 15 ppm).

The FDA recommended that sevoflurane not be used with fresh gas flows of less than 2 L/minute. This recommendation has been revised in 1997 to suggest that flow rates of 1 L/minute are acceptable but should not exceed 2 minimum alveolar concentrations (MAC)-hours. Some investigators feel that Compound A should not be a real clinical concern and that restricting the use of low fresh gas flows with sevoflurane cannot be justified.

d. Argon: If oxygen is supplied from an oxygen concentrator, there will be an accumulation of argon with low fresh gas flows.[37]

e. Nitrogen: Even with initial denitrogenation, nitrogen will accumulate in the closed breathing circuit (199). If oxygen is being supplied by an oxygen concentrator, malfunction of one of the concentrators can cause nitrogen to appear in the product gas**.** Infrared monitors add air to the sample gas after the sample is analyzed. If the gas exhausted is returned to the breathing system, nitrogen accumulation will be greater than expected.[37]

f. Other: An acrylic monomer is exhaled when joint prostheses are surgically cemented**.** During this period, the system should be vented to prevent rebreathing of this chemical.[38]

5. Uncertainty about Inspired Concentrations: One of the effects of rebreathing is that the inspired concentrations cannot be accurately predicted. However, absolute or near-absolute knowledge of inspired anesthetic agent concentrations is not necessary for safe anesthesia conduct, because patients' responses to drugs vary widely.

6. Faster Absorbent Exhaustion: The lower the fresh gas flow, the faster the absorbent is exhausted.

CONCLUSION: Today, LFA is such a safe and simple procedure that there are no reasons not to use it routinely. It can be even argued that the use of unnecessary FGF should be regarded as inappropriate. Reduction of anesthesia gas consumption results in significant savings up to 75%, decrease of greenhouse gas emissions and lower impact on the ozone layer.

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