

Flammability of Endotracheal Tubes in Oxygen and Nitrous Oxide Enriched Atmosphere

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Endotracheal tube (ETT) fire has been reported secondary to laser and electrocautery ignition. The flammability of polyvinylchloride (PVC), silicone (Si), and red rubber (RR) ETTs in oxygen (O₂) and/or nitrous oxide (N₂O) in nitrogen was determined and compared by means of the O₂ and N₂O indices of flammability. The O₂ index of flammability is the minimum O₂ fraction in nitrogen that will support candle-like flame using a standard ignition source. The O₂ index of flammability for PVC ETTs is 0.263, for Si 0.189, and for RR 0.176. The N₂O index of flammability is the minimum N₂O fraction in N₂ that will support candle-like flame using a standard ignition source. The N₂O index of flammability for PVC ETTs is 0.456, for Si ETTs 0.414, and for RR ETTs 0.374. The indices are additive. Flammability is a valid method of comparing safety of various endotracheal tube materials. There is a need for new endotracheal tube material with a higher index of flammability. The significance of these findings and the clinical applications are discussed. (Key words: Anesthetic equipment: endotracheal tubes. Anesthetics, gases: nitrous oxide. Complications, explosions, fires: nitrous oxide and oxygen indices of flammability. Electrical systems: electrocautery. Laser: fire. Oxygen.)

FORMERLY, FIRES AND EXPLOSIONS were related to the combination of a flammable anesthetic agent, an oxidizing agent, and an ignition source, such as an alcohol lamp, cautery, or static sparks. Presently, flammable anesthetic agents are seldom used. Technological advances, however, have created new potential sources of ignition (laser, radiofrequency electrocautery, etc.) that offer ready access to fuels other than flammable anesthetic agents in flame-supporting atmospheres. Endotracheal tube (ETT) fire, a catastrophic intraoperative occurrence, has been associated with laryngeal laser surgery. The recent report of a polyvinylchloride (PVC) ETT fire ignited by pharyngeal electrocautery during tonsillectomy under nitrous oxide (N₂O), oxygen (O₂), and halothane anesthesia illustrates a different ignition source.¹

The use of the "oxygen index of flammability" is widely accepted in the plastics industry to determine

acceptability of products for use in an O₂ enriched atmosphere.‡ We introduce the analogous concept of the "nitrous oxide index of flammability," since both O₂ and N₂O atmospheres exist in the clinical setting and both support combustion.

Various reports compare the ignitability of PVC, silicone (Si), and red rubber (RR) ETTs by laser.²⁻⁵ This study compares the relative flammability, rather than the ignitability, of PVC, Si, and RR ETTs using a propane flame as the ignition source.

Materials and Methods

Gases were obtained from commercial cylinders and were of medical grade (fig. 1). The individual gases were routed through individual precision ball flowmeters, 25 cm in length (Liquid Carbonics, Harrison, NJ), calibrated for the specific gas, and accurate to ±3%. Flowmeter output entered a gas valve unit, a common line, and a mixing chamber containing glass beads 3-10 mm in diameter. From the mixing chamber, the gases entered the lower end of a cylindrical glass column measuring 7.5 cm in diameter and 60 cm in length. The ETT to be tested was supported in the column by a clamp. Ignition was accomplished at the top of the ETT with a propane flame 6-10 mm in length. Contact time of the ETT with the flame was 3-5 s. Upward gas flow was maintained at 30-35 l/min. The test was performed in a chemical/flame hood.

In part I of the study, the O₂ index of flammability was determined. The concentration of O₂ in nitrogen (N₂) in the test column was slowly increased until a candle-like flame was maintained on the ETT following removal of the propane flame. Thirty seconds were allowed for equilibration of gases after any new gas flow settings before ignition was attempted. The O₂ index of flammability was determined for PVC (Portex Inc., Wilmington, MA), Si (National Catheter, Argyle, NY), and RR (Rusch, West Germany) ETTs. At the O₂ concentration corresponding to the oxygen index of flam-

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‡ Fenimore CP, Martin FJ: Candle-type test for flammability of polymers. *Modern Plastics* 44:141, 1966

mability for the particular ETT, increasing the N₂ concentration by 1% or decreasing the O₂ by 1% extinguished the flame. Five independent determinations of the O₂ index of flammability were made for each of the three types of ETTs.

The O₂ index of flammability was calculated using the following formula at the flow settings just supporting candle-like flame.

$$O_2 \text{ index} = \frac{O_2 \text{ flow l/min}}{O_2 \text{ flow l/min} + N_2 \text{ flow l/min}^\circ}$$

In part II of the study, the nitrous oxide index of flammability was determined by repeating the above procedures substituting N₂O for O₂. Five independent determinations of the N₂O index of flammability were made for each of the three types of endotracheal tubes. The following equation was used to calculate the N₂O index of flammability using the flow settings at the concentration just supporting candle-like flame.

$$N_2O \text{ index} = \frac{N_2O \text{ flow l/min}}{N_2O \text{ flow l/min} + N_2 \text{ flow l/min}^\circ}$$

In part III of the study, the flammability of the three types of ETTs in a combination of O₂, N₂O, and N₂ was determined using upward gas flow, top ignition. Initially, a gas flow of O₂ in N₂ corresponding to an O₂ concentration of one-half the O₂ index of flammability as determined in part I of the study for that particular type ETT, was begun. N₂O was then introduced, increasing its concentration while maintaining the concentration of O₂ constant by decreasing the N₂ concentration until a candle-like flame was just maintained on the ETT on removal of the propane flame. This process was repeated using one-quarter, one-third, two-thirds, and three-quarters of the O₂ index of flammability. Five independent determinations were made at each fraction of the O₂ index, and all of the above were repeated for each of the three types of ETTs.

The above sequence was repeated beginning with N₂O in N₂ corresponding with one-half the N₂O index of flammability for that particular type ETT, as determined in part II of our study, and introducing O₂ slowly while decreasing the N₂ concentration, so as to maintain a stable N₂O concentration until a candle-like flame was just maintained on the ETT on removal of the propane flame. This sequence was repeated using one-quarter, one-third, two-thirds, and three-quarters of the N₂O index of flammability. Five independent determinations were made at each fraction of N₂O index, and all of the above were repeated for each of the three types of ETTs.

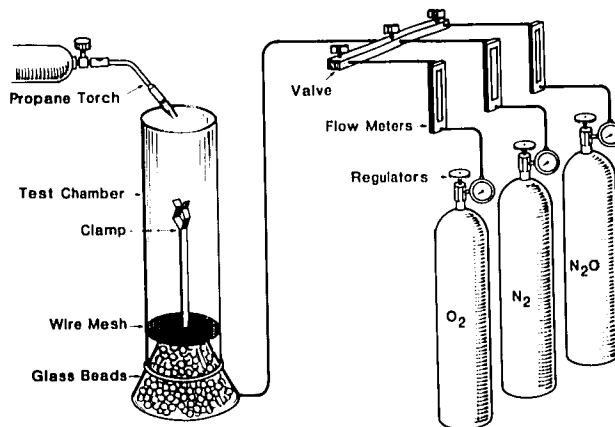


FIG. 1. Schematic representation of apparatus for the determination of O₂ and N₂O index of flammability.

Gas concentrations were confirmed by analysis performed on gas mixtures in the column after equilibration at all flowmeter settings. Analysis of N₂O was by infrared spectrophotometry, and analysis of O₂ was by the fast paramagnetic technique (Puritan Bennett, Wilmington, MA).

The O₂ and N₂O index for each type of ETT was determined by averaging each set of five flammability determinations for that tube type (mean ± S.D.) and calculating the respective 99% confidence intervals.

Results

The O₂ index of flammability for PVC tubes is 0.263, for Si tubes 0.189, and for RR tube 0.176. The N₂O index of flammability for PVC tubes is 0.456, for Si tubes is 0.414, and for RR tubes is 0.374 (table 1). Standard deviations for flammability within each tube type were small enough relative to the 99% confidence interval that each true index is within ±0.01 of its measured index.

Table 2 lists the results of part III. The combination of O₂ and N₂O supported candle-like flame at levels of one total index, *i.e.*, the indices are linearly additive. For

TABLE 1. Oxygen and Nitrous Oxide Indices of Flammability

ETT	O ₂ Index	99% Confidence Limit	N ₂ O Index	99% Confidence Limit
PVC	0.263 (±.004)	±.005	0.456 (±.006)	±.007
Si	0.189 (±.009)	±.01	0.414 (±.007)	±.008
RR	0.176 (±.003)	±.003	0.374 (±.005)	±.006

TABLE 2. Minimum Combinations Just Supporting Candle-like Flame

ETT	O ₂ %	Fraction O ₂ Index	N ₂ O %	Fraction N ₂ O Index
PVC	19.8	.75	11.4	.25
	17.6	.67	15.1	.33
	13.2	.5	22.8	.5
	8.7	.33	30.6	.67
	6.6	.25	34.2	.75
Si	14.2	.75	10.4	.25
	12.7	.67	13.7	.33
	9.5	.5	20.7	.5
	6.2	.33	27.7	.67
	4.7	.25	31.1	.75
RR	13.2	.75	9.4	.25
	11.8	.67	12.3	.33
	8.8	.5	18.7	.5
	5.8	.33	25.1	.67
	4.4	.25	28.1	.75

example, for PVC tubes, 13% O₂ (0.5 O₂ index), 23% N₂O (0.5 N₂O index), and 64% N₂ (diluent) just supported candle-like flame.

In figure 2, the concentration of O₂ is plotted against the concentration of N₂O. The curves represent the points just supporting candle-like flame for the respective ETT types. The area to the right of each curve represents combinations of O₂ and N₂O that render that particular ETT flammable. The area to the left of each curve represents combinations of O₂ and N₂O that render that particular ETT non-flammable. PVC tubes have the greatest area to the left of the curve, *i.e.*, the greatest area of non-flammability.

Ignition of the three types of ETTs in a 50% O₂, 50% N₂O environment resulted in an uncontrollable flame that rapidly consumed the ETT.

Gas analysis agreed to within $\pm 1\%$ of flowmeter settings.

Discussion

The O₂ index of flammability is defined as the minimum O₂ fraction in N₂ that will just support candle-like flame for a given fuel source using a standard ignition source.[§] Since N₂O also supports combustion and is used in the clinical setting, we introduce the analogous concept of the N₂O index of flammability defined as the minimum N₂O fraction in N₂ that will just support candle-like flame for a given fuel source using a standard ignition source.

[§] Goldblum KB: Oxygen index: Key to precise flammability ratings. Society of Plastics Engineers Journal 25:50-52, 1969

It is necessary to distinguish between ignition, the amount of energy needed to ignite a fuel in a given atmosphere, and flammability, the ability of a fuel to sustain a flame in a given atmosphere. In the clinical setting, there are many possible sources of ignition, including electrocautery, laser, and high-speed drills. This study quantitates the relative flammability regardless of ignition source.

Both the O₂ and N₂O indices are higher for PVC ETTs than for Si and RR ETTs. When an ignition source is in close proximity to the ETT, PVC tubes may be preferable to Si or RR tubes, provided a gas mixture is chosen that does not support combustion (to the left of the PVC curve in fig. 2).

Considerations for laser surgery include resistance of the ETT to laser penetration (Si > RR > PVC),⁶ the O₂ and N₂O indices of the ETT (PVC > Si > RR), and the fraction of inspired oxygen (FI_{O₂}) patient requirements. Wrapping RR ETTs with metallic tape does not guarantee protection from laser hit.^{5,6} Laser hit may not penetrate RR, but ignition of the external surface can result in a propagated flame in air (O₂ index = 0.176). Wrap-

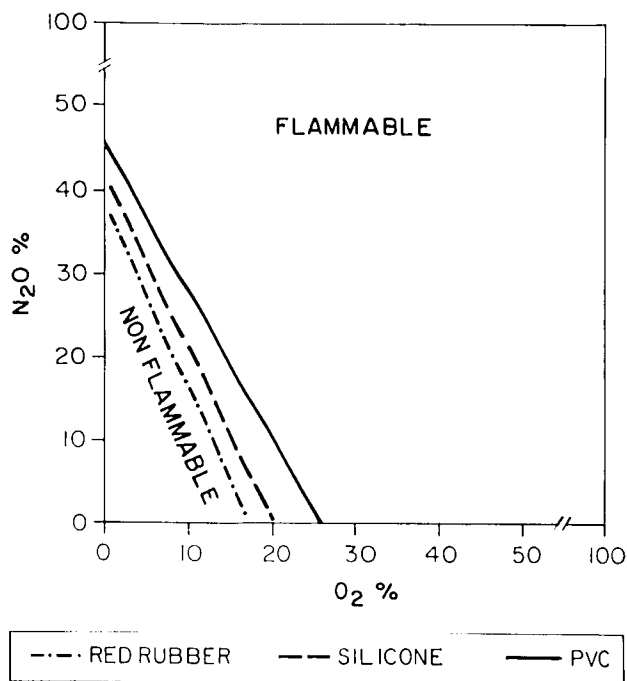


FIG. 2. The points just supporting candle-like flame are plotted for the three types of ETTs in gas mixtures of O₂ and N₂O (diluent N₂). Points to the right of each curve are flammable. Points to the left of each curve are non-flammable. For example, a gas mixture of 50% O₂ and 50% N₂O will render all three types of ETTs flammable, while a combination of 23% O₂ and 5% N₂O in N₂ will render PVC ETTs non-flammable and the Si and RR ETTs flammable.

ping of PVC ETTs with metallic tape similarly does not guarantee protection from laser hit. Laser hit will penetrate PVC, but a propagated flame will not occur provided ventilating gas composition is to the left of the PVC curve in figure 2. Patient requirements may dictate an FI_{O_2} to the right of all ETT curves in figure 2.

These data suggest the need for continued search for a "safe" ETT, *i.e.*, one with a higher O_2 and N_2O index of flammability, whose curve would be shifted to the right of those curves displayed in figure 2, and one with greater resistance to laser penetration.

Oxygen has long been accepted as an oxidizing agent that will readily support combustion. This paper reinforces the concept of N_2O as an oxidizing agent.

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