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Intraluminal Flame Spread in Tracheal Tubes

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Intraluminal combustion in polyvinyl chloride tracheal tubes was investigated. Two flame types were observed: intraluminal and downstream. The flame-spread velocity, burning rate, and equivalence ratio of the intraluminal flame were determined. The products of the intraluminal flame were analyzed, revealing compounds capable of further combustion.

Below a certain oxidant flow rate, the tubes do not ignite. At low flow rates that support a flame, the burning rate is minimal and the equivalence ratio reveals no fuel available for the downstream flame, suggesting that ignition of tracheal tubes is least likely in the absence of intraluminal flow.

We conclude that the downstream flame is the flame type that is most dangerous and that the intraluminal flame is the generator of fuel and ignition energy for the downstream flame.

INTRODUCTION

Operating room fires continue to be reported, particularly in the context of ignition of tracheal tubes in oxygen-enriched anesthetic atmospheres during airway-laser[1–3] and electrosurgical unit[4–6] surgery. Extraluminal surface combustion can occur if the oxygen concentration outside the tube exceeds the limiting oxygen index of flammability.[7] Intraluminal combustion can also occur.[3] We studied intraluminal combustion in polyvinyl chloride tracheal tubes and observed two distinct flame processes—an intraluminal flame based on the flame-spread model studied by de Ris,[8] Fernandez Pello, *et al.*,[9] and Ray and Glassman,[10] and a downstream flame in which volatilized fuel exits the end of the tube and burns in the oxygen of the ambient atmosphere. In addition, we qualified the released volatiles by chemical and gas chromatographic analysis, quantified them by determining the difference in weight of the tube before and after combustion (burning rate), and derived the degree of deviation from stoichiometric burning (equivalence ratio) to assess excess fuel released from the intraluminal flame available for the downstream flame over a range of oxygen flow rates.

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MATERIALS AND METHODS

One hundred percent oxygen was obtained from compressed gas cylinders and the tank pressures reduced to 30 psig by pressure regulators. Flow was controlled by needle valves, and flow rate was determined by a 100-mL bubble flow meter or by a mass flow controller. Oxygen flow up to 20 lit·min^{-1} was directed, via plastic tubing, into a copper tube of 6.0-mm outer diameter.

Polyvinyl chloride tracheal tubes of 5.5-mm internal diameter, typically 7 cm long, were premeasured and marked, weighed on a gravimetric mass balance, and force-slipped over one end of the copper tube. The copper tube was horizontally supported, and the tracheal tube was otherwise unsupported. Polyvinyl chloride tracheal tubes were chosen since they are clear and allow observation of the intraluminal surface. The experiment was performed in ambient air under a flame hood.

Once the oxygen flow rate was established, the free end of the tracheal tube was ignited by a pilot flame burning in air. The intraluminal flame that developed was observed as it spread against the direction of the oxygen flow. When it existed, the downstream flame remained anchored on the free end of the tube. Before the intraluminal flame reached the copper tube, the oxygen was abruptly terminated and the intraluminal flame was observed to extinguish quickly, leaving a discoloration at the point of extinction. The tube upstream from the flame was unaffected.

The velocity of the intraluminal flame, *i.e.*, the distance traveled divided by the time of travel, was measured by using two methods. In the first method, samples 1 through 7, the time for flame spread for the premeasured length of tube was determined by direct observation and stopwatch. In the second method, samples 8 through 24, experiments were videotaped with a stopwatch in the field of view that allowed slow motion or frame-by-frame observation. The second method minimized human error. The videotape method confirmed the accuracy of the direct-observation technique.[11]

The burning rate, a measure of the mass of solid fluid liberated per unit time, was determined by weighing the tube section before and after each experiment to yield the total mass loss during the experiment. The time the flame existed was determined as the total length the flame traveled divided by the flame-spread velocity previously determined. The total length of flame travel is the original length of the tube section minus the measured distance from the unburned end of the tube to the point of flame extinction.

The equivalence ratio of the intraluminal flame, defined as the deviation from stoichiometric burning, was derived from the experimental data.

In this example, stoichiometric burning is defined as burning in which there is just sufficient oxygen to convert all carbon to carbon dioxide, all chlorine to hydrogen chloride, and all remaining hydrogen to water. Calculation of stoichiometric burning of polyvinyl chloride is thus based on the formula

$$2\,C_2H_3Cl + 5\,O_2 \text{ -----} > 4\,CO_2 + 2\,HCl + 2\,H_2O.$$

The stoichiometric fuel/oxygen (F/O_{stoich}) mass ratio is therefore

$$(F/O)_{stoich} = \frac{2 \times (\text{molecular weight of } C_2H_3Cl)}{5 \times (\text{molecular weight of } O_2)} = 0.775.$$

The polyvinyl chloride material used contains a large fraction of plasticizer. However, this material was not accounted for in the stoichiometric calculation.

The equivalence ratio (ER) is defined as the experimental fuel/oxygen (F/O) ratio divided by the stoichiometric fuel/oxygen (F/O_{stoich}) ratio:

$$ER = \frac{(F/O)}{(F/O)_{stoich}}$$

The fuel/oxygen mass ratio is the ratio of the burning rate to the mass flow rate of oxygen (equal to the oxygen density, 1.3 kg/m^3, multiplied by the oxygen volumetric flow rate in $m^3 \cdot sec^{-1}$).

If the equivalence ratio of the intraluminal flame is greater than one, more fuel is liberated than the supplied oxygen can consume. Therefore, the products of this flame will contain products capable of further oxidation. If the concentration of fuel products is sufficiently high, the gases emerging from the end of the tube can support a downstream flame.

Chemical analysis of the products of the intraluminal flame was performed in a separate experiment. Polyvinyl chloride tracheal tubes approximately 2 cm in length were inserted into a quartz tube through which 100% oxygen flowed. The tracheal tube was ignited at the distal end, creating an intraluminal flame that propagated to the proximal end of the tracheal tube. The products of this flame were stored in previously gas-evacuated Pyrex collecting chambers and analyzed both by chemical and gas chromatographic methods. Chemical analysis was performed by back titration of $Ca(OH)_2$ trapped gases. Gas chromatographic analysis was performed by stainless steel capillary column separation followed by flame ionization and thermal conductivity detection.

Statistical analysis was performed on the experimental flame spread and burning rate data. The data were assumed to obey Hoerl's equation,[12] $y = ax^be^{cx}$, where y designates the flame-spread or burning-rate data and x the oxygen flow rate. Values for a, b, and c were obtained from a nonlinear regression of the data.

RESULTS

Table I lists the data obtained for flame-spread velocity, burning rate, and equivalence ratio. The column labeled Oo_2 lit·min^{-1} refers to the total flow of oxygen in lit·min^{-1} through the tube. In Figures 1, 2, and 3, the symbols represent the experimental values and the solid lines represent the curve-fits based on the regression of the Hoerl equation.

TABLE I.
Experimental Data.

Specimen	Oo_2 lit·min^{-1}	V_{flame} cm·sec^{-1}	BR gm·sec^{-1}	ER
1*	0.055	0.33		
2*	0.076	0.58		
3*	0.122	0.65		
4*	0.184	1.06		
5*	0.229	1.14		
6*	0.380	1.28		
7*	1.000	1.66		
8	0.053	0.31	0.000822	0.94
9	0.211	1.07	0.00835	2.38
10	0.264	1.58	0.0135	3.07
11	0.316	1.23	0.0121	2.30
12	0.369	1.28	0.0149	2.43
13	0.474	1.33	0.0192	2.43
14	0.527	1.40	0.0218	2.48
15	0.840	1.80	0.0372	2.66
16	1.041	1.85	0.0468	2.70
17	2.550	2.13	0.0875	2.06
18	5.065	1.77	0.0980	1.16
19	7.580	1.60	0.111	0.88
20	10.095	1.30	0.123	0.73
21	12.610	0.95	0.0931	0.44
22	15.125	0.64	0.0813	0.32
23	17.640	0.58	0.0672	0.23
24	20.155	0.30	0.0491	0.15

Oo_2 lit·min^{-1} = O_2 flow rate; V_{flame} cm·sec^{-1} = flame-spread velocity; BR gm·sec^{-1} = burning rate; ER = equivalence ratio.

*Flame-spread velocity determined by direct observation and stopwatch.

The column labeled V_{flame} cm·sec^{-1} refers to the flame-spread velocity of the intraluminal flame spreading toward the oxygen flow. Figure 1 is a plot of flame-spread velocity on the y axis as a function of the oxygen flow rate on the x axis. The flow dependence of the flame-spread velocity reveals an initial increase to a peak at 2.550 lit·min^{-1} oxygen flow rate and then a gradual decrease in flame-spread velocity with further increase of flow rate. An "upper flammability limit," above which the tube cannot be ignited, is observed. At the highest flow rate for which a flame existed, 20.155 lit·min^{-1}, the flame-spread velocity was 14.0% of the maximum observed flame-spread velocity. A "lower flammability limit" is also observed; for flow rates of less than approximately 0.060 lit·min^{-1}, the tube could not be ignited. In addition, when the flow is stopped the flame quickly extinguishes.

The next column in Table I is the burning rate in gm·sec^{-1}. Figure 2 is a plot of burning rate on the y axis as a function of the oxygen flow rate on the x axis. The flow dependence of the burning rate reveals an initial increase to a peak at 8 lit·min^{-1} oxygen flow rate, and then a gradual decrease in burning rate with further increase of flow rate. For the highest flow rate, 20.155 lit·min^{-1}, the burning rate is 39.8% of the

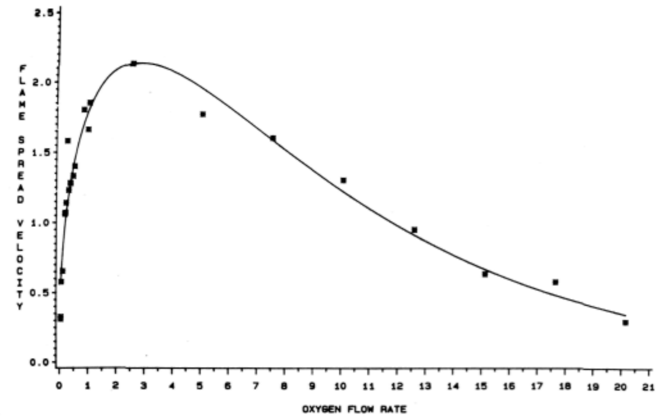

Fig. 1. Flame spread velocity. Oxygen flow rate = lit·min^{-1}; flame spread velocity = cm·sec^{-1}.

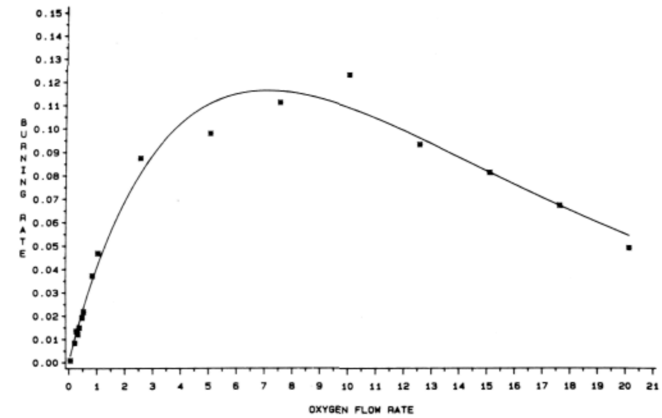

Fig. 2. Burning rate. Oxygen flow rate = lit·min^{-1}; burning rate = gm·sec^{-1}.

maximum observed burning rate. The peak for burning rate occurs at a higher flow rate than the peak for flame spread velocity.

The last column of Table I is the equivalence ratio for various flow rates of oxygen. Figure 3 is a plot of equivalence ratio on the y axis and oxygen flow rate on the x axis. It demonstrates that the equivalence ratio is less than one for the lower and higher flow-rate ranges, while for mid flow-rate range equivalence ratio is above one. While only one data point was obtained in the low flow range where the equivalence ratio was less than one, similar studies in which industrial-grade polyvinyl chloride tubing[11] was used show that the trend suggested by the present data is valid.

Chemical analysis by back titration of $Ca(OH)_2$ trapped gases reveals abundant acid interpreted to be hydrogen chloride. Gas chromatographic analysis reveals aliphatic hydrocarbons, benzene, and other aromatic compounds in addition to carbon monoxide and carbon dioxide (Table II). Hydrogen gas and water were not measured but are expected to be abundant based on general results of fuel-rich combustion.

The results of the nonlinear regression for the experimental data are reported in Table III. The first three columns indicate the values for *a, b,* and *c* obtained from the fit of the Hoerl equation,[12] $y = ax^be^{cx}$. The R^2 values, which represent the fraction of the total variation accounted for by the fitted equation, are listed in the last column. The high R^2 values indicate a relatively small degree of unexplained variation. Each of the two regression equations explain greater than 90% of the total variance accounted for by the model.

TABLE II.
Gas Chromatographic Analysis of Intraluminal Flame Products.

Species	Moles Percent (Dry Basis)
Carbon dioxide (CO_2)	36.0
Carbon monoxide (CO)	9.0
Methane (CH_4)	2.5
Ethene (C_2H_4)	1.7
Acetylene (C_2H_2)	0.9
Benzene (C_6H_6)	0.0045
SUBTOTAL	49.2

Other species not measured but likely include hydrochloric acid and deuterium (heavy hydrogen) in significant concentration.

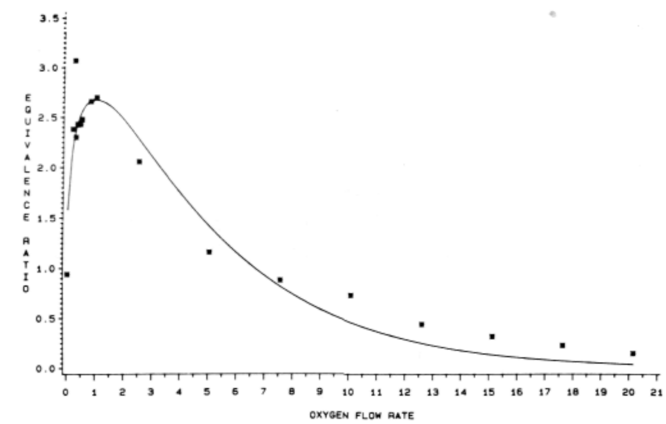

Fig. 3. Equivalence ratio. Oxygen flow rate = lit·min^{-1}; Equivalence ratio = fuel/oxygen ratio normalized by the stoichiometric fuel/oxygen ratio.

DISCUSSION

The shaft of a tracheal tube can burn in at least three flame configurations. Ossoff[3] described an extraluminal outer-surface flame in which the atmosphere surrounding the tube must equal or exceed the limiting oxygen index for the tube material.[7] An in-

TABLE III.
Results of Nonlinear Regression.

	$y = ax^be^{cx}$			
	a	*b*	*c*	R^2
FSV	2.089	0.442	−0.155	0.924
BR	0.046	0.955	−0.135	0.980

FSV = flame-spread velocity; BR = burning rate.

traluminal flame can exist when the intraluminal oxygen concentration is sufficiently high. This intraluminal flame generates gaseous fuel which, depending on the oxygen flow rate, can feed the third flame type, the downstream flame. In this article we address the intraluminal flame and the downstream flame anchored at the free end of the tube.

Ossoff[3] also described an intraluminal flame. The flame that Ossoff termed "intraluminal" is that which we have termed the downstream flame. His test specimen was an opaque red rubber tube, and therefore the intraluminal flame was not visible. Extinguishing only the evident downstream flame will not affect the intraluminal flame; therefore, it is imperative that an understanding of the nature of all flame types be obtained. We believe that the following description of the flame model accuratley reflects the nature of most tracheal tube fires reported in the literature. In general, extraluminal flames tend to be mild, while intraluminal flames and the downstream flames they produce can be violent owing to the forced supply of oxidizer with high oxygen concentration.

We extended previous flame-spread studies[8–10] to the tube geometry of a tracheal tube. That extended model is represented in Figure 4, in which a flow of oxygen is established through a polyvinyl chloride tracheal tube from left to right; the tube is ignited at the right edge. A dome-shaped flame propagates along the intraluminal surface of the tube toward the flow of oxygen. The position of the flame is at the interface of oxygen and gaseous fuel created by the opposed diffusion of oxygen and volatilized fuel. Heat transferred by the flame to the tube wall volatilizes the unburned wall, producing gaseous fuel that diffuses into the flow of oxidant, thereby advancing the flame from right to left. All oxygen is consumed at the flame in this oxygen-limited model; there is no gaseous fuel to the left of the flame and no oxygen to the right of the flame.

For most flow rates, the flame in tube geometry is underventilated (*i.e.*, there is excess fuel). The excess fuel that volatilizes downstream of the intraluminal flame can support a secondary flame termed the downstream flame. However, near the upper and lower flow limits there is excess oxygen and no fuel available for the downstream flame.

For flow rates of less than 0.060 $lit \cdot min^{-1}$, the 5.5-mm tracheal tube could not be ignited, probably due to the vertical orientation of the dome-shaped intraluminal flame at low oxidant flow rate that resulted in minimal heat transfer to the tube wall and minimal gaseous fuel volatilized. However, for the lowest flows Ray and Glassman[10] also observed a "buoyant regime" in which, as flow is decreased, the flame-spread curve plateaus due to oxidant flow induced by natural convective buoyant flow secondary to the expansion of hot gases. In the confined geometry of the 5.5-mm internal diameter tracheal tube, the

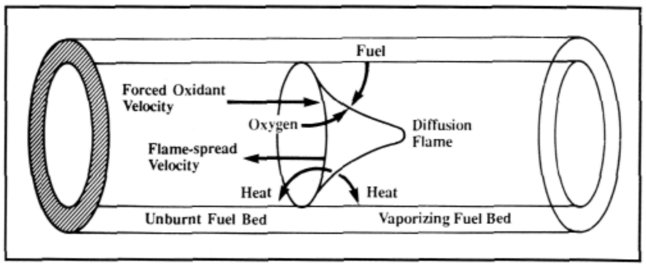

Fig. 4. Flame-spread model. Oxygen flows from left to right. Polyvinyl chloride tracheal tube ignited at right edge. Dome-shaped wall of flame spreads upstream into flowing oxygen. No oxygen to right of flame; no fuel to left of flame. Heat from flame transfers to tube wall, volatilizing fuel, which diffuses toward oxygen, which diffuses toward fuel. Flame thereby advances into flowing oxygen.

curve for flame spread at low flow decreases steeply with decreasing flow rate with no plateau since buoyant convective flow is limited within the tube. Stern[11] observed evidence of this buoyant mechanism for larger internal diameter polyvinyl chloride tubes (9.5-mm internal diameter).

For flow rates between 0.060 and 2.550 $lit \cdot min^{-1}$, the flame-spread velocity increases with increasing flow rates because of the improved heat transfer from the flame to the solid fuel due to the closer proximity of the flame to the fuel. This regime has been termed the "thermal regime" by Ray and Glassman[10] in their flat-surface fuel experiments.

For flow rates between 2.550 and 20.155 $lit \cdot min^{-1}$, the flame-spread velocity is observed to decrease almost linearly with increasing flow rate. Ray and Glassman[10] termed this regime the "chemical regime." In this regime, the increase in the opposed flow against which the flame must propagate dominates the effects of the improved heat transfer, and the flame-velocity decreases.

With increasing flow, an upper flammability limit is observed at 20.155 $lit \cdot min^{-1}$, above which the tube cannot be ignited. This "blow-out" limit is similar to blowing out a match. Above this limit, the opposed flow velocity at the leading edge of the flame is greater than the maximum flame-spread velocity that can be generated. The upper flammability limit is greater than the typical average flow rate of 5 $lit \cdot min^{-1}$ but is less than the maximum instantaneous flow rate observed during a breath (approximately 35 $lit \cdot min^{-1}$).[13] Therefore, the flow rate during portions of inhalation and exhalation is above the upper flow limit.

The products of the intraluminal flame represent a complex mixture of oxidation and pyrolysis products (Fig. 5). Complete oxidation at the diffusion flame produces carbon dioxide, hydrogen chloride, and water. Incomplete oxidation produces carbon monoxide and hydrogen gas. These products, plus the pyrolysis products created by the flame heating the downstream inner wall of the tube, flow from the intraluminal flame toward the end of the tube. Some of these

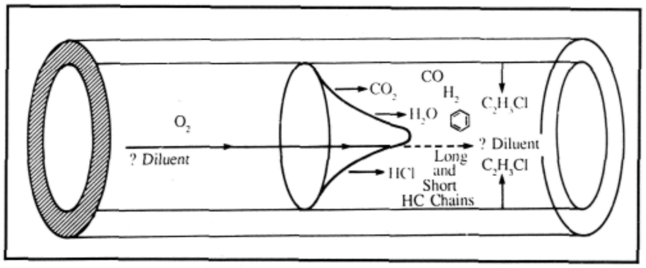

Fig. 5. Intraluminal flame products. Complete oxidation produces carbon dioxide, hydrochloric acid, and water. Incomplete oxidation produces carbon monoxide and deuterium (heavy hydrogen). Pyrolysis creates long and short hydrocarbon chains, aromatics (benzene structures, etc.), and vinyl chloride monomer.

products are toxic, such as carbon dioxide, carbon monoxide, hydrogen chloride, and benzene structures. All are fuels (save for water, carbon dioxide, and hydrogen chloride) capable of combustion on reaching a secondary oxidizing environment, producing a downstream flame at the free end of the tube.

The burning rate gives an indication of the rate of release of hot, toxic, combustible products. At low flows, the burning rate is quite low and approaches zero as the oxygen flow rate is decreased. Above approximately 8 $\text{lit}\cdot\text{min}^{-1}$ oxygen flow, the burning rate also decreases with increasing flow but is still significant at the point of blow out. Visually, the greater the oxygen flow the more violent the combustion, even beyond the maximum in burning rate. In fact, the tube is consumed to a significantly greater extent at the highest flows; ultimately, the tube is completely consumed by the spreading flame.[11]

There are two explanations for the equivalence ratio decreasing below one at the highest flow. First, as the flow rate increases the length of the intraluminal flame increases. When the intraluminal flame is close to the free end of the tube, as is the case at the beginning of the experiment, the flame does not "close" on the linear axis of the tube but emerges from the free end. Therefore, unreacted oxygen is emitted, reducing the equivalence ratio. This effect is basically an experimental one and can be eliminated by using longer tube sections. Second, as the flow rate increases so does the burning rate, until the tube-wall thickness can be completely consumed. In this case the flame, although not extinguished, runs out of fuel. The products emerging from the tube are still hot enough to vaporize fuel, but there is no tube wall remaining for volatilization. Therefore, the intraluminal flame again does not close, and oxygen is emitted.

Clinically, when a carbon dioxide laser is directed at the midsection of a tracheal tube, an intraluminal flame can be created at that point. A downstream flame can then be established in the ambient oxidant if (1) the oxidizer flow rate is such that the intraluminal flame produces sufficient fuel, and (2) there is sufficient ignition energy. That energy is available from two sources. The tail of the intraluminal flame can extend sufficiently to ignite the created fuel as it reaches the ambient oxygen, depending on the length of the tube in relation to the ignition location and the oxygen flow rate. A second ignition source exists in the residual heat of the gases created by the intraluminal flame and can be of sufficient energy for the gases to autoignite on reaching the ambient oxygen. Thus, the intraluminal flame is the generator of both fuel and ignition energy for the downstream flame, and therefore efforts to develop a laser-safe tracheal tube must also be directed toward prevention of intraluminal flame spread.

If laser ignition occurs during exhalation, the intraluminal flame can spread toward the alveoli and the downstream flame can be maintained in the breathing circuit and at the "blowhole" created by laser perforation. If laser ignition occurs during inhalation, the intraluminal flame can spread toward the breathing circuit, and the downstream flame can be maintained in alveolar oxygen and the "blowhole." In either case, the intraluminal flame does not propagate far from the ignition location in the time available before the respiratory flow changes direction. However, the products of the intraluminal flame contain copious amounts of smoke, which will be distributed far downstream at a flow rate controlled largely by the oxidant flow rate.

If the oxygen concentration on the outside of the tube exceeds the limiting oxygen index of flammability,[7,14] extraluminal shaft combustion can occur. Therefore, in the event of cuff perforation the tube should be replaced.

The data imply that laser ignition of tracheal tubes is least likely to occur in the absence of intraluminal flow. If ignition were to occur, the burn rate is least at low flow and the equivalence ratio is less than one, implying minimal fuel available for the downstream flame. Therefore, the character of a tracheal tube fire depends on the phase of the respiratory cycle in which the laser is activated. We propose that if the laser is activated during the exhalation pause, in the absence of flow, there would be the least likelihood of flame establishment. In distinction, the highest probability of establishing the most dangerous flame would be reached during the next inhalation phase. Further work to test this theory is in progress.

It would be ill advised to attempt to time the laser to correspond to flow rates above the upper flow limit, because this time is limited to less than a second and is not easily controlled. However, the time during the exhalation pause is considerably longer and can be controlled by the anesthesiologist. Therefore, a component of a possible fire mitigation strategy would be to time the laser to the exhalation pause, provided the actual flow rate during this time can be held below the lower flammability limit.

CONCLUSION

If an ignition source penetrates a tracheal tube wall, an intraluminal flame will propagate from the location of the ignition source toward the supply of oxidizer. The propagation velocity has been measured as a function of oxidizer flow rate using pure oxygen. The products of this intraluminal flame contain unreacted fuel gas that flows out of the ignition hole and free end of the tube. Depending on the oxidizer flow rate, these gases may be capable of supporting a secondary flame, termed the downstream flame. The burning rate and equivalence ratio associated with the intraluminal flame have been measured as an indication of the fuel available for the downstream flame.

The nature of tracheal tube fires depends strongly on the instantaneous flow rate of oxidizer. The instantaneous flow rate during the breathing cycle covers the entire range for which flammability is observed. Therefore, the clinical application of experimental results in which the flow rate is fixed must be made with caution. In the absence of flow, intraluminal flames cannot be established. Therefore, a future strategy for minimizing fire risk may involve the timing of the surgical device during the exhalation pause.

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