Anaesthesist 2018 · 67:426–447

<https://doi.org/10.1007/s00101-018-0445-2>

Received: 9 February 2018

Revised: 8 April 2018

Accepted: 11 April 2018

Published online: 15 May 2018

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Risks and prevention of surgical fires

A systematic review

Introduction

A surgical fire is an expression that arouses many questions; however, individuals are unlikely to consider potential procedural operation risks. A surgical fire is a rare complication that occurs in operation theatres worldwide and is often considered one of the few surgical ‘never events’, such as wrong-site surgery or retained surgical items [1]. Hence, a vast number of surgeons and anesthesiologists are unaware of this intraoperative risk. In the USA, the prevalence of surgical fires has been estimated at approximately 600 events per year, which make us question if it is possible to even consider it one of the “never events”. Since there are no reporting regulations or a formal critical incident reporting system, the total number of events is probably underestimated [2].

A surgical fire is a fire that occurs either in the patient themselves, e.g., in the trachea or respiratory tract or on the patient’s skin, explaining the inevitable life-threatening burns and associated in-

juries [3]. This is precisely the result in many cases where the endotracheal tube ignites like a blowtorch, causing severe damage to the airway and lungs [4]. To ignite a fire, only 3 factors must coincide and these circumstances are referred to in the literature as the “fire triad”, which consists of an oxidizer, an ignition source and a fuel [3]. This particular composition is mainly located in narrow spaces with low circulation, “trapping” air and volatile chemicals during the operation. These spaces are most likely to be found in the neck-nose-throat area; most of the surgical fire reports indicate that 25% are associated with otorhinolaryngological interventions [5].

This systematic review aims to call attention to this underestimated intraoperative risk and to determine the impact of each component of the fire triad. Moreover, we aim to raise surgical staff awareness to this hazard and thus prevent a surgical fire or in an unpreventable case, encourage them to react fast and to correctly protect the patient from major life-threatening injuries.

Inclusion criteria

Current scientific research on surgical fires has insufficient data with little scientific evidence. Due to the risk of injury and harm, no randomized controlled trials are available. Therefore, we strived to include prospective experimental laboratory and manikin trials, particularly those with a control group. Case reports and case series with precise event descriptions were also reviewed separately

in order to analyze and summarize the fire causes.

Sources of information

A literature search was conducted by screening PubMed, Livivo (Medline) and Google Scholar using various search terms, keywords and combinations. These search terms included, “Surgical Fire”, “Airway Fire”, “Fire in the OR”, “Fire Hazard”, “Fire Triangle”, “Fire Triad”, “Oxygen-enriched Environment”, “Fire Surgical Drape”, “Oxygen Pooling”, “Fire Supplemental Oxygen”, “Fire Prevention”, “Fire Protection”, “Fire Safety”, “Fire Electrocautery”, “Fire Electrocoagulation”, “Fire Laser”, and “Fire Skin Preparation”.

Risk of bias

With the risk of bias in non-randomized studies (ROBINS-I) tool, developed by members of the Cochrane Bias Methods Group and the Cochrane Non-Randomized Studies Methods Group, the statistical bias potential was collated and evaluated.

Statistics and limitations

The aim of the systematic search was a quantitative synthesis, according to the PRISMA search criteria and checklist (Fig. 1). After the data were extracted and summarized through RevMan software (Review Manager, Version 5.3., The Nordic Cochrane Centre, The Cochrane Collaboration, Copenhagen, Denmark),

Authors’ contributions

IK, NZ, GS: primary literature search; IK, AR, GS: secondary literature survey and appraisal; IK, GS, MC statistical analysis; IK, NZ and GS: interpretation of data and results, IK drafted the manuscript; NZ, RR, GS and MC corrected the manuscript; RR: final approval; GS: idea and supervision

All authors gratefully acknowledge and appreciate the statistical advice in methodology, interpretation of the results and final soundness provided by the Department of Medical Statistics, RWTH Aachen University, Faculty of Medicine, Aachen, Germany.

Fig. 1 ◀ PRISMA flowchart of the systematic research process

the preliminary results were presented and discussed at the Department of Biomedical Statistics of the RWTH Aachen University, Aachen, Germany.

It was advised that due to the lack of randomized controlled trials, the studies finally included should not be summarized in a meta-analysis. Statistically relevant information and experiments often differed regarding various study parameters:

- Test object: human versus animal versus textile or plastic,
- Number of cases versus dichotomous events,
- Lack of statistically relevant information: inter alia, *P* value, standard deviation,

- Group comparisons: experimental group versus control group or experimental versus experimental,
- Trial findings: fire versus fire risk.

Therefore, the context of all studies is comprehensively outlined by either a description or summary in tables. Additionally, the particular roles of oxidizers, fuel and ignition sources are evaluated.

Results

Risk of bias

Overall, the risk of bias result demonstrated a moderate risk for the observational trials (Table 1). Almost ev-

ery trial was conducted by assessors who were not blinded to the trial, which complicates the chance of not having any bias through the measurements and outcomes. Additionally, numerous experiments were performed only once for each condition, which creates bias due to highly probable random errors.

Most of the studies included were prospective, implicating a low risk of bias as a result of no confounding variables and classification of/deviation from the intervention. Moderate risk means that the studies provide sound evidence for non-randomized studies but cannot be considered comparable to well-performed randomized trials and there-

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Risks and prevention of surgical fires. A systematic review

Abstract

Surgically induced fire is a life-threatening hazard; this topic has received little attention, although only 3 factors, the so-called fire triad, are needed for surgical fires to occur: an oxidizer, fuel and an ignition source. This systematic review aims to determine the impact of each component and to delegate every staff member an area of responsibility, thus ensuring patient health through prevention or protection. The trial was registered in Prospero CRD42018082656. A database search of eligible, preferably evidence-based studies was conducted. The Robins-I tool for assessing the risk of bias revealed a moderate risk of bias. Due to insufficient data, the main findings of these studies could not be summarized through a quantitative synthesis;

therefore, a qualitative synthesis is outlined. The results are summarized according to the roles of the fire triad and discussed. (1) Role of the oxidizer: oxygen is the key component of the triad. Safe oxygen delivery is important. An oxygen-enriched environment (ORE) is caused by draping and is preferably prevented by suctioning. Fuel characteristics are affected by varying oxygen concentrations. (2) Role of the ignition source: electrocauterization is the most common ignition source, followed by lasers. Less common ignition sources include fiberoptic cables and preparative solutions, petrol or acetone. (3) Role of the fuel: surgical drapes are one of the most common fuels for surgical fires followed by the patient's hair and skin. Skin preparation solutions are

among the less common fuels. Many fire-resistant materials have been tested that do not remain fire resistant in ORE. It was concluded that the main problem is defining the real extent of this hazard. Exact numbers and exact condition protocols are needed; therefore, standardized registration of every fire and future studies with much evidence are needed. Immediate prevention consists of close attention to patient safety to prevent surgical fires from happening.

Keywords

Fire · Operation · Ignition source · Oxygen · Prevention

Risiken und Prävention chirurgisch induzierter Feuer. Eine systematische Übersicht

Zusammenfassung

Chirurgisch induzierte Feuer im Operationssaal sind eine für den Patienten in der Regel lebensbedrohliche Komplikation, die in der subjektiven Wahrnehmung aller an einer Operation beteiligten Personen eher vernachlässigt und nicht als aktives Risiko wahrgenommen wird. Dabei bedarf es zur Entstehung eines Feuers nur 3 paralleler Faktoren: Oxidans, Brennstoff und Zündquelle, zusammengefasst als die Feuertriade. Ziel dieser systematischen Übersichtsarbeit sind die Analyse und Bewertung jeder einzelnen Komponente des Verbrennungsdreiecks und deren Einordnung in den Berufsgruppen spezifischen Kontext, mit einer Festschreibung von Verantwortlichkeiten und dem gemeinsamen Ziel der Prävention. Die Studie wurde in Prospero (CRD42018082656) registriert. Dazu wurden verschiedene Datenbanken systematisch nach möglichst hoher Evidenz durchsucht sowie die „Treffer“ analysiert und bewertet. Das Risiko einer Verzerrung wurde mit „moderat“ (Robins-I-Modell) bewertet. Bedingt durch eine unzureichende Datenqualität (keine prospektiven randomisierten Studien, Tiermodelle, Kohorten

und Fallberichte/-serien) verbot sich eine quantitative Synthese der Daten. Aus diesem Grund werden die Ergebnisse qualitative-deskriptiv sowie in zusammenfassenden Tabellen und Diagrammen dargestellt. Die Ergebnisse wurden in Analogie zu ihrer Rolle in einem Verbrennungsdreieck wie folgt zusammengefasst und bewertet. (1) Oxidationsmittel: Sauerstoff ist die Schlüsselkomponente im Verbrennungsdreieck. Die Applikation von Sauerstoff bedarf hoher Sicherheitsstandards. Die Entstehung einer sauerstoffangereicherten Umgebung, verursacht beispielsweise durch Abdecktücher, kann durch die präventive Installation einer adäquaten Absaugvorrichtung verhindert werden. Die Charakteristika potenzieller Brennstoffe sind abhängig von der lokalen Sauerstoffkonzentration. (2) Zündquelle: Die Elektrokoagulation stellt, gefolgt von Lasern, die häufigste Zündquelle dar. Seltener ist der Zündvorgang durch fiberoptische Leitungen oder die Selbstentzündung von Desinfektionsmitteln und Benzin oder Aceton getriggert. (3) Brennstoffe: Abdecktücher aller Art sind der „Haupttreibstoff“ chirurgischer

Feuer, gefolgt von Körperbehaarung und Haut der Patienten. Seltener Brennstoffe sind Hautdesinfektionsmittel und Reinigungssubstanzen. Viele, vermeintlich „feuersichere“ oder „schwer entzündliche“, neue Abdeckmaterialien brennen in mit Sauerstoff angereicherter Umgebung trotzdem und entgegen der Vorgaben als Brennstoffquelle. Als Hauptschwierigkeit stellt sich die Bewertung des tatsächlichen Umfangs der Bedrohung durch chirurgische Feuer und eines potenziellen Schadens dar. Es mangelt an dringend notwendigen Informationen; genauen Zahlen, einer systematischen Erfassung aller Feuer im Operationssaal und einer exakten Definition der auslösenden Variablen und Konditionen. Die Erweiterung etablierter Safe-surgery-Protokolle um die Komponente „Determinanten zur Entstehung chirurgischer Feuer“ kann ein erster präventiver Schritt zu deren Verhinderung sein.

Schlüsselwörter

Feuer · Operation · Zündquelle · Sauerstoff · Vorbeugung

Table 1 Studies carried out on surgical fires and risk of bias

Author	Bias due to confounding	Bias in selection of participants	Bias in classification of intervention	Bias due to deviations from intended interventions	Bias due to missing data	Bias in measurement of outcome	Bias in selection of reported results	Overall bias
Barnes 2000 [12]	<i>Low risk</i> Prospectively determined study criteria	<i>Low risk</i> Selection of participants before study was performed	<i>Low risk</i> Definite classification before study was performed	<i>Low risk</i> No deviation	<i>Low risk</i> No missing data	<i>High risk</i> No information on blinding of assessor	<i>Moderate risk</i> No multiple outcome/analysis measurement different subgroups	<i>Overall Low to moderate risk</i>
Choudhry 2017 [19]	<i>High risk</i> Retrospectively determined search criteria	<i>High risk</i> Retrospective collection of 139 cases	<i>High risk</i> No precise information for every case	<i>Low risk</i> No deviation	<i>High risk</i> Missing data	<i>High risk</i> No information on preconception of reviewer	<i>Moderate risk</i> No multiple outcome/analysis measurements subgroups	<i>Overall Moderate to high risk</i>
Culp 2013 [16]	<i>Low risk</i> Prospectively determined study criteria	<i>Low risk</i> Experimental on 5 different fuel sources, determined before study was performed	<i>Low risk</i> Definite classification before study was performed	<i>Low risk</i> No deviation	<i>Low risk</i> No missing data	<i>High risk</i> No information on blinding of assessor	<i>Moderate risk</i> No multiple outcome measurement multiple analysis and subgroups	<i>Overall Low to moderate risk</i>
Eggen 1994 [21]	<i>Low risk</i> Prospectively determined study criteria	<i>Low risk</i> Experimental on surgical drape, determined before study was performed	<i>Low risk</i> Definite classification before study was performed	<i>Low risk</i> No deviation	<i>Low risk</i> No missing data	<i>High risk</i> No information on blinding of assessor	<i>Low risk</i> Multiple outcome measurement (6 times) subgroups	<i>Overall Low risk</i>
Greco 1995 [11]	<i>Low risk</i> Prospectively determined study criteria	<i>Low risk</i> Selection of 12 healthy volunteers before study was performed	<i>Low risk</i> Definite classification before study was performed	<i>Low risk</i> No deviation	<i>Low risk</i> No missing data	<i>High risk</i> No information on blinding of assessor	<i>Low risk</i> Multiple analysis/outcome measurements subgroups	<i>Overall Low risk</i>
Huddleston 2013 [8]	<i>Low risk</i> Prospectively determined study criteria	<i>Low risk</i> Selection of 33 patients before study was performed	<i>Low risk</i> Classification before study was performed	<i>Low risk</i> No deviation	<i>High risk</i> No precise presentation of all results	<i>High risk</i> No information on blinding of assessor	<i>Moderate risk</i> No multiple analysis/outcome measurement subgroups	<i>Overall Moderate risk</i>
Meneghetti 2007 [10]	<i>Low risk</i> Prospectively determined study criteria	<i>Low risk</i> Selection of 20 patients undergoing surgery before study was performed	<i>Low risk</i> Classification before study was performed	<i>Low risk</i> No deviation	<i>Low risk</i> No missing data	<i>High risk</i> No information on blinding of assessor	<i>Low risk</i> Multiple outcome measurements (left/right) subgroups	<i>Overall Low risk</i>
Mehta 2013 [6]	<i>High risk</i> Retrospectively determined search criteria	<i>High risk</i> Retrospective collection of 103 fire claims database research	<i>High risk</i> No precise information on every case	<i>Low risk</i> No deviation	<i>High risk</i> Missing data	<i>High risk</i> No information on preconception of reviewer	<i>Moderate risk</i> No multiple outcome/analysis measurement subgroups	<i>Overall Moderate to high risk</i>
Orhan-Sungur 2009 [9]	<i>Low risk</i> Prospectively determined study criteria	<i>Low risk</i> Selection of 13 volunteers before study was performed	<i>Low risk</i> Classification before study was performed	<i>Low risk</i> No deviation	<i>Low risk</i> No missing data	<i>High risk</i> No information on blinding the assessor	<i>Low risk</i> Multiple outcome measurements (left/right) subgroups	<i>Overall Low risk</i>

Table 1 (Continued)

Author	Bias due to confounding	Bias in selection of participants	Bias in classification of intervention	Bias due to deviations from intended interventions	Bias due to missing data	Bias in measurement of outcome	Bias in selection of reported results	Overall bias
Reyes 1995 [7]	Low risk Prospectively determined study criteria	Low risk Experimental measurements on different flow rates	Low risk Classification before study was performed	Low risk No deviation	High risk Missing data (only information on minimum parameters)	High risk No information on blinding the assessor	Moderate risk No multiple outcome measurements/analysis subgroups	Overall Low to moderate risk
Rocos 2012 [24]	High risk Retrospectively determined search criteria	High risk Retrospective collection of 13 cases through database research	High risk No precise information on every case	Low risk No deviation	High risk Missing data	High risk No information on preconception of reviewer	Moderate risk No multiple outcome/analysis measurement subgroups	Overall High risk
Roy 2011 [18]	Low risk Prospectively determined study criteria	Low risk Experimental; raw chicken with same properties	Low risk Classification before study was performed	Low risk No deviation	High risk Missing data (concentrations below 40% missing)	High risk No information on blinding the assessor	High risk No multiple outcome measurement/analysis or subgroups	Overall Moderate risk
Roy 2015 [17]	Low risk Prospectively determined study criteria	Low risk Experimental; ETTs with each varying oxygen concentration	Low risk Classification before study was performed	Low risk No deviation	Low risk No missing data	High risk No information on blinding the assessor	Moderate risk No multiple outcome measurements multiple analysis subgroups	Overall Moderate to low risk
Smith 2008 [20]	Low risk Prospectively determined study criteria	Low risk Experimental; 2 Fuels determined before study was performed	Low risk Classification before study was performed	Low risk No deviation	Low risk No missing data	High risk No information on blinding the assessor	Low risk Multiple outcome measurements (left/right) subgroups	Overall Low risk
Smith 2011 [23]	High risk Retrospectively determined search criteria	Moderate risk Standardized questionnaire, 349 completed; only 100 with exact details picked	High risk No precise information on every case	Low risk No deviation	High risk Missing data	High risk No information on preconception of reviewer	Moderate risk No multiple outcome/analysis measurement subgroups	Overall High risk
Tao 2013 [14]	Low risk Prospectively determined study criteria	Low risk Experimental on Sim-Man; 9 facial landmarks	Low risk Classification before study was performed	Low risk No deviation	Low risk No missing data	High risk No information on blinding the assessor	Low risk Multiple outcome measurements (left/right) subgroups	Overall Low risk
Van Cleave 2014 [13]	Low risk Prospectively determined study criteria	Low risk Experimental 8 deguttured chickens with same properties	Low risk Classification before study was performed	Low risk No deviation	Low risk No missing data	High risk No information on blinding the assessor	Low risk Multiple outcome measurements (left/right) subgroups	Overall Low risk
Williams 2006 [22]	Low risk Prospectively determined study criteria	Low risk Experimental; Fuels determined before study was performed	Low risk Classification before study was performed	Low risk No deviation	High risk Missing data on each trial that was performed	High risk No information on blinding the assessor	Low risk Multiple outcome measurements (left/right) subgroups	Overall Moderate

Table 1 (Continued)

Author	Bias due to confounding	Bias in selection of participants	Bias in classification of intervention	Bias due to deviations from intended interventions	Bias due to missing data	Bias in measurement of outcome	Bias in selection of reported results	Overall bias
Wolf 2004 [15]	Low risk Prospectively determined criteria	Low risk Experimental; 5 Fuel sources determined before study was performed	Low risk Classification before study was performed	Low risk No deviation	Low risk No missing data	High risk No information on blinding the assessor	Low risk Multiple outcome measurements (left/right) subgroups	Overall Low risk

ETT endotracheal tube

Table 2 Studies carried out examining the role of the oxidizer (oxygen)

Author/Reference	Study Type	Purpose	Sample Size	Methods	Results	Conclusion
Barnes 2000 [12]	Prospective experimental trial (non-randomized) (controlled)	Do oxygen-enriched atmospheres exist beneath surgical drapes and contribute to fire hazard potential in the operating room?	12 healthy volunteer Subjects	In supine position draped routinely at varying oxygen flowrates <i>Oxygen concentration was measured</i> (a) Without scavenger (control) (b) With scavenger (experimental)	<i>Oxygen concentration under drape</i> without supplementation; oxygen concentration < oxygen in room air with supplementation; oxygen concentration consistently elevated (> room air) (a) without scavenger – 3/6 oxygen concentration > 26% – Highest 44.67% (b) with Scavenger – 2/6 > 26% – Highest 34.08%	Oxygen enriched atmospheres develop and exist beneath surgical drapes, with flowrates as little as 1 l/min and increased significantly with flowrate. The scavenger system confirms efficacy; the oxygen concentration also rose, but reached only a mean concentration of 34.08%
Culp 2013 [16]	Prospective experimental trial (non-randomized) (non-controlled)	Flammability of surgical drapes and materials in varying concentrations of oxygen?	5 Fuel sources each at 3 different oxygen concentrations	<i>Flammability of 5 Fuel sources were analyzed under 3 varying oxygen concentrations</i> 21% (room air) 50% 100% Time to ignite till complete burn was measured	<i>Median Ignition Time</i> 21%; 0.9 s 50%; 0.4 s 100%; 1.7 s Utility drape, surgical gowns did not ignite in room air	The time to ignite till total burn decreased as the oxygen concentration increased. Flammability characteristics differed by material. Some fuels did not ignite in room air but did in oxygen enriched atmosphere (oxygen 50%/100%)

Table 2 (Continued)

Author/Reference	Study Type	Purpose	Sample Size	Methods	Results	Conclusion
Greco 1995 [11]	Prospective experimental trial (non-randomized) (non-controlled)	Potential dangers of oxygen supplementation during facial surgery?	12 healthy volunteer subjects	In supine position draped routinely at varying oxygen flow rates Oxygen concentration was measured beneath the drape and at the operative field	No oxygen supplementation → Oxygen concentration beneath the drapes lower than oxygen concentration in ambient air <i>Supplemental Oxygen</i> → Oxygen concentration beneath the drapes consistently elevated (levels at 53.5%) → Oxygen concentration at operative field only mildly, not significantly elevated when compared with ambient air → Discontinuation of oxygen supplementation for period of time – operative field; levels below 23.5% in 30 sec – beneath drapes; patients still had significantly elevated levels beneath drape at that time	Study demonstrates: (1) Oxygen that a patient breathes under the drapes quickly drops below that of room air if no supplemental oxygen is administered. (2) Oxygen pooling occurs under drapes even with relatively low oxygen flow rates. Oxygen pooling can increase the risk of explosion. (3) Concept of discontinuing oxygen supplementation: → at flow rates > 3 l/min after 60 sec still an oxygen enriched environment
Huddleston 2013 [8]	Prospective Experimental trial (non-randomized) (non-controlled)	Fire risk during ophthalmic plastic surgery?	33 Patients	Oxygen enriched environment (ORE) often caused by leakage of oxygen into surgical field → measuring oxygen concentration across the face using nasal cannula, face mask	ORE in periorbital area? Nasal cannula → 0/102 Readings Face mask → 21/70 Readings	<i>Properly positioned nasal cannula</i> → no ORE around the eyes regardless of flow rate used <i>Facemask</i> → demonstrates areas of potential fire risk around the eyes with normal flow rates
Meneghetti 2007 [10]	Prospective experimental trial (non-randomized) (non-controlled)	Operating room fires: optimizing safety?	20 Patients undergoing facial cosmetic surgery	2 commonly used methods providing supplemental oxygen (1) Nasal cannula (2) Nasopharyngeal tube Oxygen concentrations were compared at variety of points about the face	All sites superior of nostrils → with nasal cannula oxygen concentration significantly higher than nasopharyngeal tube	Statistically significant reduction in oxygen concentration using nasopharyngeal tube → oxygen concentration in the operative field were consistent with ambient air even at points extremely close to oxygen source

Table 2 (Continued)

Author/Reference	Study Type	Purpose	Sample Size	Methods	Results	Conclusion
Mehhta 2013 [6]	Retrospective trial	Operating Room fires. A closed claims analysis	103 OR Fire claims	Closed malpractice Claims in the ASA closed claims database since 1985 were reviewed. All claims related to OR Fires → analysis of fire related claims was performed to identify causative factors	Electrocautery-ignited fire details; Sources Supplemental oxygen MAC (1) Nasal Cannula 53% (2) Facemask 34% (3) ET Tube 0% GA (4) ET Tube 71% (5) Facemask 21%	Critical role of oxygen by open delivery system during use of electrocautery. 95% Oxygen as the oxidizer of electrocautery induced OR Fires
Orhan-Sungur 2009 [9]	Prospective experimental trial (non-randomized) (non-controlled)	Effect of nasal cannula oxygen administration on oxygen concentration at facial and adjacent landmarks?	13 volunteers	In supine position, draped. Oxygen delivery through nasal cannula at varying oxygen flowrates. Oxygen concentration was measured at pre-determined facial landmarks	2 l/min, 4 l/min; 11/12 and 8/12 → oxygen concentrations did not exceed 24.9% → Exceptions were within 10 cm of the outlet of nasal cannula 6 l/min → Oxygen concentrations at facial landmarks were greater (mean oxygen concentration ≥24.9%)	Concern; Supplemental oxygen is heavier than ambient air which causes Oxygen pooling under drapes. Confirmed hypothesis To reduce combustion risk, ignition sources should be kept at least 10 cm from oxygen outlet when using nasal cannula at flowrate 4 l/min
Reyes 1995 [7]	Prospective experimental trial (non-randomized) (non-controlled)	Supplemental oxygen: ensuring its safe delivery during facial surgery?	5 flowrates a 3 Coagulation Levels (N= 15)	Supplemental oxygen through nasal cannula & electrocautery coagulation as the potential for flash fire → Study determines the minimum conditions for combustion on Fiberglass Model	Minimum Parameters for ignition (1) Oxygen Flowrate 2 l/min (2) Coagulation level 30 W (3) Distance 5 cm from oxygen source	Supplementation → oxygen should be delivered deep within upper respiratory tract to prevent oxygen on electrocautery sites → Oxygen should be delivered intermittently, when electrocautery unit is not in use
Roy 2011 [18]	Prospective experimental trial (non-randomized) (non-controlled)	What does it take to start an oropharyngeal fire? Oxygen requirements to start fires in the operating room?	6 Flowrates repeated twice on raw chicken (N= 12)	Mechanical model to assess oxygen parameters necessary to start fire. ETT in central cavity of raw chicken oxygen at varying flow rates and FiO_2 electrocautery at setting 15 W	FiO_2 100% → ignition + sustained flame >45% → ignition + sustained flame ≤45% → no ignition	Chicken model has several advantages: organic, tissue based model electrosurgical device can be grounded Cavity within chicken; 300–400 ml (closely approximates oral cavity) Ideal intraoperative FiO_2 → balances risk of fire ignition with risk of hypoxia to maximize patient safety

Table 2 (Continued)

Author/Reference	Study Type	Purpose	Sample Size	Methods	Results	Conclusion
Roy 2015 [17]	Prospective experimental trial (non-randomized) (controlled)	Prevention of airway fires: testing the safety of endotracheal tubes and surgical devices in a mechanical model?	2 ETTs with each 5 varying oxygen concentrations with Laser, and repeated with RFA (N = 20)	Simulated airway surgery: Study to assess ability of CO ₂ Laser & radiofrequency ablation devices to ignite non reinforced ETT and laser-safe Tubes, at varying Oxygen concentrations (21%/29%/44%/53%/60%)	<i>Non-laser safe ETT</i> Ignition at any O ₂ Concentration <i>Lasersafe ETT</i> No ignition at any O ₂ Concentration <i>RFA</i> no ignition of either non-laser-safe/laser-safe ETT	RFA no risk of ignition in simulated airway surgery. CO ₂ Laser should be used with reinforced ETT → no laser-safe ETT easily ignites Reducing the Fraction of inspired oxygen, reduces the fire risk
Tao 2013 [14]	Prospective experimental Trial (non-randomized) (non-controlled)	The efficacy of a mid-facial seal drape in reducing oculofacial surgical field fire risk?	SimMan 9 facial landmarks, without/with mid-facial seal drape +4 under the drape (N = 22)	Controlled experiment using SimMan patient simulator and oxygen detector. Oxygen was measured at 9 facial surgical locations at varying flowrates with FiO ₂ 100%. Using nasal Cannula in draped/undraped condition	<i>Difference in mean oxygen concentration between draped/undraped</i> mean undraped 26.3% mean draped 21.4% below the drape 52.9% → Draped condition; provided safe oxygen concentration levels at all 3 flowrates. → Undraped condition; Suprathreshold oxygen concentration	A midfacial seal drape may reduce fire risk oxygen levels → may minimize risk of intraoperative fire risk
Van Cleave 2014 [13]	Prospective experimental trial (non-randomized) (non-controlled)	The effect of intraoral suction on oxygen-enriched surgical environments: a mechanism for reducing the risk of surgical fires	41 Trials on 8 raw degutted chicken	Mechanical Model was applied in order to replicate potential surgical fire conditions with/without Suction at different Locations	Overall ignition, audible pop and flash significantly more likely without suction: E. g. Location; Overall → No Suction; 62% Ignition → Suction; 10% Ignition	Suction can inhibit entirely/highly reduce qualitative severity of surgical fires. Limited by exact conditions that lead to fire
Wolf 2004 [15]	Prospective experimental trial (non-randomized) (non-controlled)	Laser ignition of surgical drape materials in air, 50% oxygen, and 95% oxygen	5 Fuel sources a 3 varying oxygen concentrations	<i>Time to ignition (TTI) of currently used drape materials in;</i> air 50% oxygen 95% oxygen materials that did not ignite, were tested for secondary ignition	Ambient Air: Phenol polymer & Polypropylene did not ignite 50% O ₂ Phenol polymer advantage compared with Polypropylene 95% All materials ignite within 0.68 s	<i>Increasing Oxygen Concentration, the TTI becomes shorter and the consequences more severe.</i> supplemental oxygen should be delivered by clinical judgement choice of drape materials on manufacturers with data on primary/secondary flammability in Air and ORE

ORE oxygen rich environment, TTI time to ignition, ASA American Society of Anesthesiologists, GA general anesthesia, MAC managed anesthesia care

Fig. 2 ▲ Role of the oxidizer

fore cannot be summarized through a quantitative synthesis.

Role of the oxidizer

A total of 13 studies were included in the analysis regarding the role of the oxidizer (■ Fig. 2): 12 studies were prospective experimental trials, and 1 trial was a retrospective analysis of closed claims related to surgical fires (■ Table 2).

In summary, the identified studies assessed the oxygen concentration in different ways, following the premise and emphasizing that oxygen-enriched environments do contribute to a gross fire hazard risk. The evidence from these studies can be subdivided based on their main findings into 3 statements:

1. Safe oxygen delivery

- In 95% of cases, oxygen is the oxidizer in electrocautery-induced OR fires [6].
- Oxygen should be delivered deep within the upper respiratory tract and intermittently when

an electro-surgical unit is not in use [7].

- Facemasks provide an ORE in comparison to a nasal cannula [8].
 - For nasal cannulas, to reduce the combustion risk, ignition sources should be kept at least 10 cm from the oxygen outlet when using nasal cannulas at a 4 l/min flow rate [9].
 - Nasopharyngeal tubes show a statistically significant reduction in oxygen concentrations in the operative field in comparison to a nasal cannula [10].
2. Oxygen-enriched environments due to draping are potentially reduced through scavenger systems.
- Without supplemental oxygen, the level of oxygen that a patient breathes under the drapes quickly drops below the level of oxygen in room air [11].
 - Oxygen pools under the drapes [11, 12].

- Concept of discontinuing oxygen at flow rates >3 l/min is not successful; oxygen concentration after 60 s still elevated [11].
 - Suctioning/scavenger systems completely inhibit and/or reduce the qualitative severity of surgical fires [12, 13].
 - A mid-facial seal drape may reduce the intraoperative ORE [14].
3. Effects of fuel characteristics on varying oxygen concentrations
- Time to ignite (TTI) shortens with increasing oxygen concentrations [15, 16].
 - Flammability differs between material [15, 16].
 - Reducing the fraction of inspired oxygen reduces the fire risk [17].
 - A chicken model (organic tissue) shows that the ideal intraoperative FiO₂ balances the risk of fire and risk of hypoxia [15, 18].

Fig. 3 ▲ The role of the ignition source – a synopsis of risk and prevention (ETT endotracheal tube, OR operating room, FIS fiberoptic illumination system)

Role of the ignition source

The included studies can be subdivided based on their main findings into 3 subgroups and statements (■ Fig. 3, ■ Table 3).

1. Electrocautery
 - High-energy devices (e.g., electrocautery) are the most frequent cause of ignition and injury [19].
 - The electrosurgical unit is the most common ignition source (59%) [20].
 - Burn-/fire-related incidents with an electrosurgical unit are more frequent ($n=71$) than those with fiberoptics ($n=25$) [18].
 - Of 103 fire claims, 90% indicated electrocautery as the ignition source, 81% occurred during MAC (monitored anesthesia care), and 95% occurred with supplemental oxygen [6].
 - Supplemental oxygen should be used with caution and at a sufficient distance from electrosurgical devices [7].
2. Laser
 - Non-electrocautery fires are mainly caused by medical lasers [6].
 - Lasers are the second most common ignition source (32%) [20].
 - CO₂ lasers should be used with only laser safe ETT and surgeons

should consider alternatives such as RFA (radiofrequency ablation); laser-safe and regular ETT do not ignite [17].

3. Fiber optic
 - Fiberoptic lights are one of the less common ignition sources [20].
 - FIS is still a potential ignition source [21].
 - With forced air warming blankets through fiberoptic light, no fires occurred, but on other materials, it still ignites [22].

Role of the fuel

In total, 5 studies are prospective experimental trials, with 3 trials being retrospective (■ Fig. 4, ■ Table 4).

Overall, all studies assessed the most common fuels in different ways, following the premise that fuels labelled “fire resistant” still ignite in an oxygen-enriched environment.

Study matches can be subdivided into 3 subgroups based on their main findings.

1. Surgical drapes
 - Drapes and towels are among the most common fuels [23].
 - There are numerous cases of OR drape-related fires, with polypropylene drapes being less flammable than cellulose drapes [20].
2. Alcohol preparation solution
 - Alcohol preparation solution use has been identified in a number of electrocautery-induced fires [6].
 - Despite manufacturers’ warnings, surgical fires continue to occur mainly because alcohol preparation solution is not given sufficient time to dry or because drapes and swabs are often soaked in this solution at an unsafe distance from a potential ignition source [24].
3. Fire-resistant versus regular fuels
 - Being the most common fuel identified, reinforced laser-safe ETT that are tested are fire safe and do not ignite while using CO₂ laser [23]. Only the distal tip (not reinforced) is not fire resistant [17].

- Of the tested drape materials under room air levels of oxygen, mainly polypropylene lacked the ability to ignite, and cotton material rapidly burned [16].
- The choice of draped materials should consider the proximate use of ignition sources. No combustion in room air was observed with the tested materials phenol polymer and polypropylene, but when testing second ignition, only phenol polymer lacked the ability to ignite [15].

Table 3 Role of ignition source

Author/ Reference	Study type	Purpose	Sample size	Methods	Results	Conclusion
Choudhry 2007 [19]	Retrospective	Surgical Fires and Operative Burns: Lessons Learned From a 33-Year Review of Medical Litigation?	139 Cases	Westlaw; online research dataset → data collected on patient, procedure and case characteristics	139 Cases 82% operative burns 18% Surgical Fires 43% Most common source of injury → high energy device	High energy devices continue as the most cause of injury → understanding and addressing pitfalls in operative care may mitigate errors and potentially lessen future liability
Eggen 1994 [21]	Prospective Experimental trial (non-randomized) (non-controlled)	Fiberoptic illumination systems can serve as a source of smoldering fires	6 × 2 Experiments	<i>First experiment</i> FIS end was held perpendicular to drapes, varying distance from 0–5 mm, repeated 6 times <i>Second experiment</i> 45° angle to drapes at distance 0–5 mm, repeated 6 times	<i>First experiment</i> >4 mm no combustion <i>Second experiment</i> >2 mm no combustion	FIS should not be in close proximity to any combustible material → FIS end potential ignition source
Mehta 2013 [6]	Retrospective	Operating Room Fires—A Closed Claims Analysis?	103 OR Fire Claims	Closed malpractice Claims in the ASA closed Claims database since 1985 were reviewed. All Claims related to OR Fires → analysis of fire related claims was performed to identify causative factors	90% Electrocautery is the ignition source → most electrocautery induced fires during MAC (81%) → 95% with supplemental oxygen	Electrocautery induced fires during MAC → critical role of supplemental oxygen by open delivery during use of electrocautery Causes of nonelectrocautery fires included lasers ($n = 9$) and a defibrillator ($n = 1$), occurring between 1989 and 2003. high fire risk procedures → fire prevention protocol
Reyes 1995 [7]	Prospective experimental trial (non-randomized) (non-controlled)	Supplemental oxygen: ensuring its safe delivery during facial surgery?	5 flowrates a 3 Coagulation Levels ($N = 15$)	Supplemental oxygen through nasal cannula & electrosurgical coagulation as the potential for flash fire → Study determines the minimum conditions for combustion on Fiberglass Model Electrosurgical Unit at 20, 30, 40 coagulation Level	<i>Coagulation Level 20</i> 1 cm Distance to oxygen <i>Coagulation Level 30</i> 5 cm distance to oxygen <i>Coagulation Level 40</i> 5 cm distance to oxygen	Electrosurgical coagulation in presence → potential source of fire → supplemental oxygen with caution and enough distance to electrosurgical device
Roy 2015 [17]	Prospective experimental trial (non-randomized) (controlled)	Prevention of airway fires: testing the safety of endotracheal tubes and surgical devices in a mechanical model?	2 ETTs with each 5 varying oxygen Concentrations with Laser, and repeated with RFA ($N = 20$)	Simulated airway surgery: Study to assess ability of CO ₂ Laser & radiofrequency ablation devices to ignite non-reinforced ETT and laser-safe Tubes, at varying Oxygen concentrations (21%/29%/44%/53%/60%)	<i>Non-laser-safe ETT</i> Ignition at any O ₂ Concentration <i>Laser-safe ETT</i> No ignition at any O ₂ Concentration <i>RFA</i> no ignition of either non-laser-safe/laser-safe ETT	RFA no risk of ignition in simulated airway surgery. CO ₂ Laser should be used with reinforced ETT → no laser-safe ETT easily ignites Reducing the Fraction of inspired oxygen, reduces the fire risk

Table 3 (Continued)

Author/ Reference	Study type	Purpose	Sample size	Methods	Results	Conclusion
Smith 2008 [20]	Prospective (non-randomized) (controlled)	Fire/burn risk with electro-surgical devices and endoscopy fiberoptic cables?	2 Fuels atop/buried within tested with electro-surgical device, fiberoptic light (N = 8)	Systematically explore fire risk on 2 Fuels associated with (1) Fiberoptic cables, (2) Electro-surgical devices Review of MAUDE (manufacturer and user facility device experiences) → reportable occurrences involving fiberoptic light and electro-surgical devices from 1998–2006	<i>Fiberoptic Cable</i> resting cable on top → no ignition burying – yellow discoloration in cotton – hole in polypropylene <i>Electrosurgical device</i> burned immediately through polypropylene	<i>Reviewed</i> 25 burn/fire related incidents involving fiberoptic cables 71 electro-surgical units
Smith 2011 [23]	Retrospective trial	Operating room fires in otolaryngology: risk factors and prevention?	349 completed questionnaires 100 with details	Questionnaire was designed to elicit characteristics of OR Fires experienced by otolaryngologists and send to 8523 members of American academy of otolaryngology	88/100% 1 OR Fire/Career 10/100 2 OR Fire/Career 2/100 5 OR Fire/Career	<i>Electrosurgical unit is the most common</i> Ignition source (59%) Laser 32% Light cord 7%
Williams 2006 [22]	Prospective Experimental trial (non-randomized)	Fiberoptic light source-induced surgical fires—the contribution of forced-air warming blankets?	Each material 10 trials over gown (control) or lying over FAWB	Fiberoptic light sources as fire ignition source: Study to determine whether forces-air warming blanket (FAWB) could affect ignition/spread of fire versus 5 different types of material	No smoke Polyaminated non-woven Reinforced Polyaminated Smoke Basic fabric Reinforced woven fiber layers <i>Damage to patient gown?</i> (1) No Damage to underlying patient – Polyaminated no woven material – Reinforced Polyaminated – Basic fabric (2) Damage to underlying Patient – Reinforced woven – Reinforced Foam <i>With FAWB?</i> No Damage to gown occurred through any part of drape during any trial	<i>In actual surgical setting</i> → FAWB can provide protection for patient skin <i>FAWB creates 2 layers</i> → superior layer often melted → forced air prevented inferior layer from coming into contact with fiberoptic light source thus protecting underlying patient gown

FAWB forced air warming blanket

Fig. 4 ▲ Role of the fuel

- A forced-air warming blanket (FAWB) can provide protection to the patient's skin. The FAWB creates 2 layers. The superior layer often melts, whereas the forced air prevents the inferior layer from coming into contact with the ignition source [22]

Discussion

Role of the oxidizer

Oxygen is crucial for breathing. Despite being crucial for life, oxygen is an element with potentially devastating consequences. In the context of surgical fires and the fire triad, oxygen plays the key role. No oxidizer means no oxygen feeding the fire. Hardly any specific fuel and ignition sources are needed when the oxygen concentration reaches 100% and autoignition becomes possible even for inert fuels, such as particles in dust or patients' hair. Only friction is needed for heat as an ignition source.

In summary, the major issue to prevent surgical fires is to prevent the occurrence of an oxygen-enriched environment (ORE). Illuminating the role of oxygen in fire ignition, we must understand that there is a lower flammability limit and an upper flammability limit (LFL and UFL). Limiting fuel concentrations may support flame propagation. Fuel

concentrations outside that range are inflammable. The limiting oxygen concentration is the minimum O₂ concentration that will propagate flame [25]. Oxygen enrichment significantly increases the fire hazard of materials by widening the specific flammability limits, namely, decreasing the LFL and increasing the UFL while decreasing the minimum energy needed for ignition. Material ignites more easily and burns more rapidly [26]. Nevertheless, choosing a fire-resistant and probably safe material is hard to realize because even if these materials are fire resistant in room air, their flammability characteristics change within OREs.

How does oxygen enrichment occur precisely? Supplemental oxygen leads to pure oxygen accumulating in the more basal regions covered by the surgical drapes. Oxygen is of a higher specific weight compared to room air and results in "oxygen pooling" [7]. Therefore, why not operate without supplementary oxygen?

In a spontaneously breathing patient, oxygen is utilized, and oxygen concentrations under tight drapes quickly drop below that in room air [11]. If supplementation of oxygen is necessary, which strategies might be safe to prevent an ORE? Van Cleave et al. [12] and Barnes and Frantz [13] both proved the efficacy of suction systems to clear the ORE under the drapes in order to prevent surgi-

cal fires. A second optional intervention is keeping oxygen preferably in a closed supplementation system through intubation directly deep in the patient's respiratory tract to keep oxygen from leaking into the lower areas. Huddleston et al. [8] and Meneghetti et al. [10] proved that a nasal cannula inhibits the occurrence of OREs better than a facemask but is inferior compared to endotracheal intubation [8, 10].

Especially when an electrosurgical unit is used, it is suggested that oxygen delivery should be stopped for at least 1 min [27]. Thus, with higher flow rates of oxygen even after a 60 s stop in supplementation, an ORE is still present [11], and it is doubtful whether surgeons are willing to interrupt an ongoing operation for some minutes before electrocoagulation.

With respect to the surgeons' and scrub nurses' responsibilities for compatible hardware and situational awareness, it still remains the anesthesiologists' duty to maintain the balance between sufficient oxygenation and avoidance of hypoxia by managing to keep the supplementation of oxygen as safe and low as possible to prevent any hypothetical occurrence of a surgical fire. This might be achieved by using plain air and low concentrations of oxygen on healthy patients.

Table 4 Role of the fuel

Author/Reference	Study type	Purpose	Sample size	Methods	Results	Conclusion
Culp 2013 [16]	Prospective experimental trial (non-randomised) (controlled)	Flammability of surgical drapes and materials in varying concentrations of oxygen?	5 Fuel sources each at 3 different Oxygen concentrations	Flammability of 5 Fuel sources were analyzed 1. Blue operating towel (cotton) 2. Utility Drape (Polypropylene) 3. Surgical gown (Polypropylene) 4. Surgical Drape (Polypropylene) 5. Laparotomy sponge (cotton) <i>under 3 varying oxygen concentrations</i> 21% (Room Air) 50% + 100% (ORE) Time to ignite till complete burn was measured	Room Air: Combustion – Laparotomy sponge – Blue operating room towel – Surgical Drape <i>No combustion</i> – Utility Drape – Surgical gown <i>ORE</i> – Every sample did burn	Utility drape and surgical gown mainly out of polypropylene → do not ignite in Room Air, but in ORE Mainly cotton material rapidly burned even in room air Burn time decreased as oxygen levels increased
Mehta 2013 [6]	Retrospective Trial	Operating Room Fires. A Closed Claims Analysis?	103 OR Fire Claims	Closed malpractice claims in the ASA closed Claims database since 1985 were reviewed. All Claims related to OR Fires → analysis of fire related claims was performed to identify causative factors	Alcohol Containing Prep Solution 12%	Wet alcohol containing prep solutions have been implicated in a number of cautery induced fires (however use of supplemental oxygen is the predominant cause in most OR Fires)
Rocos 2012 [24]	Retrospective Trial	Alcohol skin preparation causes surgical fires?	Database Research	NRLS (national reporting and learning service database) was interrogated for all incidents of surgical fire between 3/2004–3/2011 Every report manually revised to discover the cause of fire	13 surgical Fires reported 11 directly related to spirit based surgical skin preparation/preparation soaked swabs and drapes – 8 Cases Chlorhexidine – 1 Case Povidone-Iodine (alcohol based) Ignition source Solution soaked drapes	Despite manufacturer's instructions and warnings, surgical fires continue to occur <i>Main Causes</i> Skin preparation solution not being given enough time to dry Swabs soaked with fluid were left in operating field in unsafe distance to ignition source Solution soaked drapes
Roy 2015 [17]	Prospective (non-randomized) (controlled)	Prevention of airway fires: testing the safety of endotracheal tubes and surgical devices in a mechanical model	2 ETTs with each 5 varying oxygen Concentrations with Laser, and repeated with RFA (N = 20)	2 ETTs 1. Laser-safe ETT (aluminium/fluoroplastic wrapped silicon) 2. Traditional ETT 3. (Polyvinylchloride) with each 5 varying oxygen Concentrations with Laser, and repeated with RFA	Phase 1 CO ₂ (1) Traditional ETT – Room Air: Ignition but no sustained Flame – ORE: immediate sustained flame (2) Laser-safe ETT – No ignition/sustained flame at any oxygen concentration – just distal tip (metallically not reinforced) resulted in ignition Phase 2 RFA no ignition of either ETT	Non-reinforced ETT (Traditional ETT) should never be used when CO ₂ Laser-safe ETT behaved good as expected → one important finding is that distal tip of laser tube is not protective against fire formation

Table 4 (Continued)

Author/Reference	Study type	Purpose	Sample size	Methods	Results	Conclusion
Smith 2008 [20]	Prospective (non-randomized) (controlled)	Fire/burn risk with electrosurgical devices and endoscopy fiberoptic cables	2 Fuels atop/buried within tested with electrosurgical device, fiberoptic light (N = 8)	Systematically explore fire risk associated with fiberoptic cables, electrosurgical devices on; (1) Cotton towel (2) Polypropylene Drape	<i>Fiberoptic Cable</i> resting cable on top → no ignition burying – yellow discoloration in cotton – hole in polypropylene <i>Electrosurgical device</i> – burned immediately through polypropylene	Numerous Cases of OR drape related fires Polypropylene drapes & cotton towels are less flammable than cellulose drapes. <i>Advisory</i> neve leave a fiberoptic cable resting on drape/towel Polypropylene rather than cellulose
Smith 2011 [23]	Retrospective Trial	Operating room fires in otolaryngology: risk factors and prevention	349 Completed Questionnaires 100 with details	Questionnaire was designed to elicit characteristics of OR Fires experienced by otolaryngologists and send to 8523 members of American academy of otolaryngology	88/100% 1 OR Fire/Career 10/100 2 OR Fire/Career 2/100 5 OR Fire/Career <i>most common Fuels</i> 1. Endotracheal Tube 39% 2. OR Drapes/towels 18% 3. Flash Fire 11% <i>Less common</i> Alcohol based preparation solution Sponges Hair/skin	<i>Highest risk procedures (Surgical scenarios in which fire occurred)</i> 27% Endoscopic airway procedure 24% Oropharyngeal surgery 23% Cutaneous/transcutaneous surgery 18% Tracheostomy 81% occurred while supplemental oxygen was in use
Williams 2006 [22]	Prospective Experimental Trial (non-randomized)	Fiberoptic light source-induced surgical fires—the contribution of forced-air warming blankets?	Each material 10 trials over gown (control) or lying over FAWB	Fiberoptic light sources as fire ignition source: Study to determine whether forces-air warming blanket (FAWB) could affect ignition/spread of fire versus 5 different types of material	<i>No smoke</i> Polyaminated non-woven Reinforced Polyaminated <i>Smoke</i> Basic fabric Reinforced woven fiber layers <i>Damage to patient gown?</i> (1) No Damage to underlying patient – Polyaminated no woven material – Reinforced Polyaminated – Basic fabric (2) Damage to underlying Patient – Reinforced woven – Reinforced Foam <i>With FAWB?</i> No Damage to gown occurred through any part of drape during any trial	In actual surgical setting → FAWB can provide protection for patient skin FAWB creates 2 layers → superior layer often melted → forced air prevented inferior layer from coming into contact with fiberoptic light source thus protecting underlying patient gown

Table 4 (Continued)

Author/Reference	Study type	Purpose	Sample size	Methods	Results	Conclusion
Wolf 2004 [15]	Prospective experimental trial (non-randomized) (non-controlled)	Laser ignition of surgical drape materials in air, 50% oxygen, and 95% oxygen	5 Fuel sources and 3 varying oxygen concentrations	Time to ignition (TTI) of currently used drape materials in Room Air and ORE. (1) Huck towels (2) 3 commonly used surgical drapes materials that did not ignite, were tested for secondary ignition	Room Air No combustion Phenol polymer Polypropylene Combustion Huck towel Cotton polyester Non-woven cellulose-polyester ORE All tested materials ignited Secondary ignition Just Phenol polymer no second ignition	Choice of drape materials should involve consideration of proximate use of ignition source secondary ignition test is a necessary component to flammability

Table 5 Flashpoints of various materials and gases

Paper	360°
Cotton	450°
Polypropylene	390–410 °C
Phenol polymer	480°
Polyvinylchloride	455 °C
Isopropanol	12°
Povidine iodine	>100 °C

Role of the ignition source

When reflecting on a fire in the operating room, the first thought might be how is it possible for a fire to ignite so easily in such a setting? In this context, we need to understand some basics of chemistry and physics. Chemically speaking, combustion is an exothermic redox reaction with heat emission. First, the educts are in a metastable state of equilibrium, e.g. carbon and oxygen react with activation energy to carbon dioxide and heat. Following this, the reaction continues independently due to the emitted heat serving as the activating energy. In accordance with the principles of Le Chatelier, if we raise the educt concentration parallel to the oxygen concentration, the equilibrium would move to the side of the products, causing more combustion [28]. For example, by raising the oxygen concentration, the activation energy needed is lowered [26]. At a certain point, the activation energy is so low that reactions are induced without any added activating energy. Energy is withdrawn by the surrounding area, resulting in exergonic, spontaneous combustion [28]. For activation energy in the context of a surgical fire, the ignition source is electrocautery in 90% of the reviewed cases [6], followed by laser energy [20]. In the case of laser application, the hazards of combustion are well known, and most of the time, necessary precautions are implemented. Using laser-safe endotracheal tubes instead of regular endotracheal tubes serves as a good example and might be neglected when electrosurgical units are used in this setting. When the activation energy decreases in an ORE, even a fiber optic cable might cause ignition [20, 21]. High-frequency energy (syn. diathermy, electrosurgery, radiofrequency surgery)

with at least 200 kHz and up to 200° is used to cut, devitalize, coagulate or thermofuse with low or no hemorrhage and belongs to the substantial surgical devices in every OR [29].

A laser is a technical device with a medium such as gas (CO₂ laser) or a crystal (YAG laser) emitting radiation that has a particular wavelength. Laser light is absorbed by tissue and causes the thermal destruction of tissue proteins, meaning laser coagulation. The advantage of laser-associated surgery is the in-depth precision it has. Additionally, it has several applications in ophthalmology, otorhinolaryngology and dermatology, which are high-risk disciplines in relation to surgical fires [30]. These high-energy devices are frequently used in highly specialized operations and might hardly be eliminated from clinical practice just to prevent surgical fires.

Frequent efforts have been made to make electrosurgical devices more fire safe in order to reduce the incidence of OR fires. A shroud of protective carbon dioxide covering the tip of the electrosurgical pencil displaces oxygen and hereby prevents ignition [31]. From the surgeons' point of view, knowledge of the risk on surgical fires during the procedure is mandatory, especially if an oxygen source is in near proximity to the surgical field. Second, it is crucial that there is a high level of awareness throughout the entire procedure. The high-energy device should never be left uncovered, and oxygen supplementation should be restricted or even stopped before the device is used.

Role of the fuel

In summary, frequent materials used in the operating room can serve as a fuel under the right circumstance. Smith and Roy [23] named the most common fuels: endotracheal tubes and surgical drapes. Less common fuels include preparation solutions and the patients' hair or skin. To define fire-safe materials, various surgical drape materials under varying oxygen concentrations have been investigated [16, 20]. The materials tested showed that polypropylene and phenol polymer do not ignite under room air

Table 6 Case reports

Paper	Patient	Oxygen delivery	Ignition source	Fuel
Supplemental oxygen: Ensuring its safe delivery during facial Surgery [7] Fires during surgery; Two fatal Incidents in LA [34]	55-year-old woman basal cell carcinoma dorsum of nose	Supplemental oxygen 5 l/min	Electrosurgical unit used for hemostasis	Alar region → flash fire → ignited the suction tubing
	19-year-old infant emergency cardiac surgery	Oxygen enriched environment	ESU Pencil	Gauze sponge + surgical drapes
	26-year-old woman emergency surgery after car accident	Oxygen enriched environment	ESU System	Surgical drapes (out of cellulose material)
Fiberoptic illumination System can serve as a source of smouldering fires [21]	32-year-old woman laparoscopy	General anesthesia → no oxygen enriched environment	FIS cable (max. intensity)	Surgical drape
	60-year-old man transurethral resection of prostate	Nasal oxygen → oxygen enriched environment	FIS cable	Paper drapes
Fiberoptic light source-induced surgical fires—the contribution of forced-air warming blankets [22]	25-year-old man laparoscopic appendectomy	General anesthesia	Fiberoptic light	Surgical drapes FAWB DuraPrep Solution (74% alcohol based)
	62-year-old man tracheostomy	?	Electrocautery	DuraPrep solution → drying for 3 min Drape copious body hair Polyvinylchloride ETT
Fatal inhalation injury caused by airway fire during tracheostomy [36]	45-year-old man emergency tracheostomy	Intubated with cuffed ETT Ventilated with 100% oxy prior to tracheal incision	Diathermy	
Fire in the operating room: a case report and laboratory study [37]	73-year-old man bilateral parietal burr holes to evacuate subdural hematoma	MAC Clear plastic mask 6 l/min	ESU to incise pericranium	Head was shaved skin prepared with iodine in 74% isopropyl alcohol → 2 min drying time
Fire in the surgical Center [38]	50-year-old woman bilateral blepharoplasty compression garment caught fire and fire spread through oxygen catheter + patients face	Supplemental oxygen through spectacle-type catheter 4 l/min	Monopolar electric scalpel increased scalpels power to obtain appropriate hemostasis	Antisepsis with CHX Surgical drape with opening
Electrocautery induced Airway fire during tracheostomy [39]	33-year-old woman elective tracheostomy after 15 min loud pop + fire in the surgical field	Supplemental oxygen	Electrocautery device	Povidone iodine surgical drapes
Burn Center Management of Operating Room Fire injuries[40]	65-year-old woman basal cell carcinoma on face → require	Flowrate 5 l/min	Electrocautery unit	Surgical drape
	39-year-old woman elective plastic surgery for excision of three peri-orbital lesions	Supplemental Oxygen via Face-mask	Electrocautery	Face mask
	14-year-old girl surgical excision of a nasal polyp	Supplemental Oxygen at 2 l/min	Electrocautery	Surgical sponge oral O ₂ Cannula
82-year-old man caecal perforation → right hemicolectomy		Abdominal gas	Monopolar diathermy	Povidone-iodine 10% solution surgeons hand

Table 6 (Continued)

Paper	Patient	Oxygen delivery	Ignition source	Fuel
Letter to the Editor [41]	74-year-old male reopening of thoracotomy	FiO ₂ 0.8	Electrocautery	Tissue surgical drape
Fires in the operating room [42]	2-year-old boy hemiorthaphy	Inhalation Sevoflurane CO ₂ Absorbent	–	Anesthesia machine
A rare cause of Fire in the Operating Room [43]	42-year-old man right upper lobectomy	Gas leak through the lung tissue Supplemental oxygen at 10l/min	Electrocautery	Gauze
Alcohol based surgical prep solution and the risk of fire in the operating room. [44]	25-year-old male burst fracture C6 vertebra → decompression	Intubated for close circuit	Electrocautery	Cutasept (63% Isopropanol)
Intraoperative flash fires associated with disposable cautery [45]	3-year-old child dermoid excision	Intubated uncuffed endotracheal tube no significant leak	Electrocautery	Cotton
	66-year-old woman	Nasal cannula 3 l/min oxygen pooling under drapes	Electrocautery	Draped below chin
	Large keratocanthoma	1 l/min mask	Electrocautery	Drape
Airway fire during surgery: Management and prevention [46]	8-year-old boy adenotonsillectomy	ETT 6 l/min big leak around ETT	Electrocautery	ETT caught fire
Fires and burns occurring in an electrocautery after skin preparation with alcohol during neurosurgery [47]	33-year-old man hematoma evacuation	–	Monopolar electrocautery	Disinfected with 75% alcohol
Electrocautery ignited Surgical Field Fire caused by high oxygen Level during Tracheostomy [48]	76-year-old man coronary artery bypass	ORE	Electrocautery	povidone iodine surgical drapes
Operating Room flash fire from use of cautery after aerosol spray [49]	42-year-old woman cholecystectomy	Supplementation of O ₂ NO	Electrocautery	Aerosol spray
Surgical field fire during repair of bronchoesophageal fistula [50]	74-year-old man esophagectomy adenocarcinoma	100% oxygen after hypoxemia	Electrocautery	Sponge
Free gas in the peritoneal cavity: the final hazard of diathermy [51]	77-year-old woman laparotomy for repair of suspected bowel perforation	Abdominal gas	Cutting diathermy	Patient tissue explosion
A Patient who was burned in the operative field [52]	47-year-old woman laparoscopic cystectomy + myomectomy	–	Electrosurgical unit	Large amount of alcohol disinfection skin on abdomen + surgical drape
Cardiac arrest following ventilator fire: a rare cause [53]	65-year-old woman subtotal thyroidectomy	O ₂	Electrically driven ventilator	Ventilator explosion
Fires in the operating room and intensive care unit awareness in the key to prevention [54]	74-year-old woman tracheostomy	ETT fraction of inspired oxygen 40%	Electrosurgical unit	Povidone iodine/isopropyl alcohol surgical drapes

Table 6 (Continued)

Paper	Patient	Oxygen delivery	Ignition source	Fuel
Fire during Thoracotomy, a need to control the inspired oxygen concentration [53]	66-year-old man thoracotomy for mesothelioma	Lung air leakage	Electrocautery	Dry lap tape caught fire
Fire in the operating room during tracheostomy [55]	4-year-old boy tracheostomy	NO 50% oxygen gas anesthetics	Electrocautery	Povidone iodine
	14-year-old boy tracheostomy	NO oxygen anesthesia	Electrocautery scalpel blade	Open tracheal lumen
	Obese adult	NO 50% oxygen → oxygen advanced to 100%	Electrocautery	Flash fire from from tracheostomy site

FIS fiberoptic illumination system, ETT endotracheal tube, MAC managed anesthesia care, ESU electro-surgical unit, CHX chlorhexidine

conditions. With respect to the flash-points for gases/liquids and ignition temperatures for solids, all of them do have solid high temperatures (Table 5).

Of 35 case reports (Table 6), surgical drapes were frequently advocated as the fuel.

Ignition temperatures for solids (cotton, polypropylene or phenol polymer) are almost similar.

Cotton itself ignites very fast due to high permeability to air and has a higher surface than compressed synthetic material. Second, polypropylene or phenol polymer drapes are almost always strengthened with fire-resistant substances.

Preparation solutions are a less frequent but an unneglectable source of fuel. Povidone iodine itself has a flashpoint at 100° but it is mostly a mixture containing 70% isopropanol [32], which has a flashpoint at only 12° and is highly flammable. These solutions should always be given the right amount of time to dry and vaporize [27]. In analogy, for swabs, which are mostly made of cotton, the ignition temperature would be over 400° but if they are still soaked in isopropanol and positioned around the operative field, they are a considerable hazard that may result in ignition and induction of a surgical fire.

For the prevention of surgical fires, the routine use of fire-resistant materials, dressings and blankets might be a hypothetical solution. Thus, most of these materials, even “inflammable” materials, might ignite in an ORE. For example, polypropylene and phenol polymer do not ignite in room air, but they do ignite in 50% oxygen [16]. In addition, this concentration might be found under surgical drapes caused by “oxygen pooling”. Thus, the component that seems to be the less influenceable is the fuel. Scrub nurses or operation assistants have to guarantee that highly inflammable materials, such as soaked drapes or swabs, are not positioned in proximity to any ignition source. Furthermore, preparation solutions must be given the time needed to dry and evaporate before the operation starts.

Practice advisory (Fig. 5)

1. Education: teach fire safety, with emphasis on the risk created by oxygen-enriched atmospheres.
2. Rehearsal: OR fire drills, in which a formal rehearsal with the entire OR team with simulation and training on surgical fire is conducted.
3. Preparation: scoring and discussing the fire risk.
4. Prevention strategies

First and foremost, it is mandatory to take precautions to prevent a surgical fire from occurring. According to the Memorial Medical Center, a fire risk assessment tool should be added to every OR checklist before a procedure starts. The tool consists of scoring the potential risk of the triad components and their interventions. An overlapping task, regardless of the components, is a team conversation in which the score is defined and channelling and tunnelling between an oxygen-rich environment and the surgical field is prevented.

The main findings of the interventions are summarized regarding their role.

1. *Oxidizer intervention* consists of discontinuing oxygen supplementation for at least 1 min prior to the use of an ignition source and titrating the oxygen concentration to the lowest concentration possible. Furthermore, considering ETT, use either cuffed for airway surgery or a laser-safe one when a laser is utilized.
2. *Ignition source intervention* consists of leaving the electrosurgical device in a holster 100% of the time, the laser on stand-by when not in use, and the fiber optic light source “off” when not in use. Use of an ignition source should be announced.
3. *Fuel intervention* consists of preventing pooling of prep solutions and allowing these solutions to dry for at least 3 min. Furthermore, saline-soaked sponges and sterile water are needed in the field to extinguish a potential fire [33].

According to the American Society of Anesthesiologists, if the fire occurs in the airway then the tracheal tube has to be removed first, followed by turn-

Fig. 5 ▲ Practice advisory, see text for details

ing off any supplementation of gases. All flammable materials should then be removed, and saline should be poured into the patient's airway. In the case of a non-airway fire, it is not necessary to remove the tracheal tube. Once the fire is extinguished, ventilation should be maintained or re-established, and in the case of an airway fire, the tracheal tube should be checked and a bronchoscopy has to be considered [3]. If the fire cannot be extinguished at the first attempt, a CO₂ extinguisher should be used, followed by activating the fire alarm, evacuating the patient, closing the OR door and turning off the gas supply to the room [3]. Immediately after the patient's status is stable and the situation is under control, a record of the exact operating conditions should be taken, including oxygen flow rates, oxygen delivery methods, the ignition source, and the fuel that caught fire first.

Conclusion

Surgical fires are a rare but life-threatening complication in the OR. The real prevalence of surgical fires is uncertain. The "fire triad", consisting of an ignition source, an oxidizer and fuel, illustrates the interaction of these components and emphasizes the fatal role of an oxygen-enriched environment. Even "fire-safe" materials may be flammable or at least smouldering in oxygen-rich environments. With respect to the further prevention of this "never event", mandatory protocols should be implemented in OR safety guidelines [33]. Moreover, in the case of a fire, operational procedures to counteract the fire should be presented and trained. Finally, a standardized reporting system would increase our knowledge of potential catalysis and of the total number of surgical fires. The best method of protection is situational awareness of all team members (■ Fig. 6) and, at the least, basic knowledge about

the specific components in the individual setting, leading to the ignition of a surgical fire.

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Compliance with ethical guidelines

Conflict of interest. I. Kezze, N. Zoremba, R. Rossaint, A. Rieg, M. Coburn and G. Schälte declare that they have no competing interests.

This article does not contain any studies with human participants or animals performed by any of the authors.

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Fig. 6 ▲ Fire triad components regarding staff members. Modified according to [24, 56]

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Lesetipp

Traumatische Verletzungen der Halswirbelsäule

Die traumatischen Verletzungen der Halswirbelsäule umfassen neben den Verletzungen in Folge eines Hochrasanz-Traumas auch die sogenannten Niedrigenergie-Traumen, meist verursacht durch „einfache Stürze“ älter werdender Patienten.

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