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Reducing the risk of oxygen-related fires and explosions in hospitals treating Covid-19 patients

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ABSTRACT

On 24 April 2021, a disastrous fire in an Iraqi hospital took the lives of 82 people. Since the outbreak of the pandemic in March 2020, incidents of oxygen-related hospital fires in various countries around the world have caused over 200 deaths, the majority of whom were patients extremely ill with the novel Coronavirus. Fires involving medical oxygen are not a new phenomenon but are more common in the operating theatre where oxygen is routinely administered. In these settings, strict safety protocols are normally enforced and surgical staff are well trained in dealing with oxygen hazards. It appears that some hospitals may not have been fully prepared for the elevated risk of oxygen-related fire in intensive care units due to the high demand for oxygen therapy in severely ill Covid-19 patients. Indeed, gas producers and public health authorities were also slow to recognize and alert hospitals to the potential dangers. Oxygen is essential to life and generally makes up about 21 % of the gases in the air we breathe. Pure oxygen reacts with common materials such as oil and grease to cause fires, and even explosions, when released at high pressures. A leaking valve or hose, and openings at interfaces of masks and tubes, when in a confined space or where air circulation is low, can quickly increase the oxygen concentration to a dangerous level. Even a small increase in the oxygen level in the air to 24 % can create a fire hazard. In an oxygen-enriched environment, materials become easier to ignite and fires will burn hotter and more fiercely than in normal air. There is also a potentially heightened risk of using ethanol-based and organic solvents as cleaning agents in an oxygen rich atmospheres. This paper will provide an overview of oxygen accident scenarios that may be relevant for hospital intensive care units, with particular reference to recent events and similar accidents that have occurred in the past. The paper will recommend that hospitals recognize their chemical risks as part of their risk governance responsibility and assign chemical risk management a prominent role in their overall management. Investigation of dangerous events to extract causes and lessons learned should be utilized to highlight opportunities for prevention as well as emergency response. The industrial gas industry also needs to actively support hospitals in adoption of more rigorous risk management approaches, building on lessons learned in chemical process safety for managing flammable and explosive atmospheres.

1. Introduction

Since the outbreak of the Covid-19 pandemic in March 2020, incidents of hospital fires in various countries around the world have caused the deaths of over 200 people, the majority of whom were patients extremely ill with the novel Coronavirus. The worst tragedy to date occurred on 24 April 2021 when a deadly fire tore through a Baghdad hospital, killing at least 82 people and injuring more than 100 others. Yet months before there was already evidence that oxygen-related fires have been occurring at alarming frequency since the start of the pandemic. JRC research conducted after a hospital fire killed 11 people in Gazantiep, Turkey on 19 December 2020, counted over 20 incidents of fires caused by oxygen-rich environments in hospitals reported in the media occurring between March and the end of December 2020 (European Commission Joint Research Centre (JRC), 2021). By June 2021, nearly 40 incidents have been reported, of which at least half resulted in death and injury. Of these, 21 resulted in at least one

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fatality with many incidents causing multiple fatalities, mainly among patients already extremely ill from the Covid-19 virus. Although in other cases, hospitals successfully responded to such incidents and avoided injury, most events still required evacuation of staff and severely ill patients, while at the same time depriving oxygen ventilation to those in critical condition for the duration of the event.

These incidents appear to be a direct result of the rapid increase in ventilator use in hospitals due to the COVID-19 outbreak. The concentrated presence of oxygen ventilators in an enclosed area, such as a hospital room, can create an oxygen-enriched environment. Oxygen is not toxic but it maintains combustion. It normally makes up around 21 % of the atmosphere by volume. However, when its concentration exceeds 23 %, it can create a fire hazard. Pure oxygen reacts with common materials such as oil and grease to cause fires, and even explosions, when released at high pressures.

This paper will describe how higher concentrations of oxygen can lead to serious fires in medical settings where oxygen therapy is used in patient treatment. It will give evidence of the particular dangers it poses for Covid-19 intensive care units (ICUs), where there may be several ventilators located in one room, and conditions within the ICU that can make a fire more or less likely to occur. The paper will recommend that hospitals consider ICUs as potentially hazardous environments and suggest borrowing strategies developed for chemical process safety in managing flammable and explosive atmospheres to prevent accidents that can lead to loss of life and significant material damage.

2. Oxygen hazards and hospital experiences with oxygen-related fires

In the course of saving lives and ensuring successful recovery from illness, hospitals use chemicals in many forms. Some of these chemical products may be hazardous. For example, hazardous chemicals are routinely used for cleaning, disinfecting and sterilizing work surfaces, medical supplies and instruments. Oxygen and nitrous oxide are oxidizing agents that are widely employed in healthcare for various patient treatments, such as respiratory ailments, surgery and hyperbaric therapy. The use of these oxidizers can expose staff and patients to severe fire and explosion hazards if the proper precautions are not undertaken. The hazardous character of oxygen, in particular, has become increasingly evident with the intense use of oxygen therapy for extremely ill Covid-19 patients.

2.1. Properties of oxygen

Chemists and process safety specialists recognize the hazardous aspects of oxygen in relation to its contribution to corrosion and its role in chemical reactions. The European Industrial Gases Association (EIGA) identifies the following properties of oxygen that are relevant in managing oxygen-related risks in hospitals: (European Industrial Gases Association, 2018).

- Most materials burn fiercely in oxygen and the reaction can even be explosive. As the oxygen concentration in air increases, the potential fire risk increases and combustion is accelerated.
- Oxygen gives no warning. As a colourless, odourless gas, and without any obvious physiological effect on humans, oxygen and oxygen-enriched atmospheres cannot be detected by normal human senses.

The heightened risk of oxygen-rich atmospheres is explained through the classic theory of the fire triangle. Three elements are required to produce a fire or explosion (see Fig. 1):

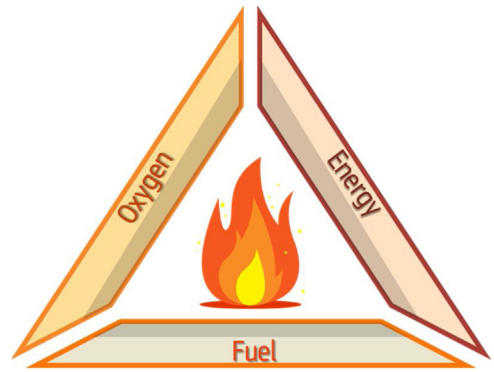

Fig. 1. The fire triangle.

- combustible material (fuel)
- oxygen
- an ignition source (energy)

When one of these elements is not present, a fire cannot occur. As the oxygen concentration and pressure in the atmosphere increases, the fire will become more vigorous. At the same time, the minimum temperature or ignition energy needed to produce the combustion reaction is much lower. Moreover, as the oxygen concentration increases, the temperature of the flame will also increase higher and consequently the destructive capability of the flame is greater.

Oxygen also reacts with most materials, in particular, all organic materials and most metals, such that, almost anything can be a fuel source in the presence of oxygen. Even materials that would not normally burn in air, including fire-resistant materials, can burn vigorously in oxygen-enriched air or pure oxygen environments. Items made of elastomers, textiles and plastics with a high surface area will burn quite fiercely.

Furthermore, flammable materials, such as oil, grease and cleaning solvents, will become even more flammable in oxygen-rich atmospheres. With an excess of oxygen, they will burn with great intensity so that fire spreads quickly and burns rapidly through more fire-resistant materials, including metal components of equipment and infrastructure.

Fires involving medical oxygen are not a new phenomenon but are more common in the operating theatre where oxygen is routinely administered. In the last ten years, there has been considerable attention from the American fire prevention and anesthesiology community to prevention of fires in operating theatres after the Emergency Care Research Institute (ECRI), a global nonprofit patient safety organization based in the United States, cited surgical fires in third place on its list of top ten health technology hazards. At the time ECRI estimated that 500–600 surgical fires occurred annually in the United States alone (Emergency Care Research Institute (ECRI), 2009). As a result, a number of US-based organizations including the American Society of Anesthesiologists, the Anesthesia Patient Safety Foundation, the Emergency Care Research Institute, and the U.S. Food and Drug Administration have produced written and video-based guidelines on fire prevention in operating rooms (OR) (Anaesthesia Patient Safety Foundation (ASPF), 2021; Apfelbaum et al., 2013; Emergency Care Research Institute (ECRI), 2021; U. S. Food and Drug Administration (FDA), 2018).

Notably, the 2010 campaign to raise awareness of surgical fire risks was a re-launching of awareness surrounding these risks that had been around for decades, but that had declined with the move away from flammable anesthetics in the 1960s and 1970s. The reduction in the use of flammable anesthetics, a particularly explosive fuel source in oxygen-rich environments, only removed one obvious and particularly dangerous element of the fire triangle. It was not widely recognized that other changes in surgical practice could also elevate risk. For example, the increasing use of laser technology in the 1990s introduced a potential ignition source for some types of operations, and thus, completed the fire triangle, given that oxygen treatment remains an operating room staple, and that most materials are combustible (Yardley and Donaldson, 2010).

The U.S Fire Administration, a division of the U.S. Federal Emergency Management Agency (FEMA), also issued a technical report in 1999 addressing the hazards of oxygen-enriched atmospheres while presenting lessons learned from ten flash fire incidents related to medical oxygen cylinders Incidents were mostly related to emergency medical service agencies and fire departments but not hospital settings. The findings, although clearly represent the hazards of oxygen enriched atmospheres, are limited to failures of oxygen cylinders and flow components such as regulators and valves while there is no information addressing tertiary ignition sources or electrical failures related to hospitals or ICUs.

2.2. Risk of oxygen-related fires due to intense use of oxygen therapy for Covid-19 patients

Intensive care units will generally be equipped to deliver oxygen therapy for patients who need large volumes and help keeping the air sacs in their lungs open. Covid-19 patients may proceed from low-flow oxygen supplementation via nasal cannula to a nonrebreather (NRB) face mask. If their condition worsens, they may then be offered mechanical ventilation, including non-invasive ventilation (NIV) administered via masks, high flow nasal cannula,[1] or intubation (so-called invasive ventilation). Oxygen supply can be delivered through portable oxygen tanks (of nearly pure oxygen), through pipeline delivery systems that reply on the presence of an oxygen station, including an oxygen generator and a bulk liquid oxygen supply, and various types of medical oxygen concentrators that can be portable or stationary and absorb oxygen from the air.

Oxygen-rich environments in ICUs generally can result from any number of emission sources, including leaking valves and hoses, and openings at interfaces of masks and tubes. When in a confined space or where air circulation is low, these emissions can quickly increase the oxygen concentration to a dangerous level. Almost anything can be considered fuel for an oxygen-enriched fire, and everything burns more intensely, alcohol and oil-based substances will burn most vigorously and even explosively. Apparel and linen may burn more fiercely while the efficiency of fire-redundancy of physical barriers installed to minimize virus contagion, such as cubicle curtains, may be affected resulting in an elevated burning rate. The most common source of ignition is electrical, usually a short circuit in nearby electrical equipment (and on rare occasions, the ventilator itself). However, the intense use of mechanical ventilators for Covid-19 patients may also overload the electrical infrastructure, causing electrical wires to heat up and start a fire. Notably, the intense use of oxygen for Covid-19 patients also can elevate risk in oxygen storage and supply systems for a variety of reasons, for example, by creating stress on older delivery systems, increasing portable tanks in storage, more opportunities for handling and storage errors, etc.

The most common medical oxygen sources and their characteristics are represented in Table 1. Delivery of gaseous oxygen to ICU and medical ward endpoints can be achieved via oxygen cylinders, oxygen plants and liquid oxygen transformation systems and oxygen concentrators. While oxygen plants and transformation systems and some oxygen cylinders can be connected to a pipeline distribution system, portable cylinders and concentrators are directly connected to the equipment serving each individual patient. Thus, oxygen cylinders and concentrators can be found in close vicinity to patients while requiring substantial user interaction to operate. It is not within the scope of this study to address the hazards of liquid oxygen systems.

Table 1
Common medical oxygen sources and their characteristics (World Health Organization and the United Nations Children's Fund, 2019).

Medical oxygen sources & Characteristics	Connection to pipeline distribution system	Electricity-powered	Direct connection to patient	User care
Cylinders	Yes	No	Yes	Moderate
Concentrators	No	Yes	Only	Moderate
Oxygen plant (PSA)	Only	Yes	No	Minimal
Liquid oxygen transformation	Only	No	No	Minimal

3. Oxygen-related fires in hospitals

Nowadays in most parts of the world it is considered good practice for hospitals to identify and manage their safety and health risks. The risk assessment process generally starts with hazard identification, after which the hazard is evaluated in terms of frequency and potential harm and a risk level is associated with the hazard. A review of literature on oxygen-related hazards seems to indicate that oxidization hazards outside the ICU may not be routinely considered as risks of high significance.

3.1. Awareness of oxygen hazards outside the operating theatre

In contrast to surgical fires, until recently, there has been very little written about potential risks of oxygen-enriched environments outside the operating room. Sankaran et al. describes two successive incidents of electrical fires in a neonatal care unit (NICU) in 1998 (Sankaran et al., 1991). In a 1994 paper on non-anesthetic hospital, MacDonald acknowledges that, on rare occasions, incidents have occurred in association with hospital oxygen storage and distribution systems, oxygen tanks, and nebulizers (MacDonald, 1994). There is no mention of the risk of fire associated with oxygen therapy treatment in other contexts, in particular, within the ICU, including neonatal ICUs and maternity wards that also may use oxygen treatments (e.g., incubators and oxygen hoods).

Risks associated with oxygen-enrichment are most often mentioned in nursing publications but much harder to find outside this domain. In particular, very little information can be found on oxygen fire hazards in guidance on hospital management, oxygen treatment, and management of ICUs. Zuazua Rico et al. noted as recently as 2015 (or thereabouts, the publication is undated) that "The risks added to an intensive care unit under normal conditions versus to other hospital services are little analyzed in the existing bibliography. The large amount of oxygen used by mechanical ventilation devices, in addition to the number of electronic devices arranged around the patient, create an environment that is certainly dangerous that is not taken into account among workers (Zuazua Rico et al., 2021)." Zuazua also published survey results in 2015 that indicated that 73.1 % of 67 intensive care nurses at a hospital in Spain were unaware of the risks present in the hospital and in the ICU (Zuazua Rico, 2015). These observations echoed an earlier claim by Gowardman and Moriarty that "There is little reported . . . concerning the potential problems of mixtures of electricity and

[1] High-flow nasal cannula (HFNC) therapy is an oxygen supply system capable of delivering up to 100 % humidified and heated oxygen at a flow rate of up to 60 L/min. Conventional nasal cannula generally delivers at rates of up to 5 L/min.

gases which support combustion in intensive care units where this combination is frequent (Gowardman and Moriarty, 1998)."

The National Health Service of the United Kingdom published its Review of Five London Hospital Fires and their Management, and exclusively targeted dissemination of lessons learned associated with the emergency response without any prevention recommendations (Wapling et al., 2009). Murphy and Foot's 2011 paper highlights that many hospital ICUs are not adequately prepared to respond to a fire emergency, citing the frequency of hospital fires, but it does not specifically consider the possibility of fire hazards originating in the ICUs (Murphy and Foot, 2011). In its fact sheet concerning 2012–2014 hospital fire data, the U.S. Federal Emergency Management Agency (FEMA) attributed hospital fires to 12 different sources but does not mention the potential contribution of elevated levels of oxygen (U.S. Federal Emergency Management Agency (FEMA), 2021). Data presented in *Hospitals Don't Burn*, the Hospital Fire and Evacuation Guide, published by the Pan-American Health Organization (PAHO) and the World Health Organization (WHO) in 2018, outlines eight main contributors to hospital fires, based on U.S. National Fire Protection Association data, but oxygen-enriched environments are not mentioned (Pan-American Health Organisation and World Health Organization, 2018). Neither publication refers to the role that oxygen treatments can contribute to fire hazards in hospitals, neither in association with ICUs or operating theatres. The data, as indicated in Fig. 2, do show typical ignition sources for oxygen-related fires, including cooking, heating, electrical equipment and appliance malfunction, open flame, and smoking.

3.2. Incidence of serious hospital fires involving oxygen prior to 2020

Although early versions of the modern oxygen ventilator have been used in ICUs since the 1970s, there is no substantial record of serious oxygen-related fires occurring outside the operating room before the mid-2000s. A search in Google in English and European languages, as well as Arabic, Chinese, Japanese and Korean, turns up one incident in which a respirator exploded in the Maimonides Medical Center in Brooklyn, New York, in 1993, killing 3 patients (The New York Times, 2021). Two fires in maternity wards, where infants are supported by oxygen incubators, are reported to have occurred in India and the United States in 2008 and 2009 (CTV News, 2021; Economic Times, 2021). Chowdhury lists 51 hospital fires that occurred between 2004 and 2012 in various parts of the world (but mostly India), of which 11 incidents are associated with incubators and ventilators. Since Chowdhury only lists the sources of the fire, it could be that several others in the list may also have been associated with intensive care units. Indeed, four more accidents indicate that babies either died or were saved from the fire, suggesting that oxygen treatment of infants may have played a role (Chowdhury, 2013).

There are other fires in hospitals reported since 2000 that also seem to indicate the possible involvement of an oxygen-rich environment. If media reports can be considered reliable, there sometimes appears to be no suspicion that an oxygen-enriched environment may have played a role even when the event started in an ICU. Those that appeared to involve oxygen-enriched environments are listed in Table 2. For example, media reports indicate the fire in Calderon Guardia Hospital, San Jose, Costa Rica on 12 July 2005, that killed 19 people (16 patients and 3 staff), probably started from an electrical short in or near the neurosurgery unit where patients were on respirators. A medical report on the fire highlights the materials used in the hospital that probably helped to fuel it, and points out that most of the victims were trapped in the neurosurgery unit on respirators. It is notable that rapid escalation is a characteristic of oxygen-enriched fires. According to the medical report on the Calderon Guardia Hospital fire, there was "evidence of [patients] not having been able to move from their place" and it is presumed that this is because the patients were either unconscious or attached to respirators (Villalobos and Sanabria, 2006). While these explanations are plausible, another explanation is that the fire, being fed by an oxygen-rich atmosphere, spread too quickly to allow escape or rescue of these infirm individuals. The level of awareness of oxygen hazards in hospitals may also depend on the past experience of the country. As shown in Table 2, there have been relatively recent incidents, prior to the 2020 Covid-19 pandemic, of serious fires in intensive care units in India and the United Kingdom. These incidents appeared to have caused medical communities in these countries to pay attention to the causes of the fires, in particular, the role of oxygen, rather than focusing only on the response. By and large, it appears that in many countries, it is not common practice to investigate hospital fires to identify lessons learned for preventing them.

A search of scientific literature produces only four articles on lessons learned for preventing oxygen-related fires in the ICU that have been published since Sankaran et al. described the incidents occurring in the neonatal intensive care unit in 1991 (Sankaran et al., 1991). Chowdhury cites 34 incidents of fires in Indian hospitals since 2004, noting that they all occurred in locations where O_2 was being administered to patients, such as the ICU, NICU, and OR and that they involved air conditioners and electrical equipment in the vicinity of the O_2 application (Chowdhury, 2013). Five years later a group of Indian authors, Dahliwal et al., also published an article on a dangerous fire that occurred in the intensive care unit of a northern Indian hospital in 2015 including lessons learned for preventing them (Dhaliwal et al., 2018). Similarly, Kelly et al. published a detailed report on a fire in an intensive care unit that occurred on 21 November 2011. In their report, Kelly et al., provide new insights on both prevention and response to fires in the ICU (Kelly et al., 2014). This incident, along with two other unrelated hospital fires in the United Kingdom, was specifically cited in Guidelines for the Provision of Intensive Care published in 2018 by the Faculty of Intensive Care Medicine (FICM) and the Intensive Care Society (ICS). The guidelines can be considered truly groundbreaking as it appears to be the first recommendations to hospital management for preventing such incidents, rather than focusing solely on how to respond should they occur (Faculty of Intensive Care Medicine (FICM) and the Intensive Care Society (ICS), 2019). In 2017 Yartsev also published a summary of the recommendations in current literature on prevention and response to fires in intensive care units (Yartsev, 2017).

Karim et al. warn about the dangers associated with medical gas management that rely mainly on oxygen cylinders, citing that emerging economies such as Vietnam, Bangladesh and India, are particularly vulnerable, but accident history also indicates that highly developed countries, such as the U.S., are not immune (Karim et al., 2016). Similarly, Sarangi et al. contend that medical clinicians are not sufficiently aware of the importance of the design, installation, commissioning, and operation of medical gas pipeline systems to hospital safety (Sarangi et al., 2018). Lack of proper installation and maintenance of the oxygen supply system can also increase the potential for an oxygen-related fire. In 2019, two people were killed and 47 injured in a fire in a nursing hospital in Gimpo, Korea because of wrong procedures during maintenance of the oxygen pipeline supply system with the location of the oxygen tank in the boiler room (where combustible materials are present) cited as a potentially contributing factor (Korea Gas News Mobile Site, 2019).

Interestingly, media reports on the recent hospital fires in Romania in 2020 and 2021 also indicate a high awareness of the potential role of oxygen. A detailed interview of the manager of the Matei Bals hospital, that experienced a devastating fire on 29 January 2021, killing 24 people (directly due to the fire or because of oxy-

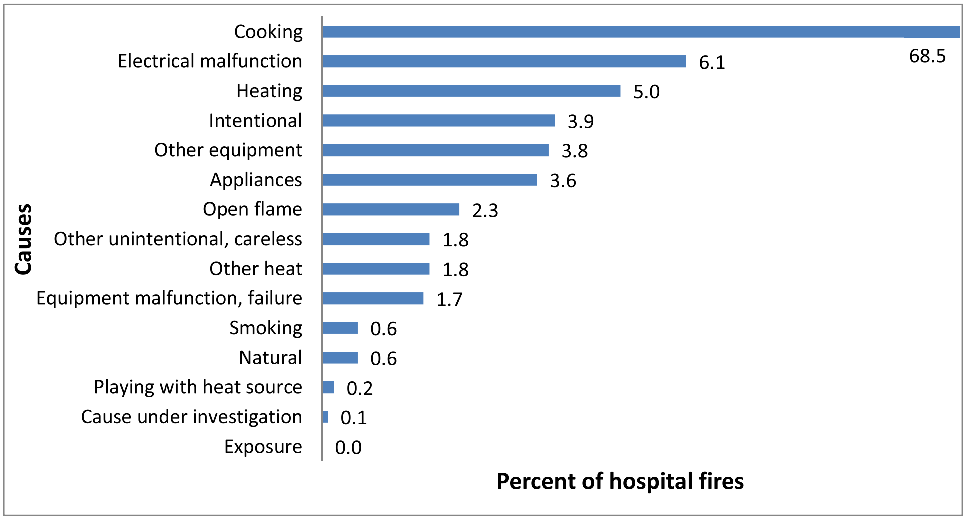

Fig. 2. Causes of hospital fires in the United States 2012-2014 (NFIRS 5.0) (U.S. Federal Emergency Management Agency (FEMA), 1999).

Table 2
Non-surgical oxygen-related fires (as reported or suspected) occurring before 2020 as found in media reports, scientific articles and other publications.

No.	Country/Region	Location	Date of Event	Location where the event started	Type of patients in the location	Causality mentioned (Fixed facilities only)	Deaths and injuries
1	India	Hyderabad	21 October 2019	Neonatal intensive care unit	Infants	Short circuit	1 infant died, 3 injured
2	Korea	Gimpo	24 September 2019	Boiler room	Intensive care	Wrong procedure (maintenance)	2 dead, 47 injured
3	Algeria	Oued Souf	24 September 2019	Maternity ward	Infants	Short circuit	8 infants died
4	Italy	Ortona	31 March 2019	Hospital room	Unspecified	Cylinder explosion	0
5	Taiwan	New Taipei City	13 August 2018	Hospital room	Terminally ill	Cylinder explosion	14 deaths 15 injured
6	Romania	Iasa	11 April 2018	Intensive care, cardiology and cardiovascular surgery	Intensive care and surgical	Electric wiring failure	0
7	India	Amravati	29 May 2017	Neonatal intensive care unit	Infants	Incubator short circuit	4 infants died
8	India	Bhubaneswar	17 October 2016	Dialysis unit	Intensive care	Short circuit	27 dead, 115 injured
9	Iraq	Baghdad	10 August 2016	Maternity ward	Infants	Electric wiring failure	12 infants died
10	India	Northern India	11 September 2015	Intensive care unit	Intensive care	Chemical reaction between stored carbolic acid crystals and some other material	0
11	Latvia	Riga	2 August 2013	Storage room	None	Contact with oil	0
12	United Kingdom	Bath	21 November 2011	Intensive care unit	Intensive care	Cylinder explosion	0
13	Romania	Giulesti	16 November 2010	Maternity ward	Infants	Electric wiring failure	5 infants died
14	Guyana	Georgetown	10 May 2010	Intensive care unit	Intensive care	Not specified	
15	Ukraine	Lugansk	18 January 2010	Intensive care unit	Not specified	Cylinder explosion	5 deaths
16	India	Patiala	30 January 2009	Neonatal intensive care unit	Infants	Short circuit	5 deaths, 5 injuries
17	India	Meerut	17 November 2008	Maternity ward	Infants	Incubator short circuit	1 injury
18	France	Creil	21 October 2008	Hospital room	Not specified	Cylinder explosion	1 death, 2 injuries
19	United States	Minneapolis, MN	24 January 2008	Hospital room	Infants	Not specified	1 injury
20	Spain	Orihuela	10 June 2007	Intensive care unit	Intensive care	Short circuit (air conditioner)	0
21	Costa Rica	San Jose	12 July 2005	Neurosurgery unit	Neurosurgery	Short circuit (ceiling lamp)	19 deaths
22	Italy	Milan	2 November 1997	Oxygen chamber	Not specified	Not specified	11 deaths
23	United States	Brooklyn, NY	2 September 1993	Hospital room	Not specified	Oxygen equipment failure	3 deaths
24	Canada	Saskatoon	04 August 1988	Neonatal intensive care unit	Infants	Short circuit	0
25	Canada	Saskatoon	08 August 1988	Neonatal intensive care unit	Infants	Short-circuit	0

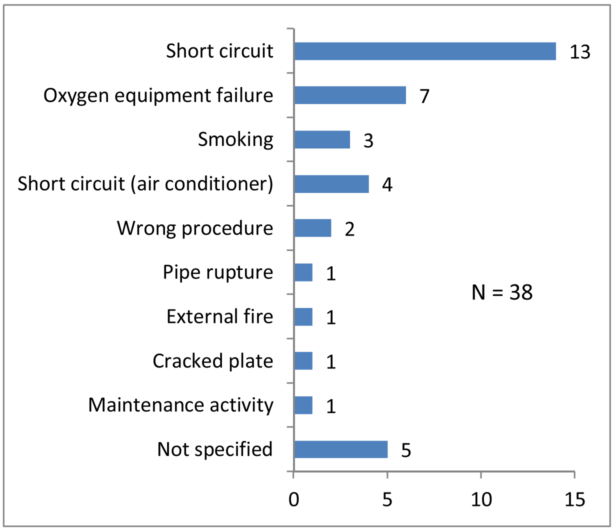

Fig. 3. Ignition sources of non-surgical oxygen-related accidents in hospitals occurring in 2020–2021.

gen deprivation) shows the reporter asking very pointed questions about high oxygen usage and sources of heat and ignition (Deutsche Welle, 2021). In association with this incident, the Romania media listed 13 major hospital fires that had occurred since 2010, including one in which six infants in a maternity ward lost their lives. Despite the awareness, Romania has had two tragic Covid-19 ICU fires, perhaps attributable, in part, to ageing hospital infrastructures. The potential role of oxygen is also highlighted by the doctors held responsible by the Indian authorities for the hospital fire in Mumbai on 23 April 2021. According to their court statement, "... the fire was an accident caused by the excess presence of oxygen in the ICU (The Times of India, 2021)." According to the media, India has experienced at least 10 hospital fires in 2020 and 2021, six of which led to multiple fatalities (The Times of India, 2021).

3.3. Oxygen-related fires in hospitals treating Covid-19 patients

A search of media of reports in multiple languages, including English, Arabic, Russian, Chinese, Japanese, and Korean, as well as a number of European languages, uncovered a total of 38 oxygen-related fires or near misses occurring between May 2020 and end of May 2021 (when this article was finalized). There have been twice as many incidents reported in the media (and other publications) in the last 14 months than in the ten preceding years. As shown in Table 3, 31 (82 %) of these incidents occurred in hospitals treating Covid-19 patients, one in neonatal care, one in cardiology, two in the emergency department, and two for which the type of patients being treated was not specified. Of the incidents associated with Covid-19 treatment, 24 incidents (77 %) started in the ICU or the Covid Ward, three (10 %) were initiated in a part of the oxygen supply network, and two occurred in storage. As indicated in Fig. 3, an electrical fault was most commonly thought to be the source of ignition across all the incidents, including 13 (34 %) associated with short circuits without identifying the actual equipment. In seven fires the oxygen equipment itself was considered the source of ignition and in four others the air conditioners. (Chowdhury highlights air conditioners as a main starting point of most of the hospital fires occurring in India.) (Chowdhury, 2013).

When the pandemic started and it became clear that oxygen therapy would be a preferred treatment for some patients, there were a few, but not very many, organizations that issued alerts about the fire hazards associated with oxygen-enriched environments. According to HSJ, the National Health Service England issued a warning to its hospitals in March 2020 stating that the high density of ventilators could enrich the air with oxygen (HSJ, 2021). An Italian newsletter for occupational safety and health, Punto Sicuro, also issued a warning about potential risk of hospital fires due to the necessity of concentrating Covid-19 patients in treatment units where oxygen therapy was prevalent (Sicuro, 2020). In addition, some consultants and producers of various hospital fire prevention services and equipment published materials on oxygen-related risks associated with ventilators, for example, Gaslab and WHA International (Gaslab.com, 2021; WHA International, 2021). Nonetheless, a web search in early January 2020 in several languages still did not find much evidence of any widespread alarm. (It appears that several organizations, such as the U.S. National Fire Protection Association and industrial gas producers in certain countries, began to issue alerts after the publication of the JRC bulletin on the topic was published in January 2020.) It may be that many hospitals were already aware of the risks and had already had updated equipment and infrastructures well before the Covid-19 pandemic. The geographic location of the majority incidents suggests that the oxygen-related fires in Covid-19 hospitals occur in less developed economies where not all hospitals have been completely modernized.

4. Managing the risks of fire in Covid-19 treatment in hospitals

The dramatic increase in intensive care unit fires during the Covid-19 pandemic gives evidence that there is a serious risk of fire in any location in a hospital where oxygen therapy is used. There have been ongoing concerns about hospital fires for a long time in most parts of the world, but very little attention has been given to sources of risk associated with oxygen therapy. In particular, the loss of life incurred from recent events highlights an urgent need for hospitals to undertake a comprehensive strategy, not only to prepare and respond to such events, but to prevent them from ever happening.

4.1. General principles

In addressing the risks of fire, it is important to establish the context in which the risk may present itself. This is the starting point for any risk management exercise and is not particular to hospitals, the use of oxygen, or the Covid-19 pandemic. Because of this pandemic, there has been a sudden surge in the number of patients being treated for acute respiratory ailments in both the ICU as well as on normal medical wards. Hospitals have expanded capacity through adding beds, converting existing wards to intensive care and setting up temporary medical wards.

Intensive care units and wards for the treatment of highly infectious patients need to have a controlled flow of air through the rooms, and particularly out of the rooms to prevent dispersion of contaminated air streams. The controlled air flow is likely to lead to an overall reduced air exchange rate, in particular in wards which have temporarily been assigned to ICU or infectious care and are not fitted with the necessary high performance room ventilation systems. Oxygen supplied to patients is not hermetically sealed, thus there is a continual stream of oxygen from the respiration oxygen supply into the room in which the patient is being treated. If the air exchange rate is low, it is likely that the background oxygen concentration in the room will rise well above the normal ambient concentration of around 21 %.

Beds for patients requiring oxygen treatment require a number of electrical and electronic devices for pumping, monitoring gas/air flow-rates and other vital parameters. For this purpose, each bed has a certain electrical power requirement. If the number of beds is

Table 3
Non-surgical oxygen-related fires (as reported or suspected) occurring in 2020–21 as found in media reports, scientific articles and other publications (p. 1 of 2).

No.	Country/ Region	Location	Date of Event	Location where the event started	Type of patients in the location	Suspected Cause	Deaths and injuries
1	Thailand	Rayong	12 May 2021	Covid-19 ward	Covid-19	Short circuit (air conditioner)	0
2	South Africa	Modimolle	4 May 2021	Covid-19 ward	Covid-19	Not specified	2 deaths
3	India	Bharuch	30 April 2021	Intensive care unit	Covid-19	Short circuit	18 deaths
4	Iraq	Baghdad	25 April 2021	Intensive care unit	Covid-19	Wrong procedure	82 deaths, 110 injuries
5	India	Mumbai	23 April 2021	Intensive care unit	Covid-19	Short circuit (air conditioner)	15 deaths
6	Bangladesh	Dhaka	17 March 2021	Intensive care unit	Covid-19	Short circuit	3 deaths
7	Brazil	Osasco, SP	2 March 2021	Emergency department	Covid-19	Short circuit	0
8	Ukraine	Chernivtsi	27 February 2021	Covid-19 ward	Covid-19	Pipe rupture	1 death, 1 injury
9	Mexico	Ixmiquilpan	21 February 2021	Oxygen storage	Covid-19	Short circuit	0
10	Ukraine	Zaporozhye	4 February 2021	Intensive care unit	Covid-19	Not specified	4 deaths
11	Romania	Bucharest	29 January 2021	Intensive care unit	Covid-19	Short circuit	24 deaths
12	India	Bhandara	9 January 2021	Newborn care unit	Infants	Short circuit	10 infants die
13	Belarus	Brest	27 December 2020	Oxygen supply station	Covid-19	Not specified	1 death
14	Egypt	Cairo	26 December 2020	Intensive care unit	Covid-19	Short circuit	8 deaths, 5 injuries
15	Russia	Astrakhan	20 December 2020	Oxygen storage	Covid-19	Wrong procedure	1 injury
16	Turkey	Gazantiep	19 December 2020	Intensive care unit	Covid-19	Oxygen equipment failure	11 deaths, 8 injured
17	Romania	Targa Mures	4 December 2020	Intensive care unit	Covid-19	Short circuit	0
18	India	Rajkot	27 November 2020	Intensive care unit	Covid-19	Short circuit	5 deaths
19	Russia	Vynnky	20 November 2020	Oxygen supply system	Covid-19	Cracked plate	0
20	Romania	Piatra Neamt	16 November 2020	Intensive care unit	Covid-19	Short circuit	10 deaths, 1 injured
21	Poland	Lodz	10 November 2020	Covid-19 ward	Covid-19	Smoking	0
22	India	Dahisar	31 October 2020	Intensive care unit	Covid-19	Oxygen equipment failure	0
23	Russia	Chelyabinsk	31 October 2020	Oxygen supply station	Covid-19	Oxygen equipment failure	0
24	Spain	Bilbao	29 October 2020	Intensive care unit	Covid-19	Smoking	1 injury
25	India	Odisha	21 September 2020	Intensive care unit	Covid-19	Oxygen equipment failure	0
26	Canada	Saskatoon	13 September 2020	Emergency department	Emergency care	Smoking	1 injured
27	India	Vadodara	8 September 2020	Covid-19 ward	Covid-19	Oxygen equipment failure	0
28	Cuba	Cienfuegos	5 September 2020	Intensive care unit	Intensive care	Not specified	0
29	Kazakhstan	Almaty	15 August 2020	Oxygen supply tank	Cardiology	Not specified	1 death
30	India	Bodeli	12 August 2020	Covid-19 ward	Covid-19	Short circuit	0
31	India	Vijayawada	9 August 2020	Not specified	Covid-19	Short circuit	11 deaths
32	India	Ahmedabad	6 August 2020	Intensive care unit	Covid-19	Short circuit	8 deaths
33	Iran	Tehran	30 June 2020	Storage	Not specified	Short circuit (air conditioner)	19 deaths, 4 injuries
34	Egypt	Alexandria	29 June 2020	Intensive care unit	Covid-19	Short circuit (air conditioner)	7 deaths, 1 injury
35	Mexico	Chihuahua	13 June 2020	Not specified	Children	Maintenance activity	1
36	France	Dechy	25 May 2020	Pipeline	Not specified	External fire	0
37	Russia	Saint Petersburg	12 May 2020	Intensive care unit	Covid-19	Oxygen equipment failure	5 deaths
38	Russia	Moscow	9 May 2020	Intensive care unit	Covid-19	Oxygen equipment failure	1 death

increased, the electrical power requirements increase accordingly. If the electrical system of the hospital has not been designed to cope with this level of loading then there is an increased fire risk due to overloading of electrical circuits. Electrical overloading may be a particular concern in older facilities where modernization has not been carried out to take account of the power supply requirements of modern intensive care beds. Moreover, if there is a high demand on equipment over a long period of time, and in addition, the equipment is in an area with restricted access, the following concerns also apply:

- Covid-19 treatment can lead to elevated oxygen concentrations in the ambient air of the wards so that combustibility of materials increases
- Higher electrical loads on electrical power supplies may occur with the risk of initiating fires due to overloading
- Poor maintenance or increased wear of equipment from unexpected high usage of equipment (e.g., ventilators), can create hot spots in the absence of air cooling or make contact sparking more likely.

4.2. *Risk management of oxygen-related fires associated with hospital intensive care treatment*

It is generally recommended that risk management in hospitals is conducted through implementation of a safety and health management system. Good practice for ensuring the system is effective over time requires at minimum that the safety and health management systems:

- Is driven by top management so that hospital administrators feel accountable and empowered to manage risk
- Assumes that hazards and risk can change over time, and there are protocols in place to identify and evaluate important changes that may elevate risk
- Follows the “Plan, Do, Check, Act” cycle for continuous improvement, with established rules for reviewing the effectiveness and improving risk management over time

The approach outlined in the OECD Guidance on Corporate Governance for Process Safety (2012) envisions that senior leaders will use their leadership role to achieve a high level of safety, ensuring that all needs and requirements for knowledge, information, communication and decision making that support safety objectives are addressed (Organization for Economic Cooperation and Development, 2012). In this role, the senior hospital management must understand that elevated oxygen concentrations pose a significant fire risk and thus a risk to patients and staff. They should ensure that the safety and health management system has a comprehensive management plan for chemical hazards that contains at minimum the following elements (that are also summarized in the checklist in Text Box 1):

Text Box 1: A Checklist for Managing Oxygen Risks.

- **Identify hospital locations and procedures where oxygen hazards may be present** and implement a risk management strategy commensurate with the level of risk.
- **Raise awareness of oxidization hazards** among all levels of management and all areas of operation, including administration, medical personnel, admissions, maintenance and housekeeping staff.
- **Establish a procedure for identifying and managing changes** that could elevate or alter the character of oxygen concentration risk In the hospital. This procedure should include protocols between all levels of management and areas of operation for communicating and acting upon changes or unexpected circumstances in a timely fashion to prevent dangerous events.
- **Promote training of medical and maintenance staff** on the safe operation of oxygen supply system as well as the safe handling, storage and operation of gas bottles. Staff should be familiar with the location and operation of the emergency oxygen shut-off valves.
- **Communicate oxygen hazards through signs and posters** in oxygen hazard areas. This communication is not only important for staff handling oxygen equipment but for when family members might have to provide oxygen to patients because of supply system failures.
- **Position and partition oxygen cylinders and manifolds** away from high fire-risk areas, such as kitchens, compressor rooms (e.g., for air conditioning) or electrical cabinets.
- **Eliminate the usage of hydrocarbon-based products**, such as alcohol-based disinfectants, lubricants, skin and hair oils or soaps in oxygen hazard zones to avoid any possible contamination of medical oxygen equipment.
- **Enhance air flow in oxygen therapy rooms**. Solutions can be mechanical (high flow ventilation systems) or practical (opening windows in adjacent rooms or corridors). Bed linen and clothing should also be ventilated after use to allow the dispersion of any oxygen excess (at least 15 min for clothing and linen).
- **Monitor oxygen levels in the atmosphere with appropriately located gas detection systems**, that give off alarms or even activate ventilation systems when oxygen concentrations are elevated.
- **Inspect and maintain equipment and the interconnected electrical infrastructure** according to recommended practice and frequency, using only competent personnel. Recall that inspection and maintenance intervals may need to be of shorter duration when surges in Covid-19 patients result in more frequent, sometimes non-stop, usage.
- **Verify that all electrical equipment is functioning properly** under increased load and continuous operation. Compressors, whether part of medical ventilators or air-condition units, are prone to electrical failures (such as short circuits causing sparks) under frequent startup and shutdown phases.
- **Investigate oxygen fires to identify causes and lessons learned** for improving prevention and preparedness strategies, routinely disseminating findings to hospital personnel.
- **Exchange information with the healthcare community, industrial gas producers, and oxygen equipment providers on recent and past events worldwide** to foster ongoing improvement in hospital safety at local, national and global levels.

4.2.1. Awareness

There is a need to increase awareness of the risks posed by elevated oxygen concentrations in hospital situations throughout the whole of the organization. Awareness raising should be a priority for hospital management, to be transported throughout the whole organization, including all medical staff infrastructure and maintenance department, and cleaning and housekeeping staff. The entire network of personnel that make the ICU wards function must be informed of their part in reducing risk of fire from oxygen-enriched environments. Awareness should be routine, rather than an afterthought, reinforced with ongoing training, drills, signage and in safety meetings with staff. In addition, the WHO recently published a poster on medical oxygen fire risk that could be placed in a hospital's oxygen hazard zones (World Health Organization, 2021b).

4.2.2. Active risk monitoring and management

The medical staff should be observant of any situations that may elevate fire risk in the ICU, including changes in number of patients on oxygen therapy, ventilators that show signs of excessive wear, presence of debris, presence of solvents in the area, etc., and have standard protocols for making sure they are reported and addressed. Hospital operations and maintenance must understand the need to consider electrical capacities and loading as well as the regular maintenance of these systems. Room ventilation must be assessed to minimize buildup of an elevated oxygen concentration as far as possible. Finally cleaning and housekeeping staff should be aware that the use of solvent based cleaning agents, such as ethyl alcohol, presents an increased fire risk in elevated oxygen atmospheres and that this should be avoided respectively minimized as far as possible. In addition, there should be established routines for exchanging information between the different functions to facilitate timely communication about problems, changes or otherwise unexpected circumstances that negatively impact the risk.

4.2.3. Assessment of electrical loading

Before assigning a ward to intensive care use with oxygen ventilation, or increasing the number of beds in a ward, an assessment of the new electrical load on the power circuits should be carried out, and the suitability confirmed with a competent electrician. The risk of a power surge when units are switched on should also be part of this assessment.

4.2.4. Inspection and maintenance

All electrical and electro-mechanical equipment should be regularly inspected for wear, heat loading (especially when in continuous use), blocked fans, and ventilation ducts. The equipment should be maintained in good condition. Defective equipment should be withdrawn from use immediately. Postponing of inspection or maintenance due to high demand through the pandemic situation should be avoided. Technical expertise should be consulted before any decision is made. For this reason, all electronic and electrical equipment that are connected to the power supply need regular inspection, testing and maintenance. These activities should cover not only functionality of the device and the electrical connections to the equipment, but also the conditions surrounding the equipment. In particular, two aspects are important with respect to fire safety. Firstly, all air ducts and cooling fans must be clean and unobstructed with hair, dust and other debris, and secondly, motors, switches and other electrical contacts should be clean and in good condition (i.e., not worn) so as to avoid sparking.

4.2.5. Oxygen detection

Oxygen excess in ambient air can be detected by monitoring devices, whether fixed or mobile. Such devices could record ambient oxygen concentration levels at frequent intervals (i.e., hourly) and subsequently register those values in a centralized system. The system could be monitored and alarm hospital administration for potential increase of oxygen concentration. Additionally, any excess in oxygen consumption that does not correspond to the demand ensued by patients currently under treatment should be addressed promptly. An oxygen leak in the storage, distribution system or the endpoints could potentially be identified if oxygen levels are being monitored and found to be disproportional to the expected consumption.

4.2.6. Room ventilation

Adequate room air flow should be assured when an elevated oxygen concentration may be expected, e.g., from an increase in use of oxygen ventilation. In an effort to prevent the spread of a highly contagious virus infection, a common practice is to reduce the air flow and mixing among areas adjacent to an infectious disease ICU. Such partitioning should allow adequate ventilation to reduce oxygen concentration while at the same time ensure protection against the spread of air-borne infections. Adapting air circulation in ICUs immediately in the face of a sudden upsurge in oxygen therapy patients may not always be possible in the short term, but it should be a priority for the hospital to make the necessary adjustments as soon as possible. Some techniques for managing air flow in Covid-19 treatment units are suggested by Fernandes Santos et al. (2020).

4.2.7. Oxygen pipeline supply systems

Maintenance and correct operation of the gas supply system are also essential to reducing risks with medical gas supply systems, including those that supply oxygen. Training on procedures for maintenance and operations personnel is necessary as well as regular maintenance to check for leaks, wear and other potential deteriorations in mechanical integrity. Sarangi et al. make a number of recommendations for maintaining of medical gas supply gas systems, with particular attention to oxygen supply (Sarangi et al., 2018).

4.2.8. Oxygen cylinder handling and storage

For hospitals that rely mainly on oxygen cylinders, rather than pipeline distribution, the intense use of oxygen for Covid-19 treatment can also elevate risks in oxygen storage and distribution. Hospitals dependent on oxygen cylinders should take care that appropriate storage conditions continue to be rigorously observed, with particular attention to maintaining these conditions when temporary storage arrangements need to be established, and respecting also the limits on how much can be stored in the same place. There are easily accessible guidelines on proper conditions for storage tanks, e.g., clean, dry, well-ventilated, away from flammable substances, etc., published by industrial gas producers such as BOC (BOC Healthcare UK, 2021). In addition, staff should be trained and follow correct handling procedures. As one option, Karim et al. recommend a strategy that uses the Failure Mode Effect Analysis (known as FMEA, a technique widely used in the nuclear and chemical industries) for analyzing risks associated with use of medical gas in hospitals (Karim et al., 2016). The WHO also recently published a poster on oxygen cylinder handling that could be posted in areas of the hospital where cylinders might be handled or used (World Health Organization, 2021a).

4.2.9. Enhanced product stewardship across industry and downstream users

Proactive product stewardship of producers of industrial gases and medical equipment via outreach to downstream users is a key ingredient of oxygen risk management. It should be a priority for these producers to provide comprehensive communication of hazards from the commissioning phase, as well as timely notification of any recent safety developments, to hospitals and other healthcare providers.

4.2.10. Management of change

As a result of the pandemic, hospitals are facing a new set of challenges. It is important that awareness is maintained at all levels of the organization to ensure that the risks associated with the new challenges are adequately addressed. Hospital management must be aware that changes in room use, number of beds, increases in ventilation with oxygen, increases in the number of highly infectious patients are all changes in the system that can affect hospital safety. These changes should be assessed for their impacts on other aspects of the system, in particular the creation of new hazards or increasing the risks of existing hazards. The decision making related to these changes should be anchored in a management process. In the realm of Process Safety, this process is known as "Management of Change" or MOC. MOC is a formal process for identifying and assessing how proposed changes could affect safety and elevate risk. The process requires that risk assessment results are taken into final decisions about whether and how the change is implemented and that the assessment and resulting decision are documented (European Commission Joint Research Centre (JRC), 2017).

4.2.11. Open communication

There must be open communication about safety concerns about changes and a culture that encourages all staff at any level in the hierarchy to speak up about changes that could elevate risk. Following identification of an important change, there should be a robust effort to communicate what those changes mean for expected behaviors and procedures. This philosophy applies not only to planned changes but to unexpected changes as they are unfolding (e.g., a sudden rise in Covid-19 patients in the ICU). Deviations from expected performance or function of equipment, loading of the electrical supply, tripping of fuses, etc., should be communicated to competent technical personal to address. Ideally, open communication about changing circumstances, deviations from the norm, equipment performance, and any other anomalies that raise concerns, should be reinforced in routine communication, for example, as part of exchanges at the start of every shift and in staff meetings.

4.2.12. Accident investigation and lessons learning

Benson et al. notes that there is a clear absence of specific and homogenous guidance on investigating oxygen-related incidents in both the collection and dissemination of data associated with oxygen-related fires and explosions (Benson et al., 2018). Hospital administrators should fully take advantage of the resources available as well as actively engage in understanding and communicating incidents of the past. Lessons learned from previous fires should be reviewed and communicated across all levels of management and areas of operations in order to promote medical staff's awareness of fire hazards related to oxygen enriched atmospheres. The effective investigation of such cases could enable hospitals, healthcare organizations and gas producers to promote meaningful improvements in risk management oxygen hazard zones in hospitals over time.

4.2.13. Emergency preparedness

In the event of an oxygen-related fire, personnel in the immediate vicinity should immediately switch off all sources of oxygen if possible to do so. In addition, hospital management should make sure that Covid-19 measures to minimize the contagion do not hinder emergency preparedness. Keeping fire doors open to avoid contagion via handle's contact could affect the fire safety by failing to provide protection from fire propagation among adjacent rooms. On the other hand sealing or locking doors, to reduce air flow between sections or isolate areas, will restrict access to means of escape. A comprehensive fire risk assessment prior to any modification should take place to determine the effect on fire safety and emergency preparedness (Surrey County Council - Surrey Fire and Rescue Service (SFRS), 2021).

5. Conclusion

There has been an alarming increase in the last 12 months in the number of oxygen-related fires in hospitals where Covid-19 patients are being treated. A number of these fires have had tragic outcomes for some patients and also some medical staff. These accidents are largely attributable to the especially intense use of oxygen to treat extremely ill Covid-19 patients. When the pandemic is surging, the ICUs of hospitals may have particularly high volumes of Covid-19 patients on oxygen.

Although there are numerous occurrences of fires originating in hospital ICUs in the past, the role of oxygen-enriched environments has not been widely recognized. With few exceptions, hospital guidance on fire safety and ICU management tends to focus on emergency response and generally ignores the importance of fire and prevention and risk management, particular in parts of the hospital where oxygen treatment can create a serious fire hazard. The rise of oxygen-related hospital fires during the Covid-19 pandemic demonstrates the urgency of establishing a comprehensive strategy for preventing such accidents.

Research and experience clearly show that fires due to oxygen –enriched environments are preventable. There is ample information available on controlling oxygen hazards, including well-established practices for assessing and managing oxygen hazards in the chemical process industries, and detailed guidance on oxygen safety and control measures published by the industrial gas producers for downstream users including the medical community. These resources provide a wealth of information that hospitals, associations for ICU medical professionals, and medical training and education centers, can adapt to build the necessary awareness and knowledge for controlling oxygen hazards in hospitals and applying comprehensive risk management strategies in order to avoid future tragedy.

Declaration of Competing Interest

The authors report no declarations of interest.

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