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Commentary

Surgical smoke and SARS-CoV-2 transmission

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The protection of health care workers from nosocomial infection is a paramount consideration in the current pandemic involving severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Not only is prevention of viral transmission the most effective means to lessen the public health impact of coronavirus disease 2019 (COVID-19), but also both quarantine and illness – that disproportionately affect health care workers – have devastating effects on the ability of hospitals to adequately care for increased patient loads. As of April 2020, for example, it is estimated that approximately 7% of all COVID-19 cases in Italy involved health care professionals [1].

Like severe acute respiratory syndrome coronavirus 1 (SARS-CoV-1) and Middle East respiratory syndrome coronavirus (MERS-CoV), transmission of SARS-CoV-2 in the hospital setting is believed to occur as a result of aerosol-generating events, and anesthesia providers are at high risk for acquisition of disease in the ongoing pandemic because of their frequent association with airway procedures [2]. For this reason, multiple organizations including the American Society of Anesthesiologists, the Anesthesia Patient Safety Foundation, and the Chinese Society of Anesthesiologists have set forth recommendations for anesthesia practice during the current pandemic [2-4]. These standards largely relate to hand hygiene, use of personal protective equipment (PPE), and precautions associated with airway manipulation (intubation and extubation).

Surgical smoke may serve as another mechanism for aerosol transmission of SARS-CoV-2 to health care workers. Because products of tissue pyrolysis have been shown to contain other viral pathogens [5-7] – and likely transmit clinical disease in the case of human papillomavirus (HPV) [5,8-11] – and because SARS-CoV-2 spreads via inhaled infectious aerosol [2,12], it is reasonable to question whether SARS-CoV-2 can be acquired by operating room personnel from exposure to surgical plume. Of note, however, despite the fact that anesthesia providers are clearly included in the latter group, and the fact that there has been extensive discussions of possible electrosurgical unit (ESU), laser and harmonic scalpel generated smoke transmission of SARS-CoV-2 in the general surgery, urology, gynecology and nursing professional communities, there is no mention of this potential hazard in published anesthesia literature to date. Unfortunately, this finding is entirely consistent with the largely absent discussion of many occupational risks in anesthesia publications, and likely relates to the relative lack of knowledge of anesthesiologists concerning common workplace hazards [5,13].

Potential Transmission of SARS-CoV-2 *via* Surgical Smoke

Notwithstanding the fact that SARS-CoV-2 is a newly described virus, and that COVID-19 is a novel disease, there are some reasonable extrapolations that can be made based on data from other viral pathogens. For example, intact virions and/or nucleic acid of human immunodeficiency virus (HIV), hepatitis B, and poliovirus have been recovered from surgical plume [5-7,14]. Despite the aforesaid findings, the *in vivo* infectivity of most smoke-borne viruses has not been established [5-7,15], although it should be noted that – unlike SARS-CoV-2 – these later pathogens are not known to be transmitted via the respiratory system.

The situation, however, is somewhat different for HPV, which has been associated with nosocomial transmission of disease in humans via surgical smoke i.e. smoke containing HPV is very likely infectious. This probable route of transmission applies to three clinical entities: (1) oral warts (HPV serotypes 6 and 11); (2) oropharyngeal cancers (HPV serotypes 16 and 18); and (3) recurrent respiratory papillomatosis, including both laryngeal papillomatosis and pulmonary papillomatosis (HPV serotypes 6 and 11) [5,9,16-18]. Not only have multiple studies demonstrated HPV deoxyribonucleic acid (DNA) both in surgical plume and in the nares of unprotected operating room personnel, but also the genotypes of plume DNA and nares DNA in the same setting have been matched. While HPV viability in these instances could not be demonstrated (due to lack of an appropriate bioassay), the *in vivo* infectivity of bovine papillomavirus (a nearly identical virus) isolated from smoke has been established [5,10]. Case reports of laryngeal papillomatosis in health care workers exposed to HPV without appropriate smoke evacuation, and surgeons with extensive histories of cervical laser ablations with HPV-16 positive tonsillar carcinomas support the conclusion that HPV disease can be acquired via surgical plume.

In infected individuals, SARS-CoV-2 is known to exist in the upper and lower respiratory tract tissue (including the nares), blood (1-10% of COVID-19 patients), the entire gastrointestinal (GI) tract from mouth to rectum (up to 50% of COVID-19 patients), and possibly the liver [19-21]. In addition, evidence exists for shedding of SARS-CoV-2 from the GI tract [19]. As such, predicated on its known anatomical locations and on the data collected from other viral pathogens, it is reasonable to assume that aerosolized products of pyrolysis of specific tissues may contain SARS-CoV-2, especially in patients with COVID-19 and higher viral loads – more common in hospitalized settings [22]. Like other viral pathogens, the infectivity of SARS-CoV-2 delivered by surgical plume, however, likely depends on multiple factors including the viability of virions in the post-pyrolytic environment, the viral load transmitted by aerosol, the minimum infective dose of virions (its intrinsic virulence), and host immunity [14,23].

On the other hand, there is no evidence that either influenza or other coronaviruses (SARS-CoV-1 and MERS) – that are commonly associated with aerosol-spread – can be transmitted by surgical plume to operating room personnel [20]. Furthermore, to date, no published data exists regarding the presence (or absence) of SARS-CoV-2 ribonucleic acid (RNA) or viral particles in surgical smoke, and there are no case reports of surgical personnel developing COVID-19 via plume. As such, at this time, the reasons for concern regarding potential SARS-CoV-2 spread via surgical smoke are that (1) SARS-CoV-2 is a virulent pathogen that is commonly transmitted by aerosol; (2) SARS-CoV-2 is present in many of the tissues undergoing pyrolysis, a process that creates aerosols capable of entering the upper and lower respiratory tracts of operating room personnel during surgeries; and (3) there is evidence supporting human-to-human transmission of a different virus (HPV) and its associated diseases via surgical plume.

What are Effective Methods for Protection from Possible SARS-CoV-2 in Surgical Plume?

Aerosol particles (<5 microns (μm) in largest dimension) are believed to be sufficiently small to stay suspended in air long enough to traverse the distances between individuals, and – unlike large droplets with dimensions >20 μm – these smaller entities can penetrate the lower respiratory tract [19]. Such aerosols are produced during coughing, sneezing, forcing pressurized gas into the aerodigestive tract, or via tissue pyrolysis. Limiting exposure to these particulate suspensions is a major component of programs designed to protect health care workers during the current pandemic.

Strategies for this purpose are predicated on minimizing production of surgical smoke (restricting ESU, laser, or ultrasonic scalpel to only necessary use), limiting extracorporeal release of surgical pneumoperitoneum during laparoscopy (or pleural gas contents during thoracoscopy), evacuation of plume by a dedicated smoke system (SES) performed in the setting of appropriate room ventilation, and filtration of smoke via properly fitted masks and dedicated particulate filters designed to remove aerosol and viral contents from the air. Filtration-based protection is based largely on viral and aerosol size. Standard surgical masks (that function specifically as barriers against aerosolized droplets) have pores with 5-15 μm diameters; N-95 masks have smaller pores and filter 95% of particles with diameters >0.3 μm; and "laser" high-filtration masks are designed to filter particles with maximum diameters >0.1 μm. Although ESU-generated particulate matter is often "ultrafine" with a mean diameter of 0.07 μm (range 0.007-0.42) [5,19,24,25], and SARS-CoV-2 has maximum dimensions of approximately 0.06 to 0.14 μm [26,27], surgical masks still provide a degree of protection against this potential means of viral transmission because such spread generally involves larger droplet particles [12].

Furthermore, the ability of masks to provide adequate protection from aerosolized SARS- CoV-2 depends not only on pore size but also on the degree of mask fit (*i.e.* if there are gaps around the mask-skin interface, smoke contents will bypass the mask filtration structure) [5,14,28-30], as well as the integrity of the filter system (dampness may adversely affect filtration efficiency [5,29]). Largely for the former reason, studies employing monodisperse latex spheres and sodium chloride aerosols containing particulate matter with maximum dimensions <5 μm (0.08, 0.9, 2.0 and 3.1 μm) [31,32], as well as live influenza virus [33], have demonstrated extensive penetration of standard surgical masks.

Filters integrated into SESs used in open surgery or attached to port evacuation devices during video-assisted minimally invasive surgery serve a similar protective function. High-Efficiency Particulate Air (HEPA) and ultra-low particulate air (ULPA) filters – designed to remove airborne particles with diameters of >0.3 μm and >0.05-0.12 μm respectively [5,26,28] – are employed in this manner. Both devices provide additional protection for operating room personnel from possible SARS-CoV-2 transmission delivered by smoke aerosol.

Proper use of a dedicated SES applied to an ESU, or in the area of harmonic scalpel or laser tissue ablation, is the most effective method for removal of surgical smoke during open surgery [5,34-36]. Such SESs consist of a capture device, a vacuum system capable of generating 30-50 cubic feet per minute (CFM) of suction (compared to wall suction with approximately 5 CFM), and either a HEPA or ULPA filtration unit. For maximum evacuation efficiency during the current pandemic environment, and to prevent possible release of captured viral aerosol back into the operating room environment, these filters need to be changed regularly – usually as signaled by a built-in indicator light [5,37]. Furthermore, correct intraoperative use of SESs involves suction activation either simultaneously or immediately prior to ablation device activation, and for 5-10 seconds after termination of device use – a goal that is usually achieved automatically by many such devices [5].

An increasing number of companies currently produce SESs, with over a dozen major manufacturers worldwide. In addition to being used in open surgeries, these evacuation devices are incorporated into many systems designed for laparoscopic insufflation purposes as well. In the latter category, an SES is available with a 0.01 μm filter pore size that optimizes gas flow to provide stable operating conditions with an intelligent integrated control unit (allowing simultaneous carbon dioxide (CO_2) inflow, pressure monitoring, and outflow with filtration), and includes valveless access ports that minimize loss of pneumoperitoneum during instrument exchange [12,38,39]. As a result, this latter system has been recommended for use during the current SARS-CoV-2 pandemic [12].

Some potential problems related to SARS-CoV-2 exposure – that can be mitigated with proper foresight – do exist with the latter system. When used in a mode that allows re-circulation of CO_2, it may predispose to concentrating viral aerosol, a feature that can be avoided by use of either the Smoke Evacuation mode or an independent SES [12]. Furthermore, when used in the former mode, unfiltered intra-peritoneal gas may be released from the access port. This emission also can be minimized by use of a separate SES or suction irrigator with an inline-filter through another port. Another solution is to employ the device in the Smoke Evacuation mode with the tube set connected to two trocars, one for insufflation and one for active filtered smoke evacuation [26].

Is there Increased Risk of Transmission of SARS-CoV-2 with Video-Assisted Minimally Invasive Surgery Versus Open Surgery?

Largely predicated on opinions derived from COVID-19 experiences in China and Italy, a concern has arisen regarding performance of laparoscopies in the current pandemic environment, specifically with regard to transmission of SARS-CoV-2 via exposure of operating room personnel to pneumoperitoneum-derived aerosol [19]. This perspective is predicated on the finding that particulate matter concentration is higher in laparoscopic smoke, presumably because it accumulates in a limited volume of insufflated gas over the course of surgery [5,40,41]. During laparoscopy, release of concentrated plume into the surgical atmosphere commonly results from leakage around trocar sites, exchange of instruments, and open desufflation of unfiltered peritoneal gas contents. Furthermore, use of wall suction during laparoscopy – to remove this smoke and improve visualization – instills these potentially infectious vapors into the operating room central vacuum system [37].

As noted previously, mechanical solutions exist to some of the above problems associated with intra-peritoneal smoke. Use of HEPA or ULPA passive surgical smoke filters (or very large scale integrated (VLSI) filters – essentially high efficiency ULPA filters) that attach to laparoscopic trocars allows for elimination of smoke contents before it is removed into the central vacuum system [5,9]. Unfortunately, the ideal characteristics of these filters have not been delineated [42]. Filtration during laparoscopy can be further complicated by CO_2 insufflation concurrent with smoke generation [5,37], a problem that has been addressed by intelligent control systems, and valveless access ports function to minimize pneumoperitoneum loss during instrument exchange. Clearly, intra-peritoneal gas should be evacuated at the end of each laparoscopic procedure into a filtered setup, rather than released into the operating room environment [43].

Other considerations relevant to minimizing release of intra-peritoneal smoke during laparoscopies and thereby reducing the risk of aerosol transmission of SARS-CoV-2 include lowering standard pneumoperitoneum pressures (e.g. using a set upper limit of 12 millimeters of mercury (mmHg) rather than 15 mmHg), and employing specific modifications for robotic surgery [12]. Reduction in intra-abdominal pressure (IAP) during procedures likely has additional benefits (for example, reduction in postoperative pain [44] and improved hemodynamics [45]) without adversely impacting the surgical process. During robotic surgery, in order to avoid potential virus-containing plume leakage, trocar reducers should be used when inserting 5 millimeter (mm) or 8 mm instruments through 12 mm trocars, and use of 5 mm instruments (inserted through 8 mm robotic ports or trocar reducers) should be minimized [12].

Of note, in response to concerns regarding use of laparoscopy with SARS-CoV-2 patients, several articles have appeared in the gynecologic, urologic, and general surgical literature defending the relative safety of this approach with respect to potential aerosol-based viral transmission, and advocating its use – with appropriate smoke-sensitive precautions – when clinically indicated. These articles have noted that there is no data regarding comparative risks of open versus laparoscopic procedures with respect to dissemination of viral disease, and that open procedures – in contrast to video-assisted minimally invasive procedures where smoke is largely contained within the peritoneal cavity during most of the surgery – routinely release significant aerosol from tissue pyrolysis directly into the operating room atmosphere [19,20]. During these latter procedures, SESs may fail to remove a portion of this plume depending on the efficacy of the capture system and the extent of pyrolysis.

What Precautions are Prudent to Minimize the Risk of SARS-CoV-2 Transmission via Surgical Smoke?

Irrespective of the current pandemic, use of precautions to minimize exposure of operating room personnel to surgical smoke should be universally employed to avoid the numerous potential physical, chemical, and biological adverse effects of plume [5,46,47]. During the current health care crisis, however, surgeons, anesthesia providers, operating room nurses, and surgical technicians need to be particularly mindful of these precautions. Best practice recommendations during the current COVID-19 pandemic specifically designed to minimize potential surgical smoke transmission of SARS-CoV-2 (Table 1) [1,12,26] include:

1. Only non-elective surgeries should be performed. Surgeries that can be delayed without patient risk should be postponed.

2. Whenever possible, all surgical patients should receive COVID screening prior to arriving in the operating room.

3. All operating room personnel should make appropriate use of PPE, including properly fitted N-95 masks and facial-eye protection.

4. Surgery should be performed only in operating rooms with adequate air ventilation that meets Center for Disease Control – National Institute for Occupational Safety and Health (CDC-NIOSH) standards, and with appropriate room filtration systems.

4. Tissue pyrolysis should be minimized (without compromising the surgical process). When it is employed, a lower energy setting should be selected to reduce smoke generation [12].

5. Use of the harmonic scalpel should be avoided since it is associated with the creation of larger aerosol particles at cooler temperatures, and hence it may have an increased propensity for viral transmission [1,5,12,48,49].

6. Tissue pyrolysis should occur only in the presence of a functioning dedicated SES with adequate vacuum (30-50 CFM) attached to a HEPA filtration system (or equivalent).

7. Special considerations apply to minimally invasive and robotic surgeries. These include:

a. CO_2 insufflation pressure should be minimized. An IAP limit of 12 mmHg is desirable.

b. Use of an intelligent integrated flow system should be employed to manage the concurrent issues of smoke generation, CO_2 insufflation, and need to maintain IAP <12 mmHg.

c. Peritoneal gaseous contents should never be intentionally released into the operating room atmosphere, either fractionally (for example, via port venting) or completely. Pneumoperitoneum should be evacuated using a vacuum system containing an inline ULPA filter (or equivalent) before closure, trocar or specimen extraction, or laparotomy.

d. During desufflation of the pneumoperitoneum, the "desufflation mode" on the insufflator should be used. In the absence of this option, the valve on the insufflation port should be closed prior to terminating CO_2 flow to avoid back-flow of peritoneal aerosol into the insufflation system.

e. Procedural steps should be instituted to prevent inadvertent release of pneumoperitoneum. Specifically, when movement of the insufflating port is desired, the port should be closed prior to tube disconnection, and the new receiving port should remain closed until attached to the insufflator tubing. Furthermore, the insufflator should be functioning before the new port valve is opened to prevent back-flow of peritoneal gas into the insufflator. Likewise, specimen removal should utilize a containment bag when possible to help maintain seal, and should only occur after peritoneal desufflation [20].

f. Surgical drains should be employed only if absolutely necessary.

General • Perform only non-elective surgery on patients after screening for SARS-CoV-2 • Ensure operating rooms meet CDC-NIOSH standards for air ventilation and filtration • Minimize tissue pyrolysis without compromising surgery • Select lower energy settings for tissue pyrolysis • Avoid use of harmonic scalpel ultrasonic ablation
Personal Protection • Operating room personnel should make appropriate use of personal protective equipment, including properly fitted N-95 masks and face-eye protection.
Smoke Evacuation – Open Procedures • Tissue pyrolysis should occur only in the presence of a functioning, dedicated smoke evacuation system with adequate vacuum (30-50 CFM) attached to an inline HEPA or ULPA filter that has been replaced according to specifications.
Smoke Evacuation – Minimally Invasive Procedures • Employ an intra-abdominal pressure limit of ≤12 mmHg • Use an insufflator with an intelligent integrated flow system • Prior to peritoneal desufflation, the patient should be flat and the least dependent port utilized for gas evacuation. • Pneumoperitoneum should be removed only via a vacuum system with an inline ULPA filter (or equivalent) that has been replaced according to specifications; do not release it into the operating room. • Abdominal desufflation should be performed prior to closure, trocar or specimen removal, hand insertion (with hand-assisted surgery), or conversion to laparotomy. • During pneumoperitoneum evacuation, "desufflation mode" should be used if available. • When desufflating or changing the insufflating port, steps should be taken to prevent backflow of peritoneal gas into the insufflator (see text). • Specimens should be removed from the peritoneal cavity in a containment bag. • Surgical drain use should be minimized. • During robotic surgery, trocar reducers should be employed, and use of 5 mm instruments should be minimized.

Table 1: Best Practice to Minimize Potential SARS-CoV-2 Transmission via Surgical Smoke

g. Prior to desufflation, the patient should be flat, and the least dependent port should be employed to evacuate pneumoperitoneum.

h. Following desufflation and subsequent trocar removal, suture closure of fascia should occur. Closure devices that permit leakage of peritoneal gas contents should be avoided.

i. The potential advantages of hand-assisted surgery should be weighed against the risks of significant peritoneal smoke leakage that can occur with this technique. If hand-assisted removal of larger specimens is required, it should be performed only after filtered desufflation of intra-peritoneal gas via the smoke evacuation system.

j. During robotic surgery, trocar reducers should be used when inserting 5 mm or 8 mm instruments through 12 mm trocars, and use of 5 mm instruments (inserted through 8 mm robotic ports or trocar reducers) should be minimized.

To date, no studies concerning attempted identification of SARS-CoV-2 in surgical smoke have appeared in the literature. However, predicated on the detection of other viral pathogens in plume (and in the case of HPV, likely *in vivo* infectious virions), and on the biology of SARS-CoV-2 – specifically an aerosol-based transmission mode and the presence of virus in tissues undergoing pyrolysis during surgery – it is reasonable to take precautions routinely against transmission of SARS-CoV-2 via surgical plume. Best practice recommendations now exist for this purpose. Comprehensive adherence to these guidelines is especially critical since patients with SARS-CoV-2 are often asymptomatic at times when they are infectious. Furthermore, many of these best practice recommendations also are useful to protect operating room personnel from the more common physical, chemical, and biologic hazards associated with exposure to contents of tissue pyrolysis.

As elective surgery resumes in the coming months, the exposure of operating room personnel to surgical smoke with the potential for aerosol transmission of SARS-CoV-2 likely will escalate. The increasing availability of improved testing of preoperative patients (with rapid turn around and greater reliability) will be critical to ensure the correct triage of resources. Despite the presence of such testing, however, recommendations for practice modification to minimize the exposure of personnel to smoke with SARS-CoV-2 positive patients should continue to be utilized universally to improve the safety of all individuals in the operating room environment.

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