Experimental Model to Test Electrostatic Precipitation Technology in the COVID-19 Era: A Pilot Study

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BACKGROUND: In the COVID-19 crisis, laparoscopic surgery is in focus as a relevant source of bioaerosol release. The efficacy of electrostatic aerosol precipitation (EAP) and continuous aerosol evacuation (CAE) to eliminate bioaerosols during laparoscopic surgery was verified.

STUDY DESIGN: Ex-vivo laparoscopic cholecystectomies (LCs) were simulated ± EAP or CAE in Pelvitrainer equipped with swine gallbladders. Release of bioaerosols was initiated by performing high-frequency electrosurgery with a monopolar electro hook (MP-HOOK) force at 40 watts (MP-HOOK40) and 60 watts (MP-HOOK60), as well as by ultrasonic cutting (USC). Particle number concentrations (PNC) of arising aerosols were analyzed with a condensation particle counter (CPC). Aerosol samples were taken within the Pelvitrainer close to the source, outside the Pelvitrainer at the working trocar, and in the breathing zone of the surgeon.

RESULTS: Within the Pelvitrainer, MP-HOOK40 (6.4×10^5 cm^{-3}) and MP-HOOK60 (7.3×10^5 cm^{-3}) showed significantly higher median PNCs compared to USC (4.4×10^5 cm^{-3}) ($p = 0.001$). EAP led to a significant decrease of the median PNCs in all 3 groups. A high linear correlation with Pearson correlation coefficients of 0.852, 0.825, and 0.759 were observed by comparing MP-HOOK40 (± EAP), MP-HOOK60 (± EAP), and USC (± EAP), respectively. During ex-vivo LC and CAE, significant bioaerosol contaminations of the operating room occurred. Ex-vivo LC with EAP led to a considerable reduction of the bioaerosol concentration.

CONCLUSIONS: EAP was found to be efficient for intraoperative bioaerosol elimination and reducing the risk of bioaerosol exposure for surgical staff. (J Am Coll Surg 2020;231:704–712. © 2020 by the American College of Surgeons. Published by Elsevier Inc. All rights reserved.)

Exposure of surgical staff in operating room facilities to surgically induced aerosols, which are released during surgical procedures such as high-frequency electrosurgery and ultrasonic cutting (USC), represents a potential health risk.[1,2] Fractions of released aerosols can reach the breathing zone of healthcare workers,[3] especially when they are close to the surgical field. In a survey among operating room facility healthcare workers in the US, 99% of the responders reported being within 5 feet (1.52 m) from the aerosol source.[4,5] Furthermore, health authorities report that about 500,000 healthcare workers are exposed regularly to surgical-induced aerosols annually in the US.[6]

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Abbreviations and Acronyms

CAE = continuous aerosol evacuation
COVID-19 = Coronavirus disease 2019
CPC = condensation particle counter
EAP = electrostatic aerosol precipitation
LC = laparoscopic cholecystectomy
MP HOOK = monopolar electrocautery endo-hook
PNC = particle number concentration in air (1/cm^3)
USC = ultrasonic cutting

Surgically induced aerosols can contain viral DNA (HPV, HIV, Hep B), but also viable tumor cells, therefore questioning the general protection of surgical teams when operating on such patients.[7-10] In the course of the COVID-19 pandemic, it is therefore reasonable to assume that such bioaerosols might harbor a relevant risk of infecting surgical staff by the coronavirus SARS-CoV-2.[11-14] Currently, some experts tend to assume that laparoscopic surgery could increase the surgeon's risk of exposure to aerosolized coronaviruses because the capnoperitoneum itself is a potential source of aerosols.[15] Moreover, a recently performed study reports higher levels of SARS-CoV-2 RNA concentrations in the peritoneal fluid than in the respiratory tract.[16] Although there is no societal consensus on limiting or restricting laparoscopic surgery, there is expert consensus to minimize any risk of coronavirus transmission by a restrictive use of high-frequency electrosurgery and ultrasonic cutting (USC) devices and the use of active aerosol evacuation or passive filter systems during laparoscopic surgery.[17,18]

Electrostatic aerosol precipitation (EAP) technology is widely used in industry as a filtration device that removes fine particles, like dust and smoke, from exhaust gases using the force of an induced electrostatic charge. More recently, EAP technology is now also available as a commercial and medically approved system. Its efficiency has been demonstrated to maintain visual surgical field clarity by bioaerosol clearance in the abdominal cavity during laparoscopic surgery.[19] Although EAP is not widely known in the community of laparoscopic surgeons, this technology has a potential to considerably minimize the exposure risk of surgical-induced aerosols for surgical staff. Therefore, this ex-vivo pilot study focuses on the efficacy of EAP to eliminate surgically induced bioaerosols. Its efficacy is furthermore compared to the intraoperative use of continuous aerosol elimination (CAE) by active filtering of the capnoperitoneum, which is currently one of the most widely used technologies for bioaerosol elimination during laparoscopic surgery.

METHODS

Legal background

Authorization from the Health Department of Bochum, Germany, was obtained to experiment with fresh post-mortal animal tissue. The tissue specimens were disposed of after the experiments in accordance with German law (Tierische Nebenprodukte-Beseitigungsgesetz). Experiments were performed in compliance with German coronavirus containment rules at the Aesculap Akademie GmbH in Bochum, Germany.

Operation room facility and experimental setup

Ex-vivo laparoscopic cholecystectomy (LC) simulations were performed in an operating room facility (6 m × 9 m × 3 m = 162 m^3) in the Aesculap Akademie GmbH in Bochum, Germany. The operating room facility contained a downward displacement airflow ventilation system with an air flow rate of 326.63 m^3/h. The operating table was located in the center of the room and set to a typical operation height of 1 m.

Ex-vivo LCs took place within an airtight Pelvitrainer (Kessler Kunststoffverarbeitung GmbH & Co. KG, and Gotthold Müller Schaumstoffe GmbH & Co.KG) that was modified to a total volume of 9 L CO_2 at a capnoperitoneal pressure of 12 mmHg. The modified Pelvitrainer was equipped with fresh liver and attached gallbladder of a German land race pig (volumetry by water displacement analyses at room temperature revealed a median liver volume of 2.0 [1.7 to 2.1] L). Accordingly, the capnoperitoneal volume within the Pelvitrainer was about 7L—approximately 2 times higher than the one for humans. The specimen was placed on the return electrode plate attached to an electrosurgical generator in the right upper quadrant of the Pelvitrainer. To mimic more realistic conditions within the Pelvitrainer, the inner surface of the Pelvitrainer was coated with a fine layer (1.5 m^2 surface area) of nitrocellulose membrane, which was previously soaked with an aqueous 0.9 wt.-% NaCl solution (Braun). The operative and technical setup was implemented in French position. To obtain maximum tightness of the capnoperitoneum, 4 balloon trocars (Kii Fios First Entry, Applied Medical) were placed by means of puncturing as follows: one 12-mm trocar below the umbilicus for the endoscope and a further 12-mm trocar in the left middle abdomen as the main working trocar, one 5-mm trocar subxyphoidal, and a further 5-mm trocar in the right middle abdomen. Airtightness of the Pelvitrainer was confirmed for each experiment by applying a capnoperitoneum with a capnoperitoneal pressure of

12 mmHg for 10 minutes with a maximum tolerated carbon dioxide leakage volume of 100 mL.

During the experiments, the research team wore standard surgical protective clothing including FFP3 breathing masks (3M Aura 1863+). The Pelvitrainer and the surrounding working place were covered with single use sterile surgical drapes. The following technical equipment was operated: a radiance G2 26" HB/Monitor (NDS Surgical Imaging), a 12-mm CMOS Full HD camera system (Aesculap), an LED light source (OP 940, Aesculap), an insufflator flow system (40/PG080, Aesculap), an electrosurgical generator for monopolar electrocautery endo-hook (MP-HOOK) surgery (GN 640, Aesculap), an ultrasonic scalpel system (Lotus, BOWA-electronic GmbH), and a smoke evacuation system (SHE SHA, BOWA-electronic GmbH).

Generation of surgical-induced bioaerosols by ex-vivo laparoscopic cholecystectomy

To generate typical surgical-induced bioaerosols, particle release was initiated by the simulation of ex-vivo LCs. Standardized incisions of the gallbladder peritoneum in the sulcus between the gallbladder fundus and the Glisson's capsule were performed for 3 seconds by means of high frequency electrosurgery (HFE) using a monopolar electrocautery endo-hook (MP-HOOK) and ultrasonic cutting (USC) device.

The operated devices and parameters to perform ex-vivo LCs were used as follows: monopolar electrocautery endo-hook (MP-HOOK), forced coagulation at 40 watts (MP-HOOK40); monopolar electrocautery endo-hook (MP-HOOK), forced coagulation at 60 watts (MP-HOOK60); and ultrasonic scalpel (USC) in standard cutting mode.

Electrostatic aerosol precipitation for elimination of surgical-induced bioaerosols

To characterize the efficacy of electrostatic aerosol precipitation (EAP) a commercial and medically approved EAP system (Ultravision, Alesi Surgical) was used to eliminate surgically induced bioaerosols during performed laparoscopic cholecystectomies. The operated EAP system is composed of a generator unit (high voltage of 7500−9500 V, current of ≤ 10 μA), a stainless-steel brush electrode (Ionwand, Alesi Surgical), and a return electrode connected to the return plate. The brush electrode produces electrons, which ionize present gas molecules.[20] The formed electrical field between brush electrode and grounded surface lead to unipolar field charging of the aerosol particles (efficient particle charging down to approximately some tenth of nanometers[21]) by the gas ions and to transportation of the particles on the field lines to the grounded surface (called electrostatic deposition). Also, charged particles that escape the electrical field will be deposed more efficiently than noncharged particles. This is due to the induction of image charges on present dipole water molecules on wet surfaces that lead to increased attractive forces.[22] Accordingly, the inner surface of the Pelvitrainer was moistened as described above.

In this study, the brush electrode was introduced into the Pelvitrainer cavity by subcostal puncture via a needle (diameter of 3 mm). The tip was pushed forward to the surgical field as close as possible without interfering with the following surgical manipulations. For all experiments, the positions of the brush electrode and the trocars were kept constant because the distance between brush electrode and bioaerosol source affects the deposition efficiency. For the purpose of comparison, all laparoscopic cholecystectomies experiments were performed with and without electrostatic aerosol precipitation (EAP).

Aerosol-analytical characterization of surgical-induced aerosols

Previous studies have shown that surgical-induced aerosols can span over a considerably wide size range, from a few nanometers to several micrometers, but the largest particle number quantities were found to be between 40 nm and 200 nm.[5] To characterize the surgical-induced bioaerosols in this study, a water-based condensation particle counter (CPC Model 3789, TSI Inc) was operated at a flow rate of 0.6 L/min to determine the total particle number concentration (PNC) in a size range from 7 nm to 1,000 nm. The CPC operation parameters were kept constant over all experiments.

Bioaerosol characterization was performed at 3 relevant locations with different states of aerosol dispersion: near the source within the Pelvitrainer (primary release from the agitated tissue), outside the Pelvitrainer immediately at the working trocar (secondary release from the capnoperitoneum), and in the breathing zone of the surgeon (nearfield exposure of surgical staff). The 3 sampling locations as well as the experimental setup at the Pelvitrainer are shown in Fig. 1.

To keep particles losses by electrostatic effects[23] constant, a conductive tube (Tygon), 60 cm long, was used for aerosol sampling. In the case of primary release characterization from the agitated tissue, the sample tube was connected to the Luer side tap of the subxyphoidal trocar by pushing the tube over the Luer outlet. In case of secondary release from the capnoperitoneum, the inlet of the aerosol sampling tube was fixed with a tripod in a static position 2 cm laterally from the inlet of the 12-mm working trocar. Aerosol sampling in the breathing zone of the surgeon (for exposure characterization) was

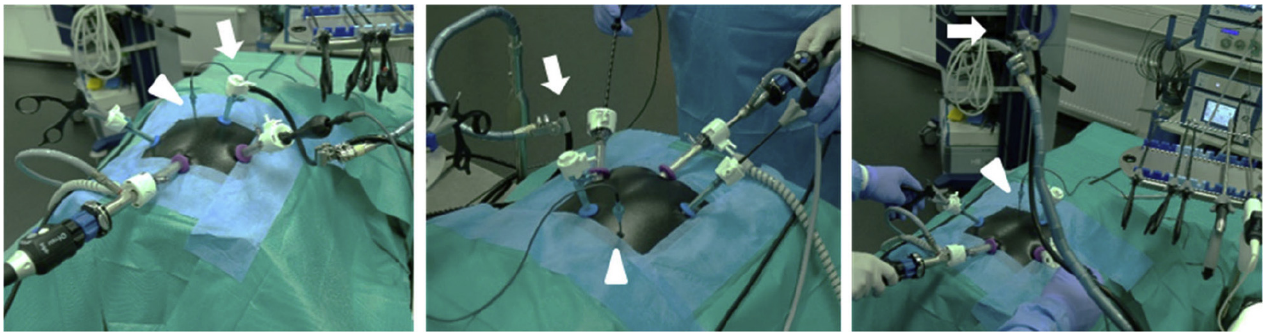

Figure 1. Photographs of the experimental setup: Pelvitrainer with trocar positions and aerosol sampling locations within the Pelvitrainer at the source (left panel), outside the Pelvitrainer at the working trocar (middle panel), and in the surgeon's breathing zone (right panel). Legend: White arrows indicate the position of the inlet of the aerosol sampling tube (left panel: at the Luer valve of the subxyphoidal 5-mm trocar for source sampling in the Pelvitrainer, middle panel: 12-mm working trocar, right panel: breathing zone of surgeon). White triangles show the trocar with inserted brush electrode.

realized via a tripod centered at a height of 70 cm above the 12-mm trocar for the endoscope (umbilicus).

Beside the differences in the sampling locations, there were also some differences in the experimental procedures. Primary release characterization within the Pelvitrainer was performed over a time frame of 100 seconds, with ambient air instead of carbon dioxide. Analyses were performed for monopolar electrocautery endohook at 40 watts (MP-HOOK40), 60 watts (MP-HOOK60), and ultrasonic scalpel (USC) with and without EAP. Between each experiment, the Pelvitrainer was restored by purging it with particle-free air (based on a high efficiency particulate air filter). Both secondary release characterization at the main working trocar and exposure characterization in the surgeon's breathing zone were performed over a time frame of 12 minutes for MP-HOOK60 in an established capnoperitoneum at a capnoperitoneal pressure of 12 mmHg. In contrast to EAP, continuous aerosol/smoke evacuation (CAE) is a well-known and suggested procedure to reduce surgical-induced aerosols during laparoscopic surgery.[18] In addition to analyses with and without EAP, the efficacy of CAE at a carbon dioxide flow rate of 12 L/minute (SHE SHA Level 2) was studied for MP-HOOK60 outside the Pelvitrainer immediately at the working trocar.

Statistical analysis

All experiments were performed in triplicate. Data analysis was performed by means of professional statistics software (SPSS V26.0, IBM Corp). Data are presented as median (minimum/maximum range) and boxplots (median and interquartile range [IQR] = Q3 − Q1) of particle number concentrations in number of particles per cm^3 of air ($1/cm^3$). For aerosol source characterization, each test was performed over 100 seconds at a time resolution of 1 second. Aerosol sampling during simulated ex-vivo LC was continuously performed over 12 minutes, with a time resolution of 1 second.

Quantitative variables were compared using the Mann-Whitney test. A value of $p < 0.05$ represented a significant difference. The Pearson correlation coefficient r was calculated for characterizing the impact of EAP on the formed bioaerosol within the Pelvitrainer; $r > 0.5$ is considered as high degree of linear correlation.

RESULTS

Bioaerosol concentration within the Pelvitrainer near the release source (primary release)

The concentration data of the bioaerosols within the Pelvitrainer have to be doubled when approximating the measured data of this study to typical human capnoperitonea, since the capnoperitoneal volume for humans is approx. 3.5 L, which is the half of the volume of the used Pelvitrainer (ie Pelvitrainer volume of 9 L minus 2 L liver volume). In Figure 2, the arising particle number concentrations (PNCs) of the performed laparoscopic cholecystectomies (ie MP-HOOK40, MP-HOOK60, and USC) with and without EAP are summarized.

According to Fig. 2, the highest median particle number concentrations (PNCs) were determined for laparoscopic cholecystectomies without EAP. With a median PNC of 7.3×10^5 ($7.4 \times 10^4 - 1.0 \times 10^6$) cm^{-3}, MP-HOOK60 showed the highest bioaerosol concentration, followed by MP-HOOK40 with 6.4×10^5 ($1.8 \times 10^4 - 1 \times 10^6$) cm^{-3} and USC with 4.4×10^5 ($1.3 \times 10^5 - 9.8 \times 10^5$) cm^{-3} ($p < 0.01$). In all 3 experiments, the continuous use of EAP decreased the prevailing bioaerosol significantly during the performed laparoscopic cholecystectomies.

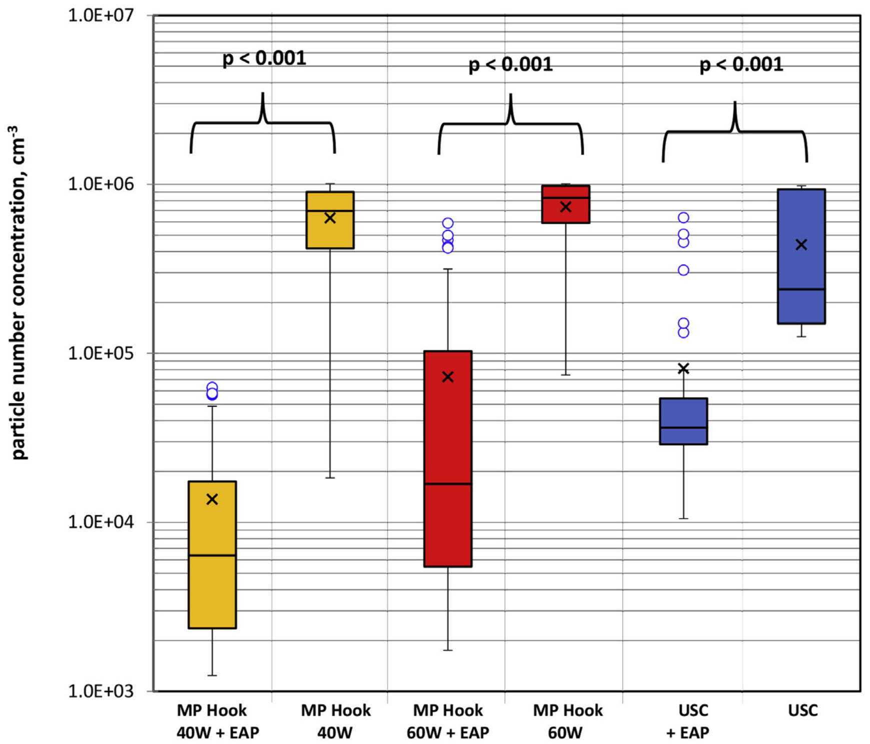

Figure 2. Bioaerosol concentration within the Pelvitrainer: Effect of ex-vivo laparoscopic cholecystectomy (LC) type (ie, MP-HOOK40, MP-HOOK60, ultrasonic cutting [USC]) with and without electrostatic aerosol precipitation (EAP) on the particle number concentration of the surgical-induced bioaerosols. MP-HOOK40, ex-vivo laparoscopic cholecystectomy based on monopolar electrocautery endo-hook forced coagulation at 40 watts; MP-HOOK60, ex-vivo LC based on monopolar electrocautery endo-hook forced coagulation at 60 watts.

The lowest median PNC with 1.4×10^4 ($1.2 \times 10^3 - 3.1 \times 10^4$) cm^{-3} was measured for MP-HOOK40 + EAP, followed by 7.2×10^4 ($1 \times 10^4 - 6 \times 10^5$) cm^{-3} for USC + EAP and 7.5×10^4 ($1.8 \times 10^3 - 5.9 \times 10^5$) cm^{-3} for MP-HOOK60 + EAP. A high linear correlation (Pearson correlation coefficients of 0.852, 0.825, and 0.759) was observed by comparing MP-HOOK40 with and without EAP, MP-HOOK60 with and without EAP, and USC with and without EAP, respectively. The lowest median PNC over all experiments was determined for MP-HOOK40 + EAP ($p < 0.01$).

Bioaerosol concentration outside the Pelvitrainer at the working trocar (secondary release)

Representative measurement data of the PNC over time of the surgical-induced bioaerosols based on MP-HOOK60 and MP-HOOK60 + EAP and each initial operating room facility background aerosol are provided in Figure 3.

Measurements of the background aerosol, which prevailed in the operation room facility at the Pelvitrainer, showed a median PNC of 9.4×10^2 ($8.3 \times 10^2 - 1.0 \times 10^3$) cm^{-3}. According to Figure 3, considerable PNC were measured in the aerosol cloud outside the Pelvitrainer near the working trocar during MP-HOOK60 without EAP. With a median PNC of 2.6×10^5 ($2.6 \times 10^3 - 9.9 \times 10^5$) cm^{-3}, laparoscopic cholecystectomy based on MP-HOOK60 led to an approximately 274 times higher median PNC, as determined for the operating room facility background aerosol ($p < 0.0001$). Performing MP-HOOK60 in combination with EAP significantly reduced the particle number concentration (PNC) in the aerosol cloud at the working trocar by a factor of approximately 152, to a median PNC of 1.7×10^3 ($9.0 \times 10^2 - 7.7 \times 10^4$) cm^{-3}. The slight increase of the PNC based on MP-HOOK60 + EAP in comparison to the background aerosol (factor 1.8) can possibly attributed to amounts of ultrafine particles < 30 nm in the bioaerosol, for which the charging probability becomes lower than 100% and decreases with decreasing particle size. To get an impression of the efficacy of bioaerosol evacuation by continuous

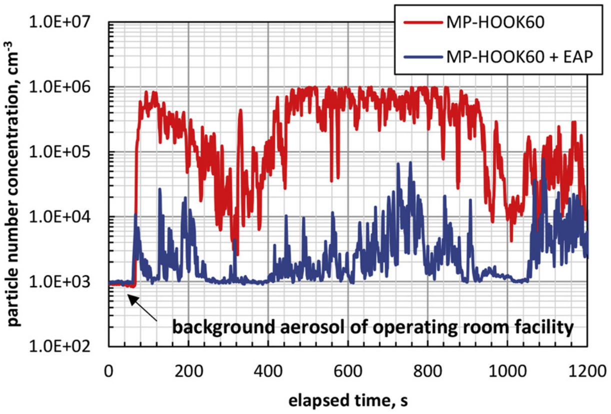

Figure 3. Bioaerosol concentration in the released aerosol cloud outside the Pelvitrainer near the working trocar: particle number concentration over time of the background aerosol and the surgical-induced bioaerosols based on ex-vivo laparoscopic cholecystectomy based on monopolar electrocautery endo-hook forced coagulation at 60 watts (MP-HOOK60) and MP-HOOK60 + electrostatic aerosol precipitation (EAP).

aerosol elimination (CAE) technology and EAP, Figure 4 depicts the PNC over time at the working trocar during a laparoscopic cholecystectomy with the monopolar electrocautery endo-hook at 60 watts (MP-HOOK60).

As can be deduced from Fig. 4, continuous aerosol evacuation (CAE) at a carbon dioxide flow rate of 12 L/minute (SHE SHA Level 2) leads during MP-HOOK60 operation to a considerable high steady state PNC level, with a median PNC of 9.4×10^5 ($9.1 \times 10^5 - 9.6 \times 10^5$) cm^{-3} that decreases gradually after switching off MP-HOOK60. In contrast, switching on EAP (without MP-HOOK60) results in an even more rapid decrease of the PNC. After switching MP-HOOK60 on during continuous EAP operation, the PNC further decreases and leads finally to a median PNC of 4.1×10^4 ($1.5 \times 10^4 - 1.1 \times 10^5$) cm^{-3} ($p < 0.0001$), which is 23 times lower than during the CAE operation with MP-HOOK60 at a carbon dioxide flow rate of 12 L/minute (SHE SHA Level 2).

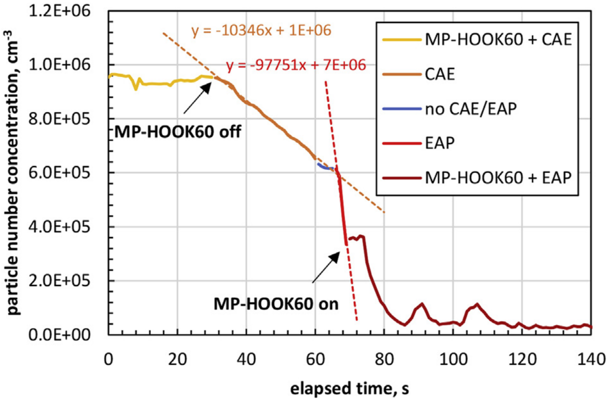

Figure 4. Representative bioaerosol concentrations in the released aerosol cloud outside the Pelvitrainer near the working trocar: effect of continuous aerosol evacuation (CAE) and electrostatic aerosol precipitation (EAP) on the particle number concentration (PNC) over time for a bioaerosol induced during an experimental laparoscopic cholecystectomy with ex-vivo laparoscopic cholecystectomy based on monopolar electrocautery endo-hook forced coagulation at 60 watts (MP-HOOK60).

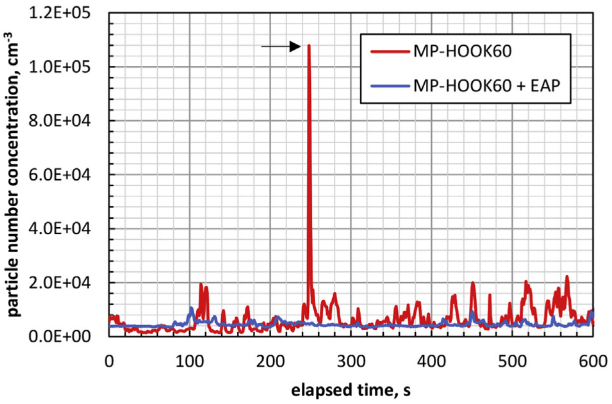

Figure 5. Bioaerosol concentration in the surgeons breathing zone during an experimental ex-vivo laparoscopic cholecystectomy: particle number concentration over time of the background aerosol and the surgical-induced bioaerosols based on ex-vivo laparoscopic cholecystectomy based on monopolar electrocautery endo-hook forced coagulation at 60 watts (MP-HOOK60) and MP-HOOK60 + electrostatic aerosol precipitation (EAP). Black arrow, high short-term bioaerosol concentration during manipulations with a 10-mm clip forceps via the working trocar.

Bioaerosol concentrations in the breathing zone of the surgeon

Figure 5 compares intrinsically measured PNC courses over time, as received from the breathing zone sampling point during MP-HOOK60 operation with and without EAP. The median PNC of the represented time course of MP-HOOK60 without EAP in Figure 5 (time frame of 600 seconds) was determined to be 4.7×10^3 ($1.4 \times 10^3 - 1.1 \times 10^5$) cm^{-3}. Indeed, MHE60 with EAP shows with a median PNC of 4.2×10^3 ($3.4 \times 10^3 - 1.1 \times 10^4$) cm^{-3} only a slightly lower median PNC. But in contrast to MP-HOOK60 without EAP, MP-HOOK60 with EAP does not show considerably high short-term PNC peak events.

DISCUSSION

There is a major lack of interest and knowledge among surgeons that the exposure to surgical-induced aerosols represents a potential health risk.[24,25] For economic reasons, hospital administrations urge surgeons to minimize intervention times. Accordingly, surgical techniques like systems for high frequency electrosurgery (HSF) and ultrasound cutting (USC) are operated at high energy levels to achieve faster tissue transection and sealing. This is accompanied by the formation of highly concentrated and sometimes toxic bioaerosols. To further reduce costs, the use of aerosol elimination systems is often avoided. But in the course of the COVID-19 pandemic, the potential risk to acquire COVID-19 by exposure with coronavirus-laden surgical aerosols has raised major concern and uncertainty among surgeons. In the meantime, national and international expert committees and professional societies have published their recommendations for avoiding unnecessary bioaerosol generation and guidelines for exposure protection.[15,17,18,26] However, unknown to most surgeons, electrostatic aerosol precipitation (EAP), as used, for example, to improve drug deposition during pressurized intraperitoneal aerosol chemotherapy,[20,22] is a cost-efficient and effective method to eliminate surgical-induced aerosols during laparoscopic surgery.

In this study, the efficacy of EAP was analyzed by ex-vivo simulations on a clinically relevant experimental setup with a phantom for laparoscopic procedures by characterizing the particle number concentration of surgically induced bioaerosols within the laparoscopic cavity (primary release from tissue), outside the laparoscopic cavity near the working trocar (secondary release from the cavity), and in the breathing zone (exposure) of the surgeon. During incision on the used swine gallbladder peritoneum by high-frequency electrosurgery with a monopolar electro hook (MP-HOOK) force at 40 watts (MP-HOOK40) respectively, 60 watts (MP-HOOK60), and by ultrasonic cutting (USC), a considerable release of particles was determined within the laparoscopic cavity.

In daily practice, the energy settings for laparoscopic cholecystectomy with monopolar electrosurgery in the US are generally in the 25 to 30 watt range.[27] Because such low energy settings did not allow adequate tissue transection of cadaveric swine gall bladders in our ex-vivo Pelvitrainer model, higher energy settings of 40 and 60 watts were used for this study. Additionally, to our very best knowledge, power settings for monopolar cholecystectomy in many German hospitals and German surgical training centers, such as the Aesculap Academy in Bochum, are generally between 40 to 60 watts.

The highest PNC was observed for MP-HOOK60. A trend toward a lower PNC was determined for MP-HOOK40. However, this difference was not statistically significant. A significant lower PNC occurred for USC in standard cutting mode as well as power settings. These findings are in line with the results of previous work, which showed higher particle release rates for monopolar-based instruments than for USC.[11,28,29] Although USC has been shown to produce fewer aerosol particles than mono- and bipolar cutting devices, the COVID-19 pandemic has raised new concerns about the use of USC. This is due to the generation of aerosols composed of tissue, blood, and blood degradation products that could be identified up to 40 cm from the source.[11]

The results of this study show that a continuous operation of EAP significantly lowers the PNC within the abdominal cavity of the phantom, irrespective of the operated tissue dissection technique. Despite the fact that released particles become airborne at the site of surgery, the largest amount is immediately deposited on the tissue in close proximity. Therefore, only small quantities of released particles can distribute in the entire capnoperitoneum. Besides improving the endoscopic view, the reduced quantity of airborne particles also lowers potential release quantities from the laparoscopic cavity via the access ports (ie trocars) into the environment of the operating room facility.

To study bioaerosol release into the operating room facility at the site of the working trocar and in the breathing zone of the surgeon, clinical conditions were simulated as realistically as possible. Therefore, the instruments were operated similar to typical clinical use, with various lengths of application. To compare environment contaminations, all ex-vivo LCs were performed according to a strict protocol. In contrast to MP-HOOK40 without EAP, MP-HOOK60 without EAP led to significant particle number concentrations at the access port (trocar) outside the laparoscopic cavity. Considerable PNCs, which were about 274 times higher than the background aerosol of the operating room facility, were monitored during the exchange, and the use of laparoscopic instruments (mainly for clip forceps and laparoscopic swaps). In contrast, continuous operation of EAP during MP-HOOK60 led to a concentration level 152 times lower at the access port, which was only 1.8 times higher than the level of the background aerosol of the operating room facility. Additionally, the performance of EAP was compared with that of the currently suggested safety measure for continuous aerosol/smoke evacuation (CAE). Therefore, MP-HOOK60 was also performed in combination with CAE at a continuous carbon dioxide flow rate of 12 L/minute (SHE SHA Level 2). During MP-HOOK60, CAE operation showed significant contaminations at working trocars that were 23 times higher than for EAP operation.

Besides the high aerosol elimination efficacy, EAP also has other important advantages over carbon dioxidedriven active and passive aerosol evacuation and filter systems. First, the efficiency of passive filter systems correlates with the level of the capnoperitoneal pressure. Therefore, surgery at lower pressure is even more difficult because the endoscopic view at the surgical site can be hampered by intraperitoneal aerosol accumulation and worse exposure of the surgical field. Second, the efficacy of active and passive aerosol evacuation and filter systems depends on a high carbon dioxide flow rate. This makes it more difficult for the surgical staff to recognize and prevent unintended carbon dioxide and bioaerosol leaking into the environment. Especially active aerosol evacuation systems, which are operated at high carbon dioxide flow rates, lead to fluctuations in the capnoperitoneal pressure that is accompanied by movements of the abdominal wall, trocars, and the camera position with a changing view of the surgical site. Therefore, such movements complicate surgical procedures and can harm the patient.

The authors are aware that the current data reflect only the clinical situation with some limitations. Foremost, the generation of surgical smoke on non-vital/non-perfused tissue in a Pelvitrainer at room temperature is certainly a major limiting factor of this study. Moreover, this pilot study includes neither in-vivo analyses nor a detailed characterization of the generated surgical aerosol in terms of size distributions. Due to the temporal lack of aerosol sizing technologies as well as the national restrictions in the course of the COVID-19 pandemic, only a condensation particle counter was operated. Therefore, the considerable release of particles during ex-vivo LC limited the incision time for release characterization to 3 seconds to avoid a passing of the concentration limit of the operated device. For studying particle release and exposure of surgical-induced bioaerosols for long-term or repeated LCs in future work, besides size-selective aerosol-analytical instruments, appropriate aerosol dilution measures[30,31] should be used. However, with regard to the coronavirus, released particles/droplets equal to or larger than the virus (65 to 125 nm) are relevant.[32] The determined particle number concentrations alone can only serve as an indicator for a lowered risk of becoming infected by aerosolized virus particles encountered during laparoscopic surgery. It is therefore necessary to carry out follow-up studies on in-vivo laparoscopic animal models with a detailed characterization of generated bioaerosols.

CONCLUSIONS

EAP is an efficient method to eliminate generated bioaerosols already at the surgical site and minimize potential bioaerosol exposure to surgical staff. EAP is currently the most efficient method for aerosol evacuation and elimination. A previous study reported the efficient capture of viruses and its concomitant deactivation using electrostatic precipitation technology,[33] so EAP should become even more promising in the future.

Author Contributions

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Analysis and interpretation of data: Giger-Pabst, Buggisch, Göhler
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