Rapid research communication

Solving the problems of gas leakage at laparoscopy

R. A. Cahill[1,3], J. Dalli[1], M. Khan[1,3], M. Flood[2] and K. Nolan[2]

[1]Centre for Precision Surgery, Section of Surgery and Surgical Specialties, School of Medicine, and [2]School of Mechanical and Materials Engineering, College of Engineering and Architecture, University College Dublin, and [3]Department of Surgery, Mater Misericordiae University Hospital, Dublin, Ireland

Correspondence to: Professor R. Cahill, Department of Surgery, Mater Misericordiae University Hospital, 47 Eccles Street, Nelson Street, Dublin 7, Ireland (e-mail: ronan.cahill@ucd.ie)

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Introduction

The COVID-19 pandemic has focused attention on surgical access[1,2], with many surgeons[3–5] and professional bodies[6] abandoning minimally invasive surgery (MIS) for emergency and elective procedures, even in healthcare systems with preserved capability. The reason cited is concern over the aerosolization hazard from surgical gases and airborne transmission of infection. In the face of this challenge, to maintain the advantages of MIS to patients, protection of both the surgical team and environment is required[7]. This has already begun, with protocols emerging for more mindful, deliberate practice with respect to pneumoperitoneum management, combined with use of controlled, filtered insufflation and smoke evacuation systems[8,9]. However, to fully address safe MIS, a better understanding of gas leakage is essential. To illustrate the full extent of the issue and to establish clinically useful modelling tools, a series of clinical and experimental explorations regarding surgical airflow around laparoscopic, robotic and transanal access sites was performed. These studies were performed with Institutional ethics review board approval (AEROSOLVE, IRB 1/378/2172).

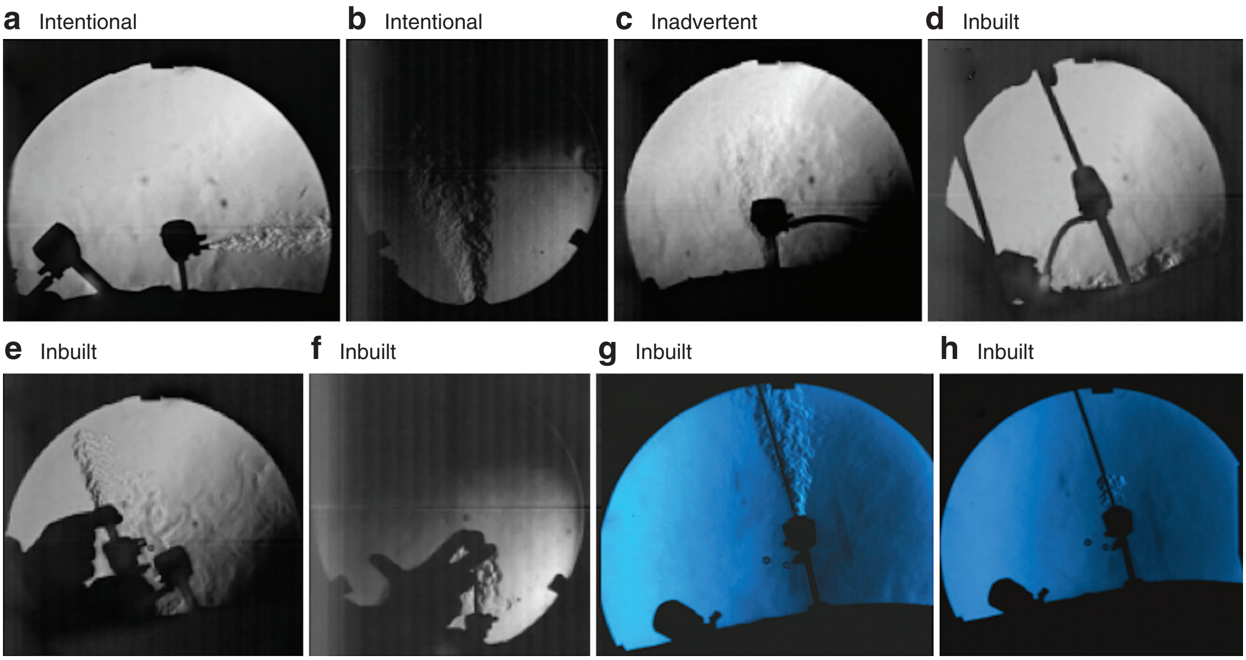
Methods

For clinical qualitative assessment, a near-infrared camera (FLIR GF343; FLIR Systems, West Malling, Kent, UK), spectrally attuned to the absorption wavelength of carbon dioxide to enable its visualization by the absorption δ, was used to observe both elective and emergency surgery performed by standard and robotic-assisted laparoscopy and transanal minimally invasive surgery. Experimentally, a high-fidelity laparoscopy model using fresh porcine cadaver was established for operation (diagnostic laparoscopy, cholecystectomy and small bowel examination), with standard instrumentation employed by experienced surgeons and carbon dioxide pneumoperitoneum. To characterize and quantify gas leaks in this model, high-speed Schlieren optical imaging, a passive imaging method whereby changes in refractive index can be visualized directly (*Fig. S1*, supporting information), was applied continuously. Leaks were studied at three different pneumoperitoneal pressures (8, 12 and 25 mmHg) using three different brands of trocar (Applied Medical, Santa Margarita, California, USA, Conmed, Utica, New York, USA; and Medtronic, Minneapolis, Minnesota, USA) in separate models, with recording by monochromatic camera (Phantom® v311/VEO4k 990; Vision Research, Wayne, New Jersey, USA). To demonstrate the droplet propulsion capability of the gas streams, a laparoscopic nebulizer (Aerogen® Pro Solo, 1–5-μm mist; Aerogen, Dangan, Galway, Ireland) humidified intra-abdominal gas and high-definition videography was used to study droplet escape via transillumination in a darkened room. *Post hoc* image processing included optical flow-based estimation of indicative leak velocity flow field using feature tracking, and two-dimensional cross-correlation image flow to predict flow patterns (laminar or turbulent, by Reynold's number calculation) and quantify volumes and evolution of observed flow structures indicative of microdroplet kinematics (allowing approximation of particle path lines). Management of leaks by compensatory local ring vacuums (Leaktrap™, Palliare Surgical, Dangan, Galway, Ireland) was investigated using the same methodology.

Results

Considerable gas leakage was observed during all procedures (*Fig. S2* and *Video S1*, supporting information), and was reliably and repeatedly evident experimentally (*Fig. 1*; *Video S2*, supporting information). Such trocar leaks are capable of actual droplet propulsion (*Fig. S3* and *Video S3*, supporting information). Trocar valve fatigue developed in

Fig. 1 Photographic stills from video capture of high-speed Schlieren imaging during laparoscopic surgery showing examples of each category of gas leak



a,**b** Category 1 intentional leak owing to venting gas from trocar to clear smoke (**a**) and removal of a trocar without first desufflating pneumoperitoneum (**b**). **c** Category 2 inadvertent leak occurring at abdominal wall around trocar base. **d**–**h** Category 3 inbuilt leak occurring through the trocar, as happens during optical port insertion (**d**) and removal of an obturator from a 5-mm port (**e**) and from a Hassan port (**f**), or because of leakage via valves at the time of insertion (**g**) or removal (**h**) of an instrument. Best viewed in *Video S2* (supporting information).

Table 1 Classification of gas leak at laparoscopy by underlying causative mechanism

Category	Definition	Example
Intentional	Those caused by deliberate action. Mitigatable by careful adherence to best practice	Venting trocar into room to clear smoke, reduce pressure, conclude procedure Specimen extraction Interruption of valve closure (e.g. specimen bag thread/drain placement across valve)
Inadvertent	Commonly occurring at skin–trocar interface placement sites	Incision too big Extreme movement/positioning of instrument
Inbuilt	Those occurring through trocars or instruments either by design or mechanical failure/fatigue	Optical trocars used with insufflation to initiate pneumoperitoneum Obturator use to (re)place trocars during procedure Robotic instrumentation Energy devices Instrument exchange Leaky valve leaflet

Leaks in each category can be continuous or intermittent and affected (either exacerbated or relieved) by pneumoperitoneal pressure changes. Examples are shown in *Fig. 1*, and *Figs S2–S5* and *Videos S1–S5* (supporting information).

some ports experimentally after as few as three instrument exchanges and, interestingly, was worst at lower pneumoperitoneal pressures (data not shown).

Mechanistically, leaks can be grouped into three categories (*Table 1*). Volumes and flow patterns of gas leaks are shown in *Table 2*, and *Fig. S4* and *Video S4* (supporting information), along with particle trajectories, showing mean velocities reaching 5 m/s and estimated leak flow rates up to 20 l/min. Instrument insertion was associated with greater turbulence of leak stream and volume (litres

Table 2 Indicative volumetric flow rate and Reynolds number estimation of gas leaks occurring around and through trocars

	Orifice diameter (mm)	Flow rate (l/min)*	Reynolds number*
Abdominal wall leak	–	0·49 (0·22–0·75)	1458 (1087–1830)
Obturator removal	5	2·71 (1·18–3·06)	2630 (1144–2973)
	12	15·50 (13·90–20·73)	7520 (6748–10 065)
Venting from insufflation tap	4·3	4·23 (2·22–6·95)	4771 (2508–6748)
Instrument insertion	5	5·45 (2·53–5·89)	5290 (2459–5504)
	10–12	16·96 (12·39–18·71)	8235 (6016–9081)
Instrument withdrawal	5	2·36 (1·18–7·48)	2288 (1144–7263)
	10–12	7·54 (7·07–11·17)	3660 (3431–5421)
Trocar removal	12	13·90 (13·90–19·01)	6748 (6245–6748)

*Values are median (range). Reynolds number (Re) below 2300 indicates laminar flow, 2300–4000 indicates transitional flow, and over 4000 indicates turbulent flow. In general, volumes, mean and maximum velocities and Re increased with higher intra-abdominal pressure.

per minute) than withdrawal, with pressure exacerbating both. Observed jet streams tended to turbulence and were eliminated at trocar top and base by ring vacuums (15 l/min, 10 kPa suction) (*Fig. S5* and *Video S5*, supporting information).

Discussion

The COVID-19 pandemic has demonstrated a problem with contemporary MIS practice. The imperative now is to improve the fundamentals of MIS, so that further such threats cause less systemic shock and best patient care continues. In the hierarchy of hazard control measures[10], engineering controls trump administrative and personal protection equipment controls, and rank below risk elimination only. This is needed whether or not the peak of the pandemic passes soon as resumption of normal services will involve patients at ongoing community risk of infection for the foreseeable future. Furthermore, even if it could be proved that COVID-19 is not transmissible from virions detectable in blood and enteric content (and perhaps also peritoneal fluid)[2–13], the precedent now is that laparoscopy may be discarded in the face of any other transmissible epidemic. There is already enough evidence to support improved practice regarding gas management, irrespective of infection risk (including non-COVID infections)[14,15]. Some estimates suggest that MIS in the USA alone creates more carbon dioxide pollution than some countries[16], and that the risks of inhaling surgical smoke equate to those of passive smoking[17].

This work has developed tools and models for the assessment of gas leakage. Carbon dioxide leakage is common, occurs at considerable velocity (equivalent to that occurring with a human cough) and volume, and is capable of transmitting particles into the operating room environment. Although some of the leaks are unsurprising, others, such as gas escape through hollow spaces needed for energy and lever transmission, were unexpected. Some of the known mismatch between carbon dioxide volumes needed to maintain pneumoperitoneum (200–400 ml/min) and the amount absorbed systemically (40 ml/min) has already been explained, showing how operative carbon dioxide consumption rates are in the order of 200–300 l/h (and higher with Airseal® (Conmed) insufflation[18]). Because of powerful insufflation, considerable ongoing gas leakage occurs without disruption of operative view or fluency.

Although intentional leaks are controllable, technological development is needed to address the inadvertent and inbuilt ones. Different leaks occur simultaneously and therefore it is insufficient to focus on any one category alone. Furthermore, although current guidelines help in terms of intentional leaks, some leakage will still occur in this category despite adherence to best practice. Patient factors such as obesity can also confound; even if ideal incisions are made at the start, skin or fascial stretch can occur during the procedure, especially with extreme instrument movement. Smoke evacuation solutions are also only partially effective. Leaks occurring through functional trocars and instrumentation as well as trocar valve fatigue (interestingly, worsened by lower-pressure pneumoperitoneum) show some limitations of the present recommendations. Without more fundamental address, high-level personal protective equipment (perhaps powered air-purifying respirators[19]) will continue to be needed to mitigate the hazards of pathogen and pollutant contamination.

With the indicative data generated by these assessments, many practice and technological solutions can begin development, but further modelling is needed for precision. Smaller trocars and instruments let lower volumes of gas escape but their higher velocity accentuates droplet trajectory. Although initial mechanical adaptations can be configured as a universal add-on for rapid deployment (including lower device classification), next-generation design is needed within trocars for use in conjunction with filtered gas evacuators and low-pressure insufflators. Whatever the exact method of amelioration, the constructs need to be robust, widely acceptable and available. Their use could also extend to other aerosol-generating interventions such as endoscopy[20] and airway intubation[21].

Historically, there has been complacency about gas pollution in the operating room from endolaparoscopy[22,23]. Although concern exists that complete eradication of cavity gas loss from instrument insertion, manipulation and withdrawal through trocars is impossible, the issues can be markedly improved. Within the stark context of a global pandemic with high healthcare staff infection rates and the cessation of elective surgical practice worldwide, the present data should inspire change.

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Supporting information

Additional supporting information can be found online in the Supporting Information section at the end of the article.