BMJ Open Respiratory Research

Chest drain aerosol generation in COVID-19 and emission reduction using a simple anti-viral filter

Clodagh Duffy,[1] Andrew Kidd,[2,3] Sarah Francis,[1] Selina Tsim,[2,3] Laura McNaughton,[2] Katie Ferguson,[2,3] Jenny Ferguson,[2,3] K Gary Rodgers,[4] Claire McGroarty,[4] Robin Sayer,[1] Kevin G Blyth [3,5]

To cite: Duffy C, Kidd A, Francis S, *et al*. Chest drain aerosol generation in COVID-19 and emission reduction using a simple anti-viral filter. *BMJ Open Resp Res* 2020;**7**:e000710. doi:10.1136/bmjresp-2020-000710

► Additional material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/bmjresp-2020-000710).

CD and AK contributed equally.

Received 11 July 2020
Revised 27 August 2020
Accepted 7 October 2020

[1]Medical Devices Unit, NHS Greater Glasgow and Clyde, Glasgow, UK
[2]Respiratory Medicine, Queen Elizabeth University Hospital, Glasgow, UK
[3]Institute of Cancer Sciences, University of Glasgow, Glasgow, UK
[4]Emergency Department, Queen Elizabeth University Hospital, Glasgow, UK
[5]Glasgow Pleural Disease Unit, Respiratory Medicine, Queen Elizabeth University Hospital, Glasgow, UK

Correspondence to
Dr Kevin G Blyth;
kevin.blyth@glasgow.ac.uk

ABSTRACT

Introduction The COVID-19 pandemic has been characterised by significant in-hospital virus transmission and deaths among healthcare workers. Sources of in-hospital transmission are not fully understood, with special precautions currently reserved for procedures previously shown to generate aerosols (particles <5 µm). Pleural procedures are not currently considered AGPs (Aerosol Generating Procedures), reflecting a lack of data in this area.

Methods An underwater seal chest drain bottle (R54500, Rocket Medical UK) was set up inside a 60-litre plastic box and connected via an airtight conduit to a medical air supply. A multichannel particle counter (TSI Aerotrak 9310 Aerosol Monitor) was placed inside the box, allowing measurement of particle count/cubic foot (pc/ft^3) within six channel sizes: 0.3–0.5, 0.5–1, 1–3, 3–5, 5–10 and >10 µm. Stabilised particle counts at 1, 3 and 5 L/min were compared by Wilcoxon signed rank test; p values were Bonferroni-adjusted. Measurements were repeated with a simple anti-viral filter, designed using repurposed materials by the study team, attached to the drain bottle. The pressure within the bottle was measured to assess any effect of the filter on bottle function.

Results Aerosol emissions increased with increasing air flow, with the largest increase observed in smaller particles (0.3–3 µm). Concentration of the smallest particles (0.3–0.5 µm) increased from background levels by 700, 1400 and 2500 pc/ft^3 at 1, 3 and 5 L/min, respectively. However, dispersion of particles of all sizes was effectively prevented by use of the viral filter at all flow rates. Use of the filter was associated with a maximum pressure rise of 0.3 cm H_2O after 24 hours of flow at 5 L/min, suggesting minimal impact on drain function.

Conclusion A bubbling chest drain is a source of aerosolised particles, but emission can be prevented using a simple anti-viral filter. These data should be considered when designing measures to reduce in-hospital spread of SARS-CoV-2.

Key messages

- The objectives of this study were to determine whether a bubbling chest drain is aerosol-generating and the efficacy of a simple anti-viral filter.
- A bubbling chest drain is a source of aerosolised particles, but emission can be prevented using a simple anti-viral filter.
- The WHO and expert groups, including the British Thoracic Society, disagree on the risks posed by pleural procedures during the COVID-19 pandemic. This reflects the absence of any prior data on whether pleural procedures generate aerosols and merit risk mitigation. This study is the first to examine this question.

INTRODUCTION

Previous coronavirus epidemics were characterised by high infection rates in healthcare workers (HCWs) and 'super-spreading' events within hospitals. Despite implementation of WHO guidance designed to reduce in-hospital spread,[1] nosocomial and HCW infection have remained prominent features of the current COVID-19 pandemic, with 43.5% of UK HCWs becoming seropositive over a 1-month period in one recent study.[2] Better understanding of in-hospital infection sources is therefore urgently needed. Pleural procedures are not currently considered aerosol-generating by the WHO,[1] and special precautions to mitigate against viral transmission and/or to protect HCWs are not currently recommended. However, this is based on the absence of any prior data regarding the aerosol-generating potential of a chest drain (where an aerosol is defined as a particle smaller than 5 µm) rather than a robust understanding of the level of risk involved. Recent studies report detection of SARS-CoV-2 in COVID-19-associated pleural effusion[3 4] and 'super-spreading' events linked to chest drain use. The latter includes a cohort of 25 Chinese patients (including 12 HCWs) infected from a single index case who underwent elective lobectomy with undetected SARS-CoV-2 infection.[5] This has prompted expert bodies, including the British Thoracic Society (BTS)[6] and the American Association

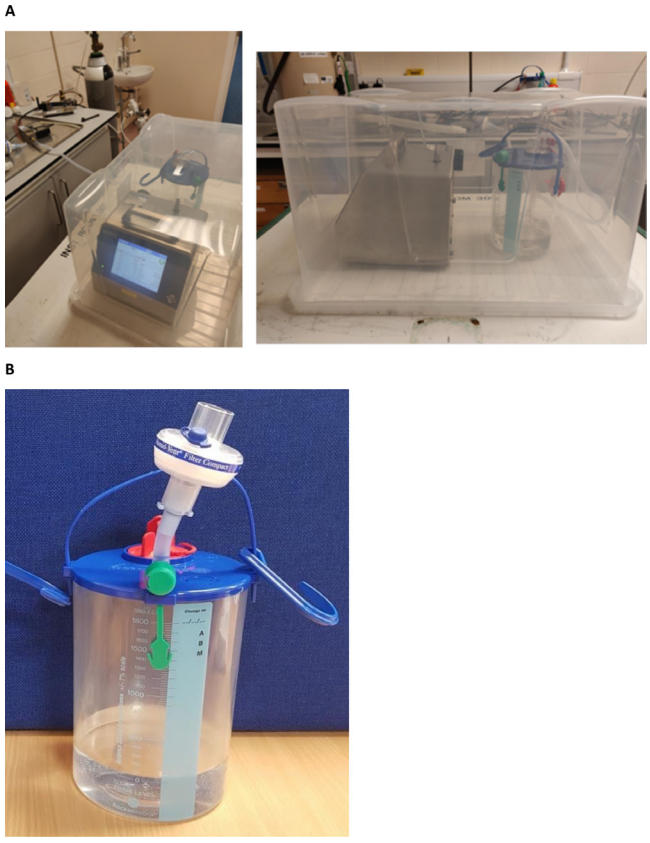

Figure 1 (A) Experimental set-up including the Aerotrak 9310 (to the left of the images) and the underwater seal chest drain bottle (Rocket R54500, to the right of the images) inside the sealed 60-litre plastic box. Standard chest drain tubing (R54502) has been used to connect the chest drain bottle to a medical air cylinder. (B) The assembled COVID-19 anti-viral filter, comprised of a heat and moisture exchange (HME) filter (Teleflex Humid-Vent Filter Compact, 19 402T), attached via a 5 cm section of standard chest drain tubing (Rocket Medical R54502) and the proximal adapter from a size 8 endotracheal tube (Portex 100/199/080). Detailed instructions for use are provided in the online supplemental appendix.

for the Surgery of Trauma (AAST)[7] to recommend risk mitigation of some form until the level of risk involved is more clearly understood. Risk mitigation options include connection of all patients to wall suction, use of a digital chest drain system or use of a bespoke anti-viral filter attached to a standard chest drain bottle.[6] The objectives of this study were to determine (a) whether a bubbling chest drain is aerosol-generating and (b) the efficacy of an anti-viral filter developed in-house. We chose this option since wall suction greatly restricts patient mobility and digital drainage systems do not contain suitable viral filters for exit gases.

METHODS

The experimental set-up used is shown in figure 1. An underwater seal chest drain bottle (R54500, Rocket Medical UK) was set up according to the manufacturer's instructions and placed inside a sealable 60-litre plastic box. The drain tubing (Ref R54502) was attached to a medical air cylinder via an airtight conduit in the wall of the box. A multichannel particle counter (TSI Aerotrak 9310 Aerosol Monitor) was placed inside the box, allowing measurement of particle count/cubic foot (pc/ft^3) within six channel sizes: 0.3–0.5, 0.5–1, 1–3, 3–5, 5–10 and >10 µm. Stabilised particle counts at different flow rates (without and with the filter attached) were compared by Wilcoxon signed rank test (R V.4.0.2 (Vienna, Austria)); p values were adjusted for multiple comparisons by the Bonferroni method. For filter comparisons, relative differences, normalised to without-filter readings, were assessed. Ethical approval was not required.

Viral filter

A COVID-19 anti-viral filter device was designed by the study team and manufactured using repurposed equipment (see figure 1, and online supplemental for detailed instructions for use). The completed assembly was comprised of a heat and moisture exchange filter normally used on a ventilator circuit (Teleflex Humid-Vent Filter Compact, 19 402T), a 5 cm section of standard chest drain tubing (Rocket Medical R54502) and the proximal adapter from a size 8 endotracheal tube (Portex 100/199/080). The safe functioning of the filter was assessed within a Failure Mode and Effects Analysis framework (BS EN ISO 14971:2012: application of risk management to medical devices). This included demonstration that over 24 hours of continuous flow at 5 L/min, the pressure within the bottle rose by no more than 0.3 cm H_2O, suggesting the filter has minimal impact on drain function.

Aerosol measurement

Particle concentrations in the air surrounding the chest drain were initially sampled without the filter attached. Baseline conditions were first sampled for 20 min. Medical air was then pumped through the circuit for 20 min at 1 L/min, before being switched off, allowing baseline conditions to re-stabilise over a further 20 min. After each 60 min experiment, the box was opened, measurements were recorded and the unit resealed. The experiment was repeated using flow rates of 3 and 5 L/min, and then all three experiments were repeated with the filter attached (see figure 1B). Each experiment was conducted on a single occasion.

RESULTS

Particle concentrations measured in each channel at 1, 3 and 5 L/min, without the filter attached are summarised in figure 2, absolute values reported in online supplemental table 1. Particle emissions increased with increasing air flow, with the largest increase observed in the smaller particles (0.3–3 µm). Concentration of the smallest particles (0.3–0.5 µm) increased from background levels by

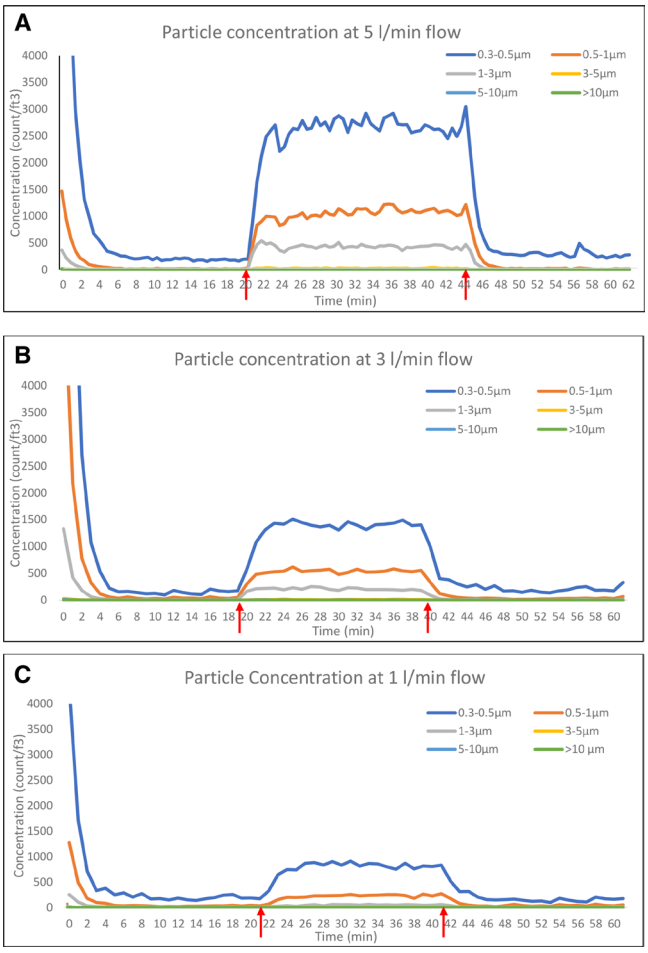

Figure 2 Particle concentrations, as measured by the TSI Aerotrak 9310 Aerosol Monitor, while air was bubbled through a standard underwater seal chest drain (Rocket R54500) without a filter at flow rates of (A) 1 L/min, (B) 3 L/min and (C) 5 L/min. The red arrows on each graph show when the air flow was turned on and then turned off again.

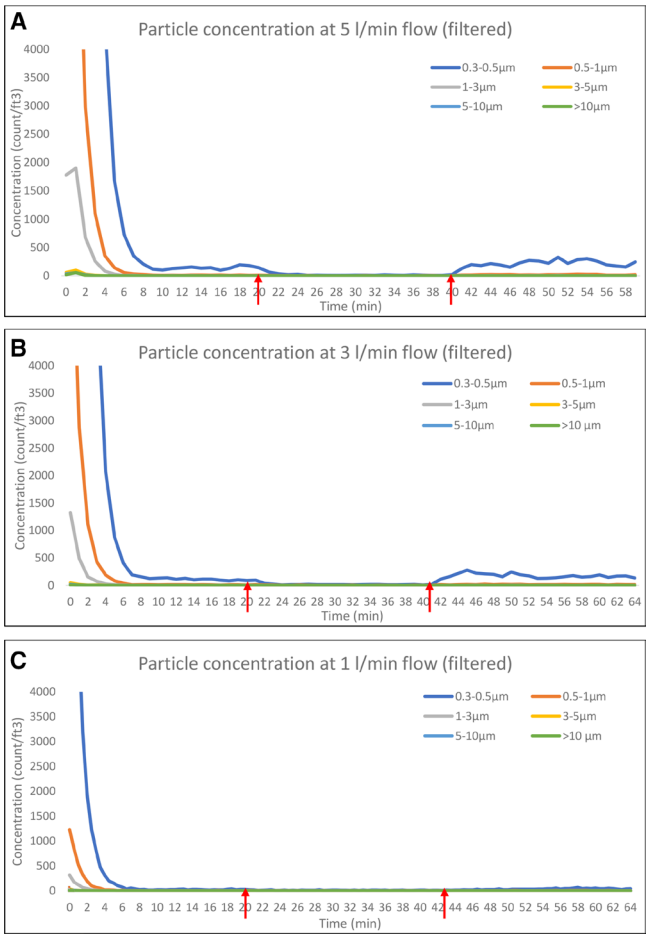

Figure 3 Particle concentrations, as measured by the TSI Aerotrak 9310 Aerosol Monitor, while air was bubbled through a standard underwater seal chest drain (Rocket R54500) with a filter at flow rates of (A) 1 L/min, (B) 3 L/min and (C) 5 L/min. The red arrows on each graph show when the air flow was turned on and then turned off again.

700, 1400 and 2500 pc/ft^3 at 1, 3 and 5 L/min, respectively (see figure 2). Particle counts (pc/ft^3) significantly increased (based on Bonferroni-adjusted p<0.00086) at all flow rates and in all channel sizes, except at 1 L/min in the 5–10 µm channel (adjusted p value not significant at 0.02).

Particle concentrations measured in each channel at 1, 3 and 5 L/min, with the filter attached are summarised in figure 3, absolute values reported in online supplemental table 1. Particle counts (pc/ft^3) were notably lower in all channels compared with without-filter measurements. Counts of the smallest particles significantly reduced between baseline and initiation of air flow (based on Bonferroni-adjusted p<0.00086) at 1 L/min (0.3–0.5 µm only), 3 and 5 L/min (0.3–0.5, 0.5–1, 1–3 µm channels), likely reflecting dilution of background aerosols by filtered air. With the filter added, normalised particle count differences were significantly lower (p<0.00086) in the smaller channels (0.3–0.5, 0.5–1, 1–3, 3–5 µm) at all flow rates, compared with without-filter values.

DISCUSSION

The data reported here indicate that particles in the aerosol range (<5 µm) are generated by a bubbling chest drain at continuous flow rates of at least 1 L/min. Aerosol emissions increased with increasing air flow, simulating a high-volume air-leak, as might be expected following thoracic surgery, in mechanically ventilated patients or patients with a large spontaneous alveolar-pleural fistula complicating bullous lung disease. These data were recorded as part of a comprehensive risk assessment process, which demonstrated no significant limitation of air flow through the chest drain circuit with the filter in situ.

Aerosols are typically generated by air moving across the surface of a liquid, with increasing air forces generating smaller particles.[1] This is consistent with the observations reported here in that unfiltered emissions of the smallest particles (0.3–0.5 µm) increased progressively from 1 to 3 to 5 L/min. Our findings are also concordant with a recent study reported by Akhtar *et al*, in which a similar anti-viral filter was evaluated and produced a qualitative

reduction in droplet emissions. However, droplet size, and therefore aerosolisation potential were not examined.[8] These data support risk mitigation in patients with suspected or proven COVID-19, as recommended by the BTS[6] and the AAST.[7] However, the absolute risk involved remains uncertain and the experimental set-up used cannot be considered exactly equivalent to a bubbling drain in a clinical setting. Pleural effusion and pneumothorax appear uncommon complications of COVID-19 (occurring in ~5% and ~1% of cases, respectively[6 8]) and an aerosol-generating chest drain can clearly only be an infection risk if SARS-CoV-2 is (a) present in any effusion drained (which may be of minimal volume in patients with pneumothorax and major air-leaks) and (b) remains viable long enough to be aerosolised. Lescure *et al*[3] and Mei *et al*[4] have recently reported cases of SARS-CoV-2 positive effusions, but in these cases air-leak was not reported as a significant component, and larger studies are needed to define the prevalence and risks of unfiltered air-leaks in COVID-19 more clearly. In a recent postmortem series, Schaller *et al* reported that 50% of patients with fatal COVID-19 had associated pleural effusion, of which 50% were PCR positive.[9] The risk of nosocomial transmission via an unfiltered air-leak may therefore be highest in patients with the most advanced disease in the event of a secondary pneumothorax complicating positive pressure ventilation. With regard to viability over time, SARS-CoV-2 has been shown to remain viable in aerosols for several hours and on surfaces for several days,[10] so could probably persist in a chest drain bottle for sufficiently long to be an infection risk.

The experiments reported here were carried out in a controlled environment with minimal background environmental disturbances. It is therefore unknown how normal background activities (eg, staff proximity, the opening and closing of doors), which can affect the rate of aerosols resuspension on surfaces, would affect concentrations in a clinical setting. Given that our data were recorded at flow rates of 1, 3 and 5 L/min, it should also be acknowledged that the particle emission profile of smaller volume air-leaks cannot be directly concluded from our data. Nevertheless, it appears clear that a bubbling chest drain is a potential source of aerosolised particles, and that dispersion can be prevented using a simple anti-viral filter. These data should be considered when designing measures to reduce in-hospital spread of SARS-CoV-2.

Contributors CD had full access to all of the data in the study, contributed substantially to the study design, data analysis and interpretation, and wrote a first draft of part of the manuscript. AK contributed substantially to the study design and interpretation, and wrote a first draft of part of the manuscript. SF and RS had full access to all of the data in the study, contributed substantially to the study design, data analysis and interpretation, and the writing of the manuscript. ST, KF, JF, LM, KGR, CM contributed substantially to the study design, data analysis and interpretation, and the writing of the manuscript. KGB conceived the study, had access to the data and takes responsibility for the integrity and the accuracy of the data analysis, had the primary role in writing and submitting the manuscript and acts as guarantor.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Competing interests KGB has received research funding from Rocket Medical UK for other studies.

Patient consent for publication Not required.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available upon reasonable request. Requests should be made to the Corresponding Author.

ORCID iD

Kevin G Blyth http://orcid.org/0000-0003-2972-6641

REFERENCES

1 WHO. Infection prevention and control of epidemic- and pandemic-prone acute respiratory infections in health care, 2014. Available: https://apps.who.int/iris/bitstream/handle/10665/112656/9789241507134_eng.pdf;jsessionid=648503CE9E2AB916BB9EC63D245DE2E9?sequence=1 [Accessed 5 Jul 2020].
2 Houlihan C, Vora N, Byrne T, *et al*. SARS-CoV-2 virus and antibodies in front-line health care workers in an acute hospital in London: preliminary results from a longitudinal study. *Medrxiv* 2020.
3 Lescure F-X, Bouadma L, Nguyen D, *et al*. Clinical and virological data of the first cases of COVID-19 in Europe: a case series. *Lancet Infect Dis* 2020;20:697–706.
4 Mei F, Bonifazi M, Menzo S, *et al*. First detection of SARS-CoV-2 by real-time reverse transcriptase-polymerase chain reaction assay in pleural fluid. *Chest* 2020;158:e143–6.
5 Li Y-K, Peng S, Li L-Q, *et al*. Clinical and Transmission Characteristics of Covid-19 - A Retrospective Study of 25 Cases from a Single Thoracic Surgery Department. *Curr Med Sci* 2020;40:295–300.
6 Hallifax R, Wrightson J, Bibby A, *et al*. Pleural services during COVID-19 pandemic, 2020. Available: https://www.brit-thoracic.org.uk/document-library/quality-improvement/covid-19/pleural-services-during-covid-19-pandemic/ [Accessed 5 Jul 2020].
7 Pieracci FM, Burlew CC, Spain D, *et al*. Tube thoracostomy during the COVID-19 pandemic: guidance and recommendations from the AAST acute care surgery and critical care committees. *Trauma Surg Acute Care Open* 2020;5:e000498.
8 Akhtar MR, Ricketts W, Fotheringham T. Use of an antiviral filter attached to a pleural drain bottle to prevent aerosol contamination with SARS-CoV-2. *Clin Med* 2020;20:e60–1.
9 Schaller T, Hirschbühl K, Burkhardt K, *et al*. Postmortem examination of patients with COVID-19. *JAMA* 2020;323:2518.
10 van Doremalen N, Bushmaker T, Morris DH, *et al*. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *N Engl J Med* 2020;382:1564–7.

COVID-19 Chest Drain Filter Modification Instructions for Use

Contents

1. Intended Use

To reduce the risk of viral particle expulsion from a R54500 Rocket Chest Drainage Bottle in the management of pneumothorax in patients suspected or confirmed infected with COVID-19.

Duffy C, *et al. BMJ Open Resp Res* 2020; 7:e000710. doi: 10.1136/bmjresp-2020-000710

2. Preparing the Filter Connector Assembly

			
Rocket Chest Drain Tubing Set, Ref R54502	8.0mm Portex Tracheal Tube, Ref 100/199/080	Sterile Scissors or Scalpel	Sterile Ruler

2.1. On a sterile tray, remove the Rocket Chest Drain Tubing Set from its packaging.

2.2. Using the Sterile Scissors or Scalpel and the Sterile Ruler, cut a 5cm section of tubing from the end of the Tubing Set.

2.3. Verify that the cut length of tubing is between 4.5-5.5cm (if otherwise, repeat step 2.2) then dispose of the remainder of the Tubing Set.

2.4. Remove the 8.0mm Portex Tracheal Tube from its packaging.

2.5. Remove the blue connector piece and dispose of the rest of the Tracheal Tube.

2.6. Attach the cut piece of tube to the blue connector. Ensure the tube is pushed to the end of the blue connector so that there is no more than a 5mm gap (see Figure 2A).

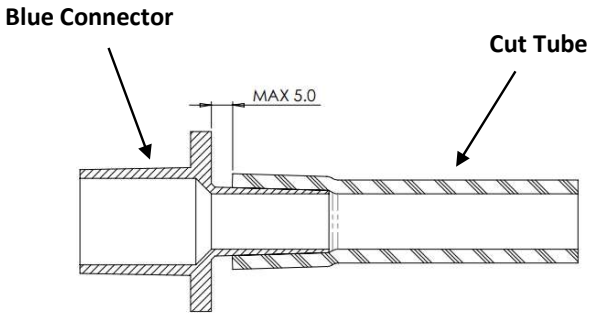

Figure 2A: Push the cut tube onto the blue connector so that there is no more than a 5.0mm gap between the end of the tube and the connector.

Duffy C, *et al. BMJ Open Resp Res* 2020; 7:e000710. doi: 10.1136/bmjresp-2020-000710

3. Setting Up the Chest Drain

		
R54500 Rocket Chest Drainage Bottle	Teleflex Humid-Vent Filter Compact, Ref 19402T	Filter Connector Assembly

3.1. Remove the Rocket Chest Drainage Bottle from its packaging.

3.2. Remove the green cap from the nozzle on the top of the Bottle.

3.3. Remove the Teleflex Humid-Vent Filter Compact from its packaging and firmly attach the opaque end of the Filter to the blue part of the Filter Connector Assembly.

3.4. Firmly push the tube end of the Filter Connector Assembly onto the exposed nozzle on the Bottle, so that only one of the rings on the nozzle is visible (see Figure 3A).

3.5. Proceed with normal use of the Rocket Chest Drainage Bottle.

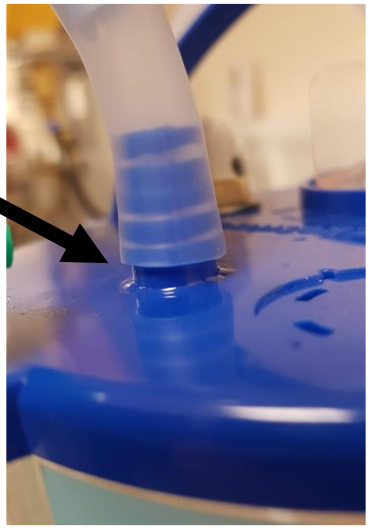

Figure 3A. Push the Filter Connector Assembly firmly onto the lowest ring of nozzle.

Figure 3B. The assembled COVID-19 Chest Drain Filter Modification.

Duffy C, *et al. BMJ Open Resp Res* 2020; 7:e000710. doi: 10.1136/bmjresp-2020-000710

4. Replacing the Filter

 Teleflex Humid-Vent Filter Compact, Ref 19402T	 Clamp	 Gauze

4.1. Wrap gauze around the exposed tube and apply a clamp, taking care to ensure that the tube is fully occluded.

4.2. Remove the old Filter by firmly holding onto the blue connector and pulling on the Filter. If the Filter cannot be easily removed, see Section 5.

4.3. Dispose of the Filter safely according to local clinical waste protocols.

4.4. Remove a new Filter from its packaging and firmly fit it to the Connector Assembly.

4.5. Remove the clamp and inspect the tube for damage. If the tube is visibly damaged or kinked the Filter Connector Assembly should be replaced as per Section 5.

5. Replacing the Filter and Filter Connector Assembly

 Teleflex Humid-Vent Filter Compact, Ref 19402T	 Filter Connector Assembly

5.1. Prepare a new Filter Connector Assembly as per Section 2.

5.2. Remove the new Teleflex Humid-Vent Filter Compact from its sterile packaging and firmly attach the opaque end of the Filter to the blue part of the Filter Connector Assembly.

5.3. Disconnect the old Filter and Filter Connector Assembly from the Bottle nozzle.

5.4. Quickly replace with the new Filter and Filter Connector Assembly, firmly pushing the tube onto the exposed nozzle so that only one of the rings on the nozzle is visible.

5.5. Dispose of the Filter and Filter Connector Assembly according to local clinical waste protocols.

Duffy C, *et al. BMJ Open Resp Res* 2020; 7:e000710. doi: 10.1136/bmjresp-2020-000710

6. Important Information

6.1. Replace the filter after 24 hours of use (See Replacing the Filter Section 4).

6.2. Wear appropriate PPE for each procedure in this document as per local guidelines.

6.3. Regularly check that the connections between the Filter, Filter Connector Assembly and Nozzle remain tight and secure, and record on the chest drain chart.

6.4. Ensure that the cap on the Teleflex Humid-Vent Filter Compact remains closed at all times.

6.5. Take care to minimise swaying or knocking of the Bottle.

6.6. Regularly check that the Filter and tube are not visibly kinked or occluded. If kinking or occlusion is detected, replace the Filter Connector Assembly and/or Filter as necessary.

6.7. If the Filter comes into contact with liquid, or appears to be visibly saturated with liquid, the Filter and Filter Connector Assembly should be replaced.

7. Warnings

7.1. For use by a medical professional only.

7.2. Only use for the Intended Use as specified in Section 1.

7.3. The device is manufactured under the MDR Health Institute Exemption and is not approved for use outside NHS Greater Glasgow and Clyde.

7.4. All parts are single use.

7.5. This modification is not designed to prevent the release of viral particles via the pressure release valve.

7.6. Follow local guidelines for infection control and safe disposal of parts.

8. Incident Reporting

Any serious incident that has occurred in relation to this device should be logged in Datix and reported to the manufacturer (below).

9. Manufacturer Details

Medical Devices Unit, NHS Greater Glasgow and Clyde
West Glasgow Ambulatory Care Hospital
Dalnair Street
Yorkhill
Glasgow
G3 8SJ

Email: gg-uhb.mdu@nhs.net

The manufacturers welcome feedback on this device modification. To provide feedback, please visit the website below and complete the COVID-19 Chest Drain Filter Modification Feedback Form.

https://medicaldevicesunit.org/covid

Supplementary Table 1. Comparison between 'baseline' and 'functioning' particle concentrations (particle count/cubic foot (pc/ft3)). 'Functioning' concentrations were measured at 1, 3 and 5L/min air flow (+/- an anti-viral filter). Values are reported as medians (standard error (SE)) and comparisons are by Wilcoxon signed rank tests, with p-values adjusted for multiple comparisons (significant values in bold). NA: Not available as both datasets consist of entirely zero readings.

1L/min						
	No filter			Filter		
Channel size	Baseline concentration (pc/ft3) (SE)	Functioning concentration (pc/ft3) (SE)	P value	Baseline concentration (pc/ft3) (SE)	Functioning concentration (pc/ft3) (SE)	P value
0.3-0.5 µm	185 (6.11)	833 (8.22)	**<0.00086**	22 (1.42)	13 (0.60)	**<0.00086**
0.5-1 µm	27 (1.52)	230 (3.70)	**<0.00086**	3 (0.25)	2 (0.26)	0.1598
1-3 µm	5 (0.54)	46 (1.91)	**<0.00086**	0 (0.09)	0 (0.11)	0.08314
3-5 µm	27 (1.53)	230 (3.92)	**<0.00086**	3 (0.25)	2 (0.26)	0.07186
5-10 µm	0 (0)	0 (0.07)	0.02627	0 (0.03)	0 (0)	1
>10 µm	0 (0)	0 (0)	NA	0 (0.03)	0 (0)	1
3L/min						
	No filter			Filter		
Channel size	Baseline concentration (pc/ft3) (SE)	Functioning concentration (pc/ft3) (SE)	P value	Baseline concentration (pc/ft3) (SE)	Functioning concentration (pc/ft3) (SE)	P value
0.3-0.5 µm	170 (11.45)	1417 (15.73)	**<0.00086**	119 (7.84)	15 (0.91)	**<0.00086**
0.5-1 µm	38 (1.76)	546 (5.11)	**<0.00086**	13 (0.81)	3 (0.36)	**<0.00086**
1-3 µm	6 (0.53)	209 (3.77)	**<0.00086**	1 (0.25)	0 (0.11)	**<0.00086**
3-5 µm	38 (1.85)	546 (5.15)	**<0.00086**	13 (0.81)	3 (0.38)	1
5-10 µm	0 (0.03)	1 (0.20)	**<0.00086**	0 (0)	0 (0)	NA
>10 µm	0 (0)	0 (0)	NA	0 (0)	0 (0)	NA
5L/min						
	No filter			Filter		
Channel size	Baseline concentration (pc/ft3) (SE))	Functioning concentration (pc/ft3) (SE)	P value	Baseline concentration (pc/ft3) (SE)	Functioning concentration (pc/ft3) (SE)	P value
0.3-0.5 µm	216 (8.25)	2692 (37.57)	**<0.00086**	144 (6.41)	12 (0.75)	**<0.00086**
0.5-1 µm	20 (0.82)	1070 (10.00)	**<0.00086**	14 (0.80)	3 (0.26)	**<0.00086**
1-3 µm	3 (0.25)	436 (6.20)	**<0.00086**	2 (0.22)	0 (0.08)	**<0.00086**
3-5 µm	20 (1.00)	1070 (10.34)	**<0.00086**	14 (0.90)	3 (0.26)	1
5-10 µm	0 (0.05)	5 (0.38)	**<0.00086**	0 (0)	0 (0.03)	1
>10 µm	0 (0)	1 (0.14)	**<0.00086**	0 (0)	0 (0)	NA