REVIEW ARTICLE

Royal Australasian College of Surgeons

SARS-CoV-2 transmission risk to healthcare workers performing tracheostomies: a systematic review

Ashwin Subramaniam ,*†‡ Zheng Jie Lim ,§ Mallikarjuna Ponnapa Reddy,*¶ Hayden Mitchell|| and Kiran Shekar**††‡‡§§

*Department of Intensive Care Medicine, Peninsula Health, Melbourne, Victoria
†Monash University, Peninsula Clinical School, Melbourne, Victoria, Australia
‡Australian and New Zealand Intensive Care Research Centre (ANZIC RC), Department of Epidemiology and Preventive Medicine, Monash University, Melbourne, Victoria, Australia
§Department of Anaesthesia, Austin Hospital, Heidelberg, Victoria, Australia
¶Department of Intensive Care Medicine, Calvary Hospital, Canberra, Australian Capital Territory, Australia
||Department of Medicine, Peninsula Health, Frankston, Victoria, Australia
**Adult Intensive Care Services, The Prince Charles Hospital, Brisbane, Queensland, Australia
††School of Medicine, University of Queensland, Brisbane, Queensland, Australia
‡‡Institute of Health and Biomedical innovation, University of Technology Brisbane, Brisbane, Queensland, Australia and
§§School of Medicine, Bond University, Gold Coast, Queensland, Australia

Key words
COVID-19, healthcare worker, Infection, SARS-CoV-2, tracheostomy.

Correspondence
A/Prof Ashwin Subramaniam, Intensive care specialist, Department of Intensive Care, Frankston Hospital, 2 Hastings Road, Frankston, Melbourne, VIC 3199.
Email: ashwin.subramaniam@monash.edu

A. Subramaniam MBBS, MMed, FRACP, FCICM; **Z. J. Lim** MBBS, Grad Cert (Perioperative Medicine); **M. Ponnapa Reddy** MBBS, FCICM, DCH, DECMO, MCTR; **H. Mitchell** MD, BMedSci; **K. Shekar** MBBS, FCICM, FCCCM, PhD.

Accepted for publication 14 May 2022.

doi: 10.1111/ans.17814

Abstract

Background: Tracheostomy is a commonly performed procedure in patients with coronavirus disease 2019 (COVID-19) receiving mechanical ventilation (MV). This review aims to investigate the occurrence of SARS-CoV-2 transmission from patients to healthcare workers (HCWs) when tracheostomies are performed.

Methods: This systematic review used the preferred reporting items for systematic reviews and meta-analysis framework. Studies reporting SARS-CoV-2 infection in HCWs involved in tracheostomy procedures were included.

Results: Sixty-nine studies (between 01/11/2019 and 16/01/2022) reporting 3117 tracheostomy events were included, 45.9% (1430/3117) were performed surgically. The mean time from MV initiation to tracheostomy was 16.7 ± 7.9 days. Location of tracheostomy, personal protective equipment used, and anaesthesia technique varied between studies. The mean procedure duration was 14.1 ± 7.5 minutes; was statistically longer for percutaneous tracheostomies compared with surgical tracheostomies (mean duration 17.5 ± 7.0 versus 15.5 ± 5.6 minutes, $p = 0.02$). Across 5 out of 69 studies that reported 311 tracheostomies, 34 HCWs tested positive for SARS-CoV-2 and 23/34 (67.6%) were associated with percutaneous tracheostomies.

Conclusions: In this systematic review we found that SARS-CoV-2 transmission to HCWs performing or assisting with a tracheostomy procedure appeared to be low, with all reported transmissions occurring in 2020, prior to vaccinations and more recent strains of SARS-CoV-2. Transmissions may be higher with percutaneous tracheostomies. However, an accurate estimation of infection risk was not possible in the absence of the actual number of HCWs exposed to the risk during the procedure and the inability to control for multiple confounders related to variable timing, technique, and infection control practices.

Introduction

A subgroup of patients with COVID-19-related severe acute respiratory failure may require prolonged periods of mechanical ventilation (MV) in the intensive care unit (ICU). Performing tracheostomies in such patients may decrease sedation requirements, facilitate ventilator weaning, and early rehabilitation.[1] However, ongoing concerns remain surrounding the transmission of

ANZ Journal of Surgery published by John Wiley & Sons Australia, Ltd on behalf of Royal Australasian College of Surgeons.

SARS-CoV-2 from patients to healthcare workers (HCWs) during the tracheostomy procedure.

Although tracheostomies are routine in ICUs, SARS-CoV-2 transmission to HCWs during tracheostomy and the influence of techniques used remains unclear. Proceduralists contracting COVID-19 following tracheostomies have been reported.[2] The aerosol-generation potential and use of bronchoscopy during percutaneous techniques may be higher due to repeated disconnection of the ventilator circuit during the procedure as compared to surgical tracheostomy.[3,4] However, percutaneous tracheostomies are preferred over surgical tracheostomies in critically ill patients and are often associated with greater familiarity within the ICU.[5,6] The use of diathermy has also been associated with increased aerosolization in surgical tracheostomies,[7] although evidence may suggest SARS-CoV-2 may not be transmissible via a cautery plume.[8] A standardized approach to personal protective equipment (PPE) required while performing a tracheostomy is yet to be firmly established,[9] with ongoing concerns about increased viral transmission to HCWs when early tracheostomies are performed.[10]

This systematic review aimed to evaluate the occurrence of SARS-CoV-2 transmission to HCWs performing/assisting with tracheostomy procedures. In addition, we aimed to evaluate the potential factors that may increase viral transmission.

Methods

This review was reported using the preferred reporting items for systematic reviews and meta-analysis framework[11] and registered on PROSPERO (CRD42021258753).

Eligibility criteria

Cohort studies that reported on HCW infections following tracheostomy (percutaneous or open/surgical) procedures on patients with confirmed COVID-19 patients were included. Studies were excluded if they did not discuss testing of HCWs following these tracheostomy procedures. Studies were also evaluated against study duration and location and excluded if a significant overlap in patient cohorts was identified.

Search strategy, information sources, and study selection

Two authors (ZL, HM) independently searched the COVID-19 living systematic review[12] from November 1st, 2019, to 16th January 2022, using the search terms 'tracheostomy' or 'tracheotomy'. This living systematic review provides a daily, dynamic update of research papers related to COVID-19 based on indices from PubMed, EMBASE and preprint servers (MedRxiv and BioRxiv), and has been used and validated in previously published COVID-19 research.[13,14] The search terms 'severe acute respiratory syndrome coronavirus 2', 'COVID-19', 'coronavirus', 'corona virus', 'HCoV', 'nCOV', '2019 CoV', 'COVID', 'COVID19', 'SARS-Cov2', 'SARS-Cov-2' or 'SARS Coronavirus 2' are used by the living systematic review to capture research articles related to the COVID-19 pandemic. All studies, including preprint and non-English language articles, were considered. The Newcastle-Ottawa Score was used by two authors (ZL, HM) to detect a risk of bias, with any discrepancies in the scoring system resolved by an additional author (AS).[15]

Study outcomes

The primary outcome was to report the occurrence of HCW infections following the performance of a percutaneous or open/surgical tracheostomy. The secondary outcomes explored the procedural aspects of the tracheostomy, including the mean time from MV to tracheostomy, procedure location, types of PPE used during the tracheostomy, and anaesthesia technique used to reduce aerosolization and viral particle transmission.

Data analysis process

The reporting of HCW infection in the original studies were qualitatively assessed. HCWs were screened post-procedurally and time to positivity, the severity of HCW infections and fatalities if any were recorded. We also qualitatively assessed the PCR status and viral load for the patients undergoing tracheostomy. Categorical variables are presented as percentages. Numerical data were collected in mean and standard deviation (SD). Comparisons between percutaneous and surgical techniques across studies were presented in forest plots. Variation in studies was calculated using the I^2 indices. Where a study presented median data, an estimation formula was used to convert median to mean values.[16] All *p*-values reported were two-tailed and the threshold for statistical significance was set at $p < 0.05$. Statistical analyses were performed using the statistical software Review Manager 5.4 (Cochrane Collaboration) and Stata/MP 15.1 (StataCorp).

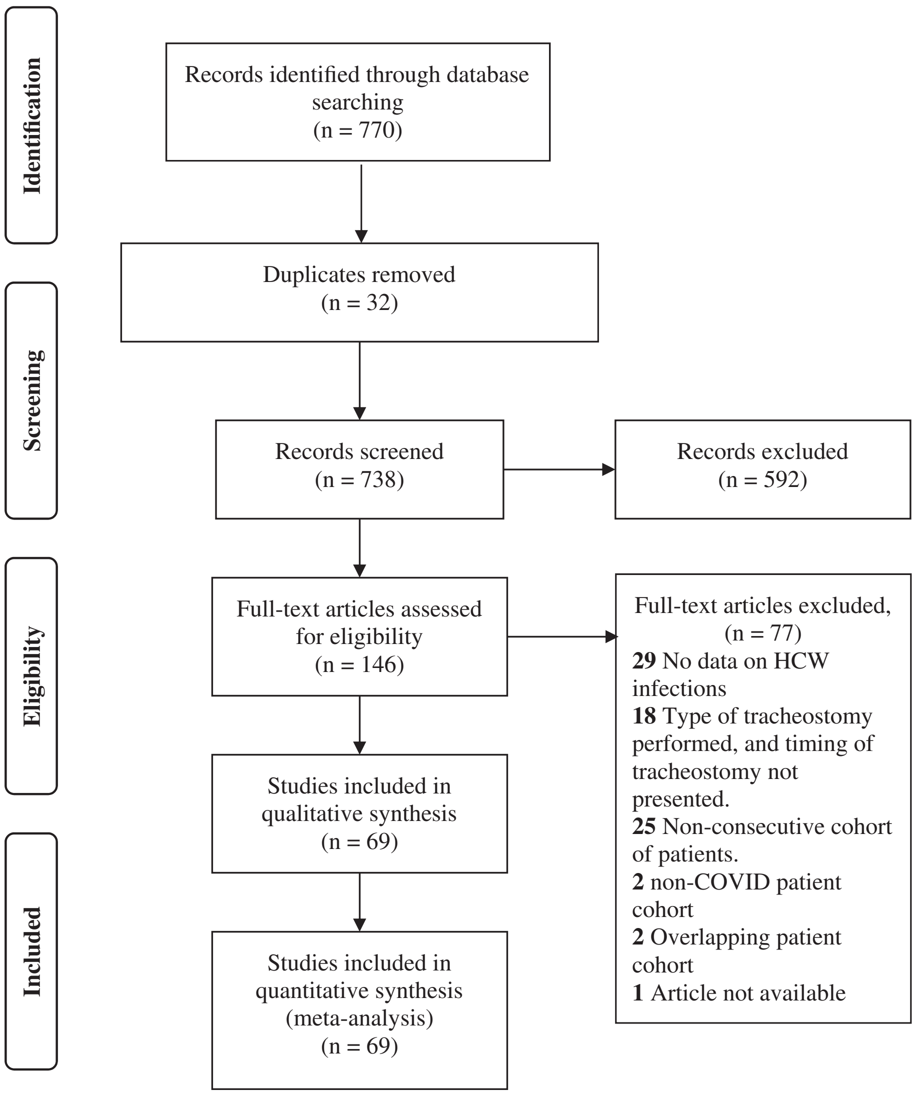
Results

Of the 770 studies obtained from the living systematic review 738 unique studies were assessed. One hundred and forty-six studies were selected for full-text review, with 69 studies reporting on 3117 tracheostomies included in the qualitative and quantitative analysis (Fig. 1). A summary of selected studies is outlined in Table 1. The references of all the included studies are listed in Supplementary Appendix. 45.9% (1430/3117) of all tracheostomies were performed surgically. Most studies were rated fair or poor (Supplementary Table 1). The COVID-19 strain (alpha, delta and omicron) was not accounted for by any of these included studies. Each study's approach to tracheostomy, including location of the procedure, anaesthesia/surgical technique, and PPE used are outlined in Table 2.

Primary outcome: HCW infections after performing/assisting a tracheostomy

Sixty-four of the 69 studies (2806 tracheostomies; 1538 [54.8%] percutaneous and 1268 [45.2%] surgical) reported no SARS-CoV-2 transmission to HCWs involved with a tracheostomy procedure, while five other studies (311 tracheostomies) reported SARS-CoV-2 positive results in 34 HCWs who performed or assisted in a tracheostomy. Among these 34 infections, 23/34 (67.6%) occurred whilst performing/assisting with percutaneous tracheostomies. An

Fig. 1. PRISMA 2009 flow diagram.



overall incidence of HCW infections could not be calculated as studies did not report on the total number of HCWs exposed during each procedure. The patients' PCR status or viral load, if still positive was mentioned in two studies and was varied. The days post-procedure to positive PCR result among HCWs was not reported in any studies. Two studies reported on HCWs being screened. One study reported on 5/8 HCWs being symptomatic, but all recovered. No studies reported on the demographic characteristics or vaccination status of the infected HCWs.

Secondary outcomes

The procedural details for all studies including the five studies reporting infections are summarized in Table 2 and Supplementary Appendix.

Mean time from MV to tracheostomy

Forty-eight studies reported the mean time from MV initiation to tracheostomy; 19 studies (414 percutaneous and 212 surgical) performed a tracheostomy within 14 days; 20 studies (506 percutaneous and 673 surgical) between 15 and 21 days, and nine studies (157 percutaneous and 106 surgical) performed a tracheostomy at >21 days (Supplementary Table 2). The overall mean time from MV initiation to tracheostomy was 16.7 ± 7.9 days (range 4.7–26.9 days); was similar between percutaneous (20 studies) and surgical (15 studies) tracheostomies (16.8 ± 9.0 days versus 16.2 ± 8.8 days, $p = 0.30$). Among the five studies where positive HCW transmission as reported, three studies reported on the time from MV initiation to tracheostomy; Moreno Romeo, Carlson and Singh reported mean times of 11 days, 13.5 days and 19 days, respectively.

Procedure location

Forty-nine studies reported on the location where tracheostomies were performed (Supplementary Table 3). Within the ICU, 27 studies performed tracheostomies at the bedside, 15 studies in negative pressure ICU rooms and three studies in isolation ICU rooms. Seventeen studies used an operating room for tracheostomies, of which two studies reported performing tracheostomies only in a negative pressure operating room.

Table 1 Summary of studies

Study[†]	Location	Study period	Number of tracheostomies			HCW infection
			Total	Percutaneous	Surgical	
Evrard (2021)	Paris, France	27 January 2020 to 18 May 2020	48	24	24	0
Matsuyoshi (2021)	Tokyo, Japan	1 January 2020 to 31 December 2020	9	9	0	0
Zhang (2020)	Hubei, China	20 January 2020 to 6 April 2020	11	6	5	0
Picetti (2020)	Parma, Italy	23 February 2020 to 30 April 2020	66	0	66	0
Rosano (2021)	Brescia, Italy	20 February 2020 to 5 May 2020	121	121	0	**15**
Turri-Zanoni (2020)	Varse, Italy	24 February 2020 to 13 April 2020	32	10	22	0
Kim (2020)	Daegu, South Korea	24 February 2020 to 30 April 2020	7	7	0	0
Sancho (2020)	Valencia, Spain	27 February 2020 to 20 May 2020	11	11	0	0
Aodeng (2020)	Hubei, China	February 2020 to April 2020	14	0	14	0
Nishio (2021)	Nagoa, Japan	February 2020 to September 2020	5	0	5	0
Riestra-Ayora (2020)	Madrid, Spain	1 March 2020 to 10 April 2020	27	17	10	0
Obata (2020)	Sapporo, Japan	1 March 2020 to 30 June 2020	12	8	4	0
Briatore (2021)	Asti, Italy	1 March 2020 to 15 May 2020	13	0	13	0
Loube (2021)	San Jose, USA	1 March 2020 to 27 April 2020	12	12	0	0
Shehatta (2021)	Doha, Qatar	1 March 2020 to 1 January 2021	35	34	1	0
Emily (2020)	Rimini, Italy	2 March 2020 to 29 April 2020	46	46	0	0
Xu (2021)	Hubei, China	3 March 2020 to 4 April 2020	8	0	8	0
Zuazua-Gonzalez (2020)	Madrid, Spain	5 March 2020 to 15 May 2020	30	0	30	**2**
Marchioni (2020)	Verona, Italy	8 March 2020 to 3 May 2020	22	0	22	0
Queen Elizabeth Hospital (2020)	Birmingham, UK	9 March 2020 to 21 April 2020	100	75	25	0
Yeung (2020)	London, UK	10 March 2020 to 10 May 2020	72	28	44	0
Courtney (2021)	London, UK	10 March 2020 to 1 May 2020	20	0	20	0
Angel (2020)	New York, USA	11 March 2020 to 29 April 2020	205	195	10	0
Botti (2021)	Reggio Emilia, Italy	11 March 2020 to 11 April 2020	47	17	30	0
Carlson (2021)	Tennessee, USA	11 March 2020 to 31 December 2020	17	0	17	**4**
Boujaoude (2021)	New Jersey, USA	12 March 2020 to 30 June 2020	32	32	0	0
Glibbery (2020)	Cambridge, UK	15 March 2020 to 20 May 2020	28	3	25	0
Martinez-Tellez (2020)	Barcelona, Spain	16 March 2020 to 24 April 2020	27	0	27	0
Johnston (2021)	Bolton, UK	16 March 2020 to 27 April 2020	18	18	0	0
Aviles-Jurado (2021)	Barcelona, Spain	16 March 2020 to 10 April 2020	50	0	50	0
Williamson (2021)	Harlow, UK	19 March 2020 to 14 April 2020	29	29	0	0
Takhar (2020)	London, UK	21 March 2020 to 20 May 2020	81	76	5	0
Nihien (2021)	Boras, Sweden	21 March 2020 to 30 September 2020	29	0	29	0
Bartier (2021)	Paris, France	23 March 2020 to 23 April 2020	59	5	54	0
Khanna (2021)	Guwahati, India	24 March 2020 to 23 September 2020	115	0	115	**5**
Singh AA (2020)	London, UK	24 March 2020 to 11 May 2020	29	3	26	0
Morvan (2020)	Mullhouse, France	25 March 2020 to 25 April 2020	16	16	0	0
Valchanov (2021)	Cambridge, UK	27 March 2020 to 15 May 2020	38	38	0	0
Schuler (2021)	Ulm, Germany	27 March 2020 to 18 May 2020	18	0	18	0
Arnold (2021)	Ilinois, USA	March 2020 to January 2021	59	59	0	0
Bhutaka (2021)	Maharashtra, India	March 2020 to December 2020	16	16	0	0
Erbas (2021)	Çanakkale, Turkey	March 2020 to August 2020	24	24	0	0
Yokokawa (2021)	Japan	March 2020 to March 2021	35	0	35	0
Bassily-Marcus (2020)	New York, USA	1 April 2020 to 30 April 2020	111	111	0	0
Taboada (2020)	Santiago, Spain	1 April 2020 to 30 April 2020	5	5	0	0
Floyd (2020)	New York, USA	1 April 2020 to 30 April 2020	38	0	38	0
Maity (2021)	Luton, UK	1 April 2020 to 20 May 2020	16	0	16	0
Porras (2020)	Santiago, Spain	1 April 2020 to 20 July 2020	10	10	0	0
Long (2021)	New York, USA	4 April 2020 to 2 June 2020	101	48	53	0
COVIDTrach (2020)	UK	6 April 2020 to 11 May 2020	564	217	323	0
Murphy (2021)	Indianapolis, USA	6 April 2020 to 21 July 2020	11	11	0	0
Krishnamoorthy (2020)	New York, USA	15 April 2020 to 15 May 2020	143	85	58	0
Thal (2021)	New York, USA	15 April 2020 to 28 May 2020	36	0	36	0
Weiss (2021)	Boston, USA	27 April 2020 to 30 June 2020	28	27	1	0
Tompeck (2021)	Arizona, USA	April 2020 to July 2020	26	26	0	0
Pradhan (2021)	Bhubaneswar, India	April 2020 to October 2020	7	0	7	0
Turkdogan (2021)	Quebec, Canada	April 2020 to January 2021	17	17	0	0
Sebastian (2021)	Delhi, India	15 May 2020 to 20 September 2020	10	0	10	0
Bhavana (2020)	Patna, India	May 2020 to September 2020	55	0	55	0
Moreno Romero (2020)	Granada, Spain	NR	28	28	0	**8**
Chao (2020)	Pennsylvania, USA	NR	53	29	24	0
Ismail (2021)	Abu Dhabi, UAE	NR	59	59	0	0
Liatsikos (2020)	Liverpool, UK	NR	33	14	19	0
Mertke (2020)	Homburg, Germany	NR	16	16	0	0
Meyer (2020)	New York, USA	NR	7	0	7	0
Singh S (2020)	Cambridge, UK	NR	27	3	24	0
Sancho (2021)	Valencia, Spain	NR	11	11	0	0
Sood (2021)	Worcester, USA	NR	12	11	1	0
Total			3143	1515[‡]	1286[‡]	34

Abbreviations: HCW: Healthcare Worker; NR: Not Reported, USA: United States of America, UK: United Kingdom, UAE: United Arab Emirates.

[†]Please see Supplementary Appendix for all references.

[‡]Reported tracheostomies.

Table 2 Procedural details

Study[†]	HCW Infection	Location of tracheostomy, barriers used, surgical technique	Anaesthesia technique	Personal protective equipment						
				Headcover	Goggles	Face shield	Mask	Gown	Gloves	Shoe cover
Evrard (2021)	0	Bedside ICU $N = 24$ Operating room $N = 24$	Clamping endotracheal tube	✓	✓	✓	✓	✓	✓	✓
Matsuyoshi (2021)	0	Negative pressure room in ICU	NR	PPE as per hospital guideline						
Zhang (2020)	0	NR	Paralysis, ventilation paused during the procedure				✓ PAPR			
Picetti (2020)	0	Bedside ICU	Ventilation paused during the procedure	✓		✓	✓ N95	✓	✓ (Double)	✓
Rosano (2021)	**15**	Bedside ICU	Ventilation not paused	✓		✓	✓ FFP3+surgical	✓	✓ (Double)	
Turri-Zanoni (2020)	0	Bedside $N = 19$; negative pressure room $N = 13$, spotter used	Paralysis, ventilation paused during the procedure		✓	✓	✓ FFP3	✓	✓ (Double)	✓
Kim (2020)	0	Negative pressure room	Paralysis during procedure	✓	✓		✓ PAPR + N95	✓ Fluid repellent	✓ (Double)	✓
Sancho (2020)	0	NR	NR		✓		✓ FFP3	✓	✓	
Aodeng (2020)	0	Negative pressure room in ICU	Ventilator paused during the procedure		✓		✓ PAPR + surgical	✓ (Double)	✓	✓
Nishio (2021)	0	Isolation room of ICU, spotter used	NR	✓	✓	✓	✓ PAPR or N95	✓	✓ (Double)	
Riestra-Ayora (2020)	0	Bedside ICU		✓	✓		✓ N95	✓	✓	
Obata (2020)	0	Drape over the patient, bedside ICU $N = 10$; negative pressure operating room $N = 2$	NR	Full PPE as per hospital guideline						
Briatore (2021)	0	Negative pressure operating room	Ventilator turned off before tracheal incision	✓	✓	✓	✓ FFP3/N95	✓ (Double)	✓ (Double)	✓
Loube (2021)	0	Negative pressure room, or enclosed ICU room with HEPA filter	Paralysis, ventilation paused during the procedure				✓ PAPR + N95			
Shehatta (2021)	0	Bedside ICU	NR	PPE as per hospital guideline						
Emily (2020)	0	NR	NR	NR	NR	NR	NR	NR	NR	NR
Xu (2021)	0	Bedside ICU.	Ventilation paused during the procedure	✓			✓ PAPR + N95	✓ (Double)	✓ (Double)	✓
Zuazua-Gonzalez (2020)	**2**	Bedside ICU	Ventilation paused during the procedure				✓ Snorkelling mask with antiviral filter	✓	✓ (Triple)	
Marchioni (2020)	0	Surgical drape around neck	NR	✓ (Double)	✓	✓	✓ FFP3 + surgical	✓ (Double)	✓ (Triple)	✓ (Double)
Queen Elizabeth Hospital (2020)	0	Bedside ICU or room, no negative pressure room			✓		✓ FFP3	✓		
Yeung (2020)	0	Operating room, no negative pressure environment	Ventilation paused during the procedure	✓	✓	✓	✓ FFP3 or PAPR, fit-tested	✓	✓	

Table 2 Continued

Study[†]	HCW Infection	Location of tracheostomy, barriers used, surgical technique	Anaesthesia technique	Personal protective equipment						
				Headcover	Goggles	Face shield	Mask	Gown	Gloves	Shoe cover
Courtney (2021)	0		Paralysis during procedure							
Angel (2020)	0	Negative pressure room in ICU	NR			✓	✓ N95 + surgical	✓ (Double)	✓	
Botti (2021)	0		Paralysis during procedure		✓		✓ N95	✓	✓	
Carlson (2021)	**4**	Operating room	Paralysis, ventilation resumption after tracheostomy		✓	✓	✓ N95	✓	✓ (Double)	
Boujaoude (2021)	0	Bedside ICU	Paralysis during procedure				✓ PAPR + N95			
Glibbery (2020)	0	Operating room $N = 25$; bedside ICU $N = 3$	Ventilator turned off during the procedure, viral filter		✓		✓ PAPR + FFP3	✓ (Double)	✓ (Double)	
Martinez-Tellez (2020)	0		Paralysis and apnoea during the procedure	PPE as per hospital guideline						
Johnston (2021)	0	Open ward area of ICU	NR	✓		✓	✓ FFP3, fit-tested	✓	✓ (Double)	
Aviles-Jurado (2021)	0	Bedside ICU. Spotter used.	Paralysis, ventilation paused during tracheostomy	✓	✓ Hermetically sealed eye protection	✓ Screen (with surgical mask)	✓ FFP3	✓ (Double)	✓ Triple gloves	✓
Williamson (2021)	0		Ventilation paused during the procedure	PPE as per hospital guidelines						
Takhar (2020)	0	Bedside ICU N = 78; operating room $N = 3$	Paralysis, ventilation paused during the procedure			✓	✓ FFP3 or PAPR	✓ (Double)	✓	
Nihien (2021)	0		Paralysis, ventilation paused during the procedure			✓	✓ FFP3 or FFP2	✓		
Bartier (2021)	0	Operating room, bedside ICU, cover used over the patient to reduce aerosolisation	Ventilator paused during the procedure				✓ FFP2 (95%), Snorkel mask with FFP2 filter (5%)			
Khanna (2021)	**5**	NR	NR	✓*	✓*	✓*	✓*	✓*	✓*	✓*
		*PPE was not used by the proceduralist if patients had a negative COVID rapid antigen test within the last 7 days								
Singh AA (2020)	**1**	NR	NR	NR	NR	NR	NR	NR	NR	NR
Morvan (2020)	0	Bedside ICU, spotter used	Paralysis during procedure	✓	✓		✓ FFP3	✓	✓ (Double)	✓
Valchanov (2021)	0	ICU isolation room	Ventilation paused during the procedure			✓	✓ FFP3	✓	✓	
Schuler (2021)	0	Bedside ICU	Paralysis during procedure			✓	✓ N95 or PAPR			
Arnold (2021)	0	Bedside	Oropharynx packed with gauze to minimize aerosolization				✓ PAPR	✓	✓	

Table 2 Continued

Study[†]	HCW Infection	Location of tracheostomy, barriers used, surgical technique	Anaesthesia technique	Personal protective equipment						
				Headcover	Goggles	Face shield	Mask	Gown	Gloves	Shoe cover
Bhutaka (2021)	0		NR		✓		✓ FFP3	✓ Fluid repellent	✓	
Erbas (2021)	0	Used aerosol box	NR	NR	NR	NR	NR	NR	NR	NR
Yokokawa (2021)	0	Negative pressure room $N = 16$; ICU or ward $N = 18$, operating room $N = 1$	NR		✓		✓ N95 or PAPR			
Bassily-Marcus (2020)	0	Bedside ICU	Ventilation paused during circuit disruption				✓ PAPR			
Taboada (2020)	0	Bedside ICU closed room	Paralysis during procedure	✓	✓		✓ FFP3	✓	✓ (Double)	
Floyd (2020)	0	Negative pressure room where available	Paralysis, ventilation paused during tracheostomy	✓	✓	✓	✓ N95+ surgical	✓	✓	✓
Maity (2021)	0	Operating room, clear plastic sheet over the operating site	Paralysis, ventilation paused during the procedure		✓	✓	✓ N95 or FFP3, fit-tested	✓	✓ (Double)	✓
Porras (2020)	0	Isolation room of ICU $N = 6$; operating room $N = 4$	NR							
Long (2021)	0	Negative pressure room in ICU, operating room when available	NR	✓		✓	✓ N95	✓	✓	
COVIDTrach (2020)	0	Negative pressure environment	NR			✓	✓ PAPR + FFP3	✓	✓ (Double)	
Murphy (2021)	0	Negative pressure room in ICU	Ventilation paused during the procedure	✓	✓		✓ PAPR + N95	✓	✓	
Krishnamoorthy (2020)	0		Apnoea during procedure	✓	✓	✓	✓ PAPR, N95 + Surgical	✓		
Thal (2021)	0	Bedside ICU $N = 24$; operating room $N = 6$; bedside medical ward $N = 6$	Paralysis, ventilation paused during the procedure, glycopyrrolate to decrease secretions	✓	✓	✓	✓ N95	✓	✓	
Weiss (2021)	0	Negative pressure ICU $N = 25$; operating room $N = 3$. Spotter used	Paralysis, ventilation paused during the procedure	✓	✓	✓	✓ N95 + surgical	✓ (Double)	✓ (Double)	✓
Tompeck (2021)	0	Standardized procedure		PPE as per hospital guideline						
Pradhan (2021)	0	Bedside ICU $N = 6$; COVID operating room $N = 6$		PPE as per hospital guideline						
Turkdogan (2021)	0	Demystifier tent, negative pressure room	Paralysis during procedure	✓ With neck cover		✓	✓ N95	✓	✓ (Double)	
Sebastian (2021)	0	NR	Paralysis, ventilation paused during the procedure	✓	✓	✓	✓ N95	✓	✓ (Double)	✓

Table 2 Continued

Study[†]	HCW Infection	Location of tracheostomy, barriers used, surgical technique	Anaesthesia technique	Personal protective equipment: Headcover	Goggles	Face shield	Mask	Gown	Gloves	Shoe cover
Bhavana (2020)	0	Bedside ICU	Paralysis during procedure	PPE as per hospital guidelines						
Moreno Romero (2020)	**8**			PPE as per hospital guideline						
Chao (2020)	0	Negative pressure ICU room or operating room	Ventilator turned off during the procedure				✓ PAPR + N95			
Ismail (2021)	0	Bedside ICU	Aerosol box, paralysis during the procedure, ventilator paused.	NR	NR	NR	NR	NR	NR	NR
Liatsikos (2020)	0		3 Drapes, paralysis and ventilation paused during the procedure	PPE as per Public Health England Guideline						
Mertke (2020)	0	Bedside ICU	NR		✓	✓	✓ N95 or FFP3	✓	✓ (Double)	
Meyer (2020)	0	Negative pressure room in ICU	Paralysis and apnoea during the procedure		✓		✓ P100 ERS + surgical	✓	✓(Double)	
Singh S (2020)	0	NR	NR	PPE as per hospital guideline						
Sancho (2021)	0	Bedside ICU	NR		✓	✓	✓ FFP3	✓	✓	
Sood (2021)	0	No personnel in the room for >1 h post-procedure, nasal clip and wet gauze packing in the mouth. Bedside ICU	Paralysis, ventilation paused during the procedure				✓ N95 + PAPR			
Cardasis (2021)	0	Operating room	Ventilator turned off before tracheal incision	✓			✓ PAPR + N95	✓ (Double)		✓

Abbreviations: ICU, Intensive care unit; PAPR, Power air-purifying respirator; PPE, Personal protective equipment.

[†]Please see Supplementary Appendix for all references.

PPE used during tracheostomy

Fifty-two studies outlined the PPE used by HCWs during the tracheostomy (Table 2). All 52 studies maintained the need for a mask (FFP2, FFP3, N95, powered air purifying respirator and makeshift snorkelling masks) during tracheostomy with four studies mandating fit-testing of masks. Two studies reported using non-medical snorkelling masks with attached filters. Head covers were used in 25 studies, goggles used in 29 studies, face shields used in 28 studies, gowns in 42 studies, gloves in 39 studies and shoe covers in 18 studies. Five studies reported using spotters to assist with donning and doffing of PPE. In addition to PPE, eight studies used physical barriers over patients to minimize HCW exposure to SARS-CoV-2 particles.

Anaesthesia technique during tracheostomy

Modifications to the anaesthesia technique was observed in multiple studies. To reduce aerosolization of SARS-CoV-2, ventilation was discontinued to achieve apnoea (32 studies), and neuromuscular blockers to maintain paralysis (24 studies) or both (16 studies) for the duration of the tracheostomy.

Procedure duration

The mean procedure duration was 14.1 ± 7.5 min (11 studies); was statistically longer with percutaneous tracheostomies, than surgical (mean duration 17.5 ± 7.0 min versus 15.5 ± 5.6 min, $p = 0.02$). Three studies that compared the percutaneous versus surgical techniques demonstrated no differences between the time from initiation of mechanical ventilation to tracheostomy for either technique (Supplementary Fig. 1). There was insufficient data to analyse the duration of the procedure on infection risks.

Discussion

This systematic review examined the occurrence of SARS-CoV-2 transmission in HCWs performing/assisting with tracheostomy procedures. Based on this review, the occurrence of SARS-CoV-2 transmission to these HCWs appears to be low. Exposure and subsequent transmission may be higher while performing percutaneous tracheostomies. However, an estimation of infection risk was not possible in the absence of accurate data on the actual number of HCWs exposed to the risk and due to an inability to control for multiple confounders related to variable timing, technique, and infection control practices. In studies where the mean time from MV initiation to tracheostomy could be calculated, a clear association between the timing of tracheostomy and increased HCW infection was not established.

The low number of reported SARS-CoV-2 positivity in HCWs is a reassuring finding, given the concerns for viral transmission from patient to HCWs during endotracheal intubation.[17] Potential reasons behind this figure could be due to the use of a single team of HCWs performing the tracheostomy or the use of a single location for tracheostomies, thereby reducing the number of exposed staff.[18] Viral transmission from tracheostomies has previously been reported during the 2003 SARS-CoV epidemic.[19–21] Studies from the Middle Eastern Respiratory Syndrome (MERS) epidemic reported delaying tracheostomies to reduce transmission,[22] with one study reporting no HCW infections after tracheostomies where anaesthesia, PPE and location precautions were implemented.[23] HCW transmissions following tracheostomies during the Ebola epidemic was not reported, with guidelines recommending delaying tracheostomy until the viral clearance is confirmed.[24]

An analysis of the five studies that reported on HCW infections showed a proportionally higher number of HCW infections in studies where percutaneous tracheostomies were performed. This finding may be due to the potentially prolonged procedure time and the use of fibreoptic bronchoscopy for airway guidance in a percutaneous procedure.[25] Guidelines have also postulated inadequate ventilation, significant upper airway gas leak and the increased risk of aerosolization in percutaneous tracheostomies.[26,27] However, this must be balanced against the fact that the proportionally higher number of HCW infections was skewed by one study reporting 15 infections.

The time from MV initiation to tracheostomy was variable. The optimal timing for the transition to tracheostomy in patients with COVID-19 has been heavily debated. While there is observational data to suggest that early tracheostomies in COVID-19 patients may be beneficial,[28,29] the initial guidelines recommend delaying tracheostomies for up to 21 days to reduce the risk of SARS-CoV-2 transmission to HCWs[26,30] and to adopt a multidisciplinary risk assessment approach to determine the best window of opportunity for a tracheostomy.[4] Recent review suggested the risk of transmission reduces beyond 14 days.[27] Another study, that did not report on HCW infections, identified that the optimal timing of tracheostomy within the first week receiving ventilation may improve patient outcomes and ease ICU capacity strain during the COVID-19 pandemic without increasing mortality.[31] While the case selection for early tracheostomy continues to evolve, what is clear is that the timing of tracheostomy is returning to 'business as usual'.[32]

The location and environment where tracheostomies were performed varied significantly between studies, with both neutral and negative-pressure environments used. Negative-pressure ICU rooms are recommended as the ideal location for tracheostomies to minimize patient transport and HCW exposure.[4,30] In this review, only 15 studies performed tracheostomies in negative-pressure ICU rooms. Studies may be limited by the lack of facilities or an open ward layout in the ICU, restricting the creation of ideal negative-pressure environments,[33,34] while other studies have cited the reluctance in transporting patients beyond the bedside that may result in repeated ventilator disconnections.[35] Tracheostomies in patients with suspected/confirmed COVID-19 should be performed in isolated environments with frequent air changes to reduce the risk of prolonged aerosolization both within the procedure room and in the surrounding ICU.[36]

A large variation in the selection and type of PPE used during a tracheostomy was observed across the included studies. Of note, SARS-CoV-2 transmission to two HCWs was observed in one study where non-hospital grade snorkelling masks were used during the tracheostomy.[37] Similarly, five HCWs tested positive to COVID-19 in one study where PPE precautions were not adhered to as patients obtained a negative COVID-19 rapid antigen test within the preceding 7 days.[38] Reducing the use of improvised, non-medical grade PPE should be considered given the risk of poor filtration and failed fit tests.[39] Concurrently, negative rapid antigen tests should not be used as a substitute for reducing PPE precautions during tracheostomies given the risk of poor test sensitivity and the potential for infections to occur between the negative test and the procedure.[40,41] Although the low number of HCW infections suggest that PPE is effective in reducing transmission, further research into the optimal standard of PPE for aerosol-generating procedures is urgently required.

There were no differences between percutaneous and surgical tracheostomy.[4,27] However From a SARS-CoV-2 transmission point of view, the perceived benefit of the surgical technique stem from it being a more controlled procedure performed under direct vision. The operative technique is dependent on local expertise and available resources. Maintenance of a bloodless field, and minimal use of diathermy are recommended to minimize aerosol-generation. Equally, airway manipulations and use of bronchoscope if at all are kept to a minimum when using surgical technique which further minimizes aerosol generation.[4,27] During a surgical insertion, advancing the tracheal tube with the balloon inflated within the trachea beyond the tracheotomy may help maintain a closed' breathing circuit'.[4,27]

Modifications in the anaesthesia technique were observed in several studies. Discontinuing MV and the use of neuromuscular blocking agents was frequent. This is congruent with international guidelines and recommendations to minimize SARS-CoV-2 particle aerosolization and transmission.[4,26,30] The use of neuromuscular blockers and discontinuing MV has also been previously used during the tracheostomy of patients with MERS, where no HCW infections occurred following the procedure.[23] In one study where 15 HCW infections occurred, discontinuing MV did not occur. This potentially highlights the importance of maintaining apnoea during the tracheostomy.[42] Modifications in the anaesthesia technique should therefore be considered in patients with COVID-19.

A minority of studies reported on the mean procedure duration of tracheostomies. Overall, percutaneous tracheostomies took a statistically longer to perform compared to surgical techniques. Although the 2-min absolute difference may not be that clinically relevant, there is evidence that longer procedure times may lead to prolonged exposure to SARS-CoV-2 particles, which may increase transmissibility to HCWs.[43] The use of physical barriers aimed at reducing contact with SARS-CoV-2 particles may prolong procedures as well, with a potential for increased infection risk if incorrectly used and cleaned.[44,45] An association between longer procedure time and HCW infection was not observed in this review. Further research into the possible correlation between prolonged procedure duration of aerosol generating procedures and increased transmissibility risk to HCWs is required.

The overall findings of this systematic review, although reassuring in terms of low reported transmissions, highlight the importance of mitigating exposures to HCWs when aerosol-generating procedures such as tracheostomies are performed. However, there is still a lot of unknowns. No studies reported on genomic data, therefore, the impact of newer SARS-CoV-2 variants and the risk of viral transmission from patient to HCW in under-investigated.[46] Furthermore, tracheostomies have now become common in COVID-cleared patients. Although this risk of transmission to vaccinated HCWs is reported,[47] to our knowledge, transmission risks to vaccinated HCWs involved in tracheostomy is still largely unknown. After a steep learning curve, HCWs have adapted to ensure safe and proactive care is delivered to the patients with COVID-19 who will benefit from tracheostomy as part of their critical illness management.[27] However, it is likely that the transmission risk will remain variable and will depend on a multitude of factors such as vaccinations including booster doses, viral mutations, infection control measures including appropriate engineering solutions and resource availability.

Some limitations need to be considered. First, most studies were rated fair or poor on the NOS. This is due to the lack of a standardized follow-up period of HCWs following tracheostomies, which may result in studies under-reporting the number of HCW infections. Second, a definitive link between participation in a tracheostomy and SARS-CoV-2 transmission in HCWs could not be established. It is plausible that HCWs could have contracted COVID-19 from other hospital locations or the community. Differences in hospital COVID-19 testing policies including the use of asymptomatic screening and differing follow-up intervals from tracheostomies may affect the number of detected transmissions. Finally, we could not control for potential confounders introduced by variations in tracheostomy timing, technique, system resource constraints, air exchange cycles and infection control practices across studies.

Conclusion

In this systematic review, we found that SARS-CoV-2 transmission to HCWs performing/assisting with a tracheostomy procedure appeared to be low, with all transmissions happening in 2020, prior to vaccinations and more recent strains of SARS-CoV-2. Transmission may be higher with percutaneous tracheostomies; however, an estimation of infection risk was not possible in the absence of accurate data on the actual number of HCWs exposed to the risk and due to an inability to control for multiple confounders related to variable timing, technique, and infection control practices.

Acknowledgement

Open access publishing facilitated by Monash University, as part of the Wiley - Monash University agreement via the Council of Australian University Librarians.

Conflict of interest

None declared.

Funding information

No funding sources to declare.

Author contributions

Ashwin Subramaniam: Conceptualization; data curation; formal analysis; methodology; project administration; resources; software;

supervision; validation; visualization; writing – original draft; writing – review and editing. **Zheng Jie Lim:** Conceptualization; data curation; formal analysis; methodology; resources; software; writing – original draft; writing – review and editing. **Hayden Mitchell:** Data curation; investigation; methodology; resources; writing – review and editing. **Mallikarjuna Ponnapa Reddy:** Conceptualization; methodology; writing – original draft; writing – review and editing. **Kiran Shekar:** Conceptualization; methodology; project administration; supervision; validation; visualization; writing – review and editing.

Data availability statement

All the authors have no objection to sharing all the collected data if needed.

References

1. Carmichael H, Wright FL, McIntyre RC et al. Early ventilator liberation and decreased sedation needs after tracheostomy in patients with COVID-19 infection. *Trauma Surg. Acute Care Open* 2021; **6**: e000591.
2. Angamuthu N, Geraldine Gagasa E, Baker D et al. Transmission of infection among health care personnel performing surgical tracheostomies on COVID-19 patients. *Surgeon* 2021; **19**: e304–e309.
3. Tay JK, Khoo ML-C, Loh WS. Surgical considerations for tracheostomy during the COVID-19 pandemic: lessons learned from the severe acute respiratory syndrome outbreak. *JAMA Otolaryngol. Head Neck Surg*. 2020; **146**: 517–8.
4. McGrath BA, Brenner MJ, Warrillow SJ et al. Tracheostomy in the COVID-19 era: global and multidisciplinary guidance. *Lancet Respir. Med.* 2020; **8**: 717–25.
5. Kornblith LZ, Burlew CC, Moore EE et al. One thousand bedside percutaneous tracheostomies in the surgical intensive care unit: time to change the gold standard. *J. Am. Coll. Surg.* 2011; **212**: 163–70.
6. Mehta C, Mehta Y. Percutaneous tracheostomy. *Ann. Card. Anaesth.* 2017; **20**(Supplement): S19–s25.
7. McGain F, Humphries RS, Mora JC et al. Aerosol generation during surgical tracheostomy in a patient with COVID-19. *Crit. Care Resusc.* 2020. Epub ahead of print.
8. Sowerby LJ, Nichols AC, Gibson R et al. Assessing the risk of SARS-CoV-2 transmission via surgical electrocautery plume. *JAMA Surg.* 2021; **156**: 883-885.
9. Lamb CR, Desai NR, Angel L et al. Use of tracheostomy during the COVID-19 pandemic: American College of Chest Physicians/American Association for Bronchology and Interventional Pulmonology/Association of Interventional Pulmonology Program Directors Expert Panel Report. *Chest* 2020; **158**: 1499–514.
10. Schultz MJ, Teng MS, Brenner MJ. Timing of tracheostomy for patients with COVID-19 in the ICU—setting precedent in unprecedented times. *JAMA Otolaryngol. Head Neck Surg.* 2020; **146**: 887–8.
11. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *BMJ* 2009; **339**: b2535.
12. Covid- Open Access Project. Living Evidence on COVID-19. Available from URL: https://ispmbern.github.io/covid-19/living-review/.
13. Lim ZJ, Subramaniam A, Reddy MP et al. Case fatality rates for patients with COVID-19 requiring invasive mechanical ventilation. A meta-analysis. *Am. J. Respir. Crit. Care Med.* 2021; **203**: 54–66.
14. Wynants L, Van Calster B, Collins GS et al. Prediction models for diagnosis and prognosis of covid-19: systematic review and critical appraisal. *BMJ* 2020; **369**: m1328.
15. Stang A. Critical evaluation of the Newcastle-Ottawa scale for the assessment of the quality of nonrandomized studies in meta-analyses. *Eur. J. Epidemiol.* 2010; **25**: 603–5.
16. Hong Kong Baptist University. Estimating the sample mean and standard deviation from the sample size, median, range and/or interquartile range. Available from URL: http://www.math.hkbu.edu.hk/∼tongt/papers/median2mean.html
17. El-Boghdadly K, Wong DJN, Owen R et al. Risks to healthcare workers following tracheal intubation of patients with COVID-19: a prospective international multicentre cohort study. *Anaesthesia* 2020; **75**: 1437–47.
18. Sorbello M, Morello G, Pintaudi S et al. COVID-19: intubation kit, intubation team, or intubation spots? *Anesth. Analg.* 2020; **131**: e128–30.
19. Chen WQ, Ling WH, Lu CY et al. Which preventive measures might protect health care workers from SARS? *BMC Public Health* 2009; **9**: 81.
20. Tran K, Cimon K, Severn M et al. Aerosol generating procedures and risk of transmission of acute respiratory infections to healthcare workers: a systematic review. *PLoS One* 2012; **7**: e35797.
21. Ramesh AV, Collin I, Gregson FK et al. Aerosol generation during percutaneous tracheostomy insertion. *J. Intensive Care Soc*. 2020; **0**: 1-2.
22. Lee JY, Kim Y-J, Chung EH et al. The clinical and virological features of the first imported case causing MERS-CoV outbreak in South Korea, 2015. *BMC Infect. Dis.* 2017; **17**: 498.
23. Choi SY, Shin J, Park W et al. Safe surgical tracheostomy during the COVID-19 pandemic: a protocol based on experiences with Middle East respiratory syndrome and COVID-19 outbreaks in South Korea. *Oral Oncol.* 2020; **109**: 104861.
24. McAlister V. Surgery in patients with Ebola virus disease. *Can. J. Surg.* 2014; **57**: 364–5.
25. Botti C, Lusetti F, Neri T et al. Comparison of percutaneous dilatational tracheotomy versus open surgical technique in severe COVID-19: complication rates, relative risks and benefits. *Auris Nasus Larynx* 2021; **48**: 511–7.
26. Sommer DD, Engels PT, Weitzel EK et al. Recommendations from the CSO-HNS taskforce on performance of tracheotomy during the COVID-19 pandemic. *J. Otolaryngol. Head Neck Surg.* 2020; **49**: 23.
27. Williams T, McGrath BA. Tracheostomy for COVID-19: evolving best practice. *Crit. Care* 2021; **25**: 316.
28. Chorath K, Hoang A, Rajasekaran K et al. Association of Early vs late tracheostomy placement with pneumonia and ventilator days in critically ill patients: a meta-analysis. *JAMA Otolaryngol. Head Neck Surg.* 2021; **147**: 450–9.
29. Queen Elizabeth Hospital Birmingham COVID-19 airway team. Safety and 30-day outcomes of tracheostomy for COVID-19: a prospective observational cohort study. *Br. J. Anaesth.* 2020; **125**: 872–9.
30. Miles BA, Schiff B, Ganly I et al. Tracheostomy during SARS-CoV-2 pandemic: recommendations from the New York Head and Neck Society. *Head Neck* 2020; **42**: 1282–90.
31. Hernandez G, Ramos FJ, Anon JM et al. Early tracheostomy for managing ICU capacity during the COVID-19 outbreak: a propensity-matched cohort study. *Chest* 2022; **161**: 121–9.
32. McGrath BA, Brenner MJ, Warrillow SJ. Tracheostomy for COVID-19: business as usual? *Br. J. Anaesth.* 2020; **125**: 867–71.
33. Johnston M, Weldon M, Smart C et al. A novel percutaneous tracheostomy technique to reduce aerosolisation during the COVID-19 pandemic: a description and case series. *Trends Anaesth. Crit. Care* 2021; **38**: 36–41.

34. Yeung E, Hopkins P, Auzinger G et al. Challenges of tracheostomy in COVID-19 patients in a tertiary Centre in inner city London. *Int. J. Oral Maxillofac. Surg.* 2020; **49**: 1385–91.
35. Taboada M, Vazquez S, Regueira J et al. Safe percutaneous dilational tracheostomy in 5 patients with ARDS by Covid-19. *J. Clin. Anesth.* 2020; **67**: 109977.
36. Tsui BCH, Pan S. Are aerosol-generating procedures safer in an airborne infection isolation room or operating room? *Br. J. Anaesth.* 2020; **125**: e485–7.
37. Zuazua-Gonzalez A, Collazo-Lorduy T, Coello-Casariego G et al. Surgical tracheostomies in COVID-19 patients: indications, technique, and results in a second-level Spanish Hospital. *OTO Open* 2020; **4**: 2473974x20957636.
38. Khanna S, Das R, Das AK et al. Outcomes of patients undergoing emergency tracheostomy during COVID 19 pandemic: our experience from a tertiary Care Centre in North-East India. *Indian J. Otolaryngol. Head Neck Surg.* 2021: 1–4. https://doi.org/10.1007/s12070-021-02464-5
39. Greig PR, Carvalho C, El-Boghdadly K et al. Safety testing improvised COVID-19 personal protective equipment based on a modified full-face snorkel mask. *Anaesthesia* 2020; **75**: 970–1.
40. Scohy A, Anantharajah A, Bodéus M et al. Low performance of rapid antigen detection test as frontline testing for COVID-19 diagnosis. *J. Clin. Virol.* 2020; **129**: 104455.
41. Yamayoshi S, Sakai-Tagawa Y, Koga M et al. Comparison of rapid antigen tests for COVID-19. *Viruses* 2020; **12**: 1420.
42. Rosano A, Martinelli E, Fusina F et al. Early percutaneous tracheotomy in coronavirus disease 2019 (COVID-19) and infection in healthcare personnel: a cohort study. *Infect. Control Hosp. Epidemiol.* 2021; **49**: 261–270.
43. Sun K, Wang W, Gao L et al. Transmission heterogeneities, kinetics, and controllability of SARS-CoV-2. *Science* 2021; **371**: eabe2424.
44. Lim ZJ, Ponnapa Reddy M, Karalapillai D et al. Impact of an aerosol box on time to tracheal intubation: systematic review and meta-analysis. *Br. J. Anaesth.* 2021; **126**: e122–5.
45. Sorbello M, Rosenblatt W, Hofmeyr R et al. Aerosol boxes and barrier enclosures for airway management in COVID-19 patients: a scoping review and narrative synthesis. *Br. J. Anaesth.* 2020; **125**: 880–94.
46. Kuppalli K, Gala P, Cherabuddi K et al. India's COVID-19 crisis: a call for international action. *Lancet* 2021; **397**: 2132–5.
47. COVID-trach collaborative Group. Transmission of SARS-CoV-2 Delta variant among vaccinated healthcare workers. *Vietnam* 2021.

Supporting information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Appendix S1 References for the included studies[1–69]
Supplementary Table 1 Newcastle-Ottawa Scale assessment of individual studies**Supplementary Table 2**. Time between mechanical ventilation to tracheostomy (days) and procedure time (minutes)
Supplementary Table 3. Location where tracheostomies were performed**Supplementary figure 1**. Time from IMV to intubation, comparison between percutaneous and surgical technique