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Bioaerosols in orthopedic surgical procedures and implications for clinical practice in the times of COVID-19: A systematic review and meta-analysis

Siddhartha Sharma [a], Rakesh John [b, *], Sandeep Patel [a], Deepak Neradi [a], Kamal Kishore [c], Mandeep S. Dhillon [a]

[a] *Department of Orthopaedics, Postgraduate Institute of Medical Education and Research, Chandigarh, 160012, India*
[b] *Department of Orthopaedics, Hull and Yorkshire Royal Infirmary, Hull, United Kingdom*
[c] *Department of Biostatistics, Postgraduate Institute of Medical Education and Research, Chandigarh, 160012, India*

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A B S T R A C T

Introduction: Orthopedic surgical procedures (OSPs) are known to generate bioaerosols, which could result in transmission of infectious diseases. Hence, this review was undertaken to analyse the available evidence on bioaerosols in OSPs, and their significance in COVID-19 transmission.

Methods: A systematic review was conducted by searching the PubMed, EMBASE, Scopus, Cochrane Library, medRxiv, bioRxiv and Lancet preprint databases for studies on bioaerosols in OSPs. Random-effects metanalysis was conducted to determine pooled estimates of key bioaerosol characteristics. Risk of bias was assessed by the RoB-SPEO tool; overall strength of evidence was assessed by the GRADE approach.

Results: 17 studies were included in the systematic review, and 6 in different sets of meta-analyses. The pooled estimate of particle density was 390.74 $\mu g/m^3$, Total Particle Count, $6.08 \times 10^6/m^3$, and Microbial Air Contamination, 8.08 CFU/m^3. Small sized particles ($</= 0.5\ \mu m$) were found to be 37 and 1604 times more frequent in the aerosol cloud in comparison to medium and large sized particles respectively. 4 studies reported that haemoglobin could be detected in aerosols, and one study showed that HIV could be transmitted by blood aerosolized by electric saw and burr. The risk of bias for all studies in the review was determined to be high, and the quality of evidence, low.

Conclusion: Whereas there is evidence to suggest that OSPs generate large amounts of bioaerosols, their potential to transmit infectious diseases like COVID-19 is questionable. High-quality research, as well as consensus minimum reporting guidelines for bioaerosol research in OSPs is the need of the hour.

1. Introduction

The SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus-2) has caused an unprecedented, catastrophic pandemic, which has adversely affected health care systems worldwide.[1–6] This is the third known epidemic caused by a coronavirus, less than two decades after the SARS outbreak in 2002 and the Middle east respiratory disease (MERS) outbreak in 2012; it is very unlikely to be the last one.[7] The morbidity, mortality and the sheer global impact that this pandemic has had on all aspects of life surpasses that of the earlier two outbreaks by a massive margin.[8] Arguably, this is the worst healthcare crisis faced by humanity in the last century since the Spanish flu outbreak in 1918.[9] The pandemic has had a massive effect on the delivery of orthopaedic and trauma care services across the globe.[10–19] Non-urgent, elective surgeries have been deferred, and there has been an increased emphasis on non-operative management of fractures.

The two major routes of spread of the SARS-CoV-2 are via droplet transmission, which is defined as transmission by droplets or large aerosols directly from an infected person to a susceptible person over shorter distances, and via fomites. However, this virus can also be transmitted via airborne transmission. This refers to small inspirable aerosols, measuring less than 5 μm, which can be dispersed over longer distances by air currents.[20] Any medical or

* Corresponding author.
E-mail address: rakeshjohn23@gmail.com (R. John).

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surgical procedure which potentially generates aerosols (Aerosol Generating Procedure - AGP), places the health care workers (HCWs) at risk of contracting the virus by all three modes. However, the risk of airborne transmission is higher with AGPs, therefore operating room (OR) personnel are more vulnerable to this disease as compared to other HCWs.

Orthopaedic surgical procedures (OSP) are known to generate bioaerosols, owing to the use of high-speed, power drilling and cutting tools, electrocautery and pulse lavage.[11,20–24] Guidelines on the use of personal protective equipment (PPE), which have been in a constant state of evolution, have been recommended for surgical procedures by various international health organisations and medical bodies.[21,25–30] Although there is a general agreement that respirator masks and full PPE are necessary during orthopaedic surgical procedures on COVID-19 patients[21,31], there is a dire urgency to soundly establish the evidence surrounding aerosol generation in OSPs. This is needed not only to aid in formulation of best practice guidelines as they pertain to orthopaedics ORs, but also to rationalize the use of PPE by OR personnel, the shortage of which continues to be a looming crisis worldwide. Literature on bioaerosols in OSPs in the wake of the COVID-19 pandemic is sparse, and limited to a few narrative and scoping reviews.[15,21,32] Hence, we conducted this systematic review and meta-analysis to identify and assimilate the available evidence on bioaerosols in OSPs and their potential for transmission of infectious diseases like COVID-19.

2. Objectives

The present study had two key objectives:

a. To determine the characteristics (amount and/or density, size, spread and infective potential etc.) of bioaerosols found in a typical orthopaedic OR environment
b. To determine the characteristics of aerosols generated by different orthopaedics power tools.

3. Methodology

This systematic review was conducted in accordance with the established guidelines from Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA).[33] A protocol of the systematic review was formulated and published *a priori*.[34]

3.1. Literature search

The search terms and search strategies were developed by two authors (SS and RJ) with input from all the authors. The primary search was conducted on the PubMed, Embase, Scopus and Cochrane Library, using a well-defined search strategy. Preprint server databases, viz. medRxiv, bioRxiv and Lancet preprints were also searched to identify unpublished studies (Table 1). For the secondary search, a manual search of references from the full-text of all included articles & relevant review articles was conducted. Furthermore, electronic databases of certain selected peer-reviewed orthopaedics journals (JBJS American, Bone and Joint Journal, Journal of Orthopaedic Trauma, Clinical Orthopaedics and Related Research, Injury and Acta Orthopaedica) were also searched to identify relevant literature.

3.2. Selection criteria

Any original research study (including cohort, case-control, case series, cadaveric studies and studies, animal models, laboratory based experimental studies) looking at aerosol generation in OSP or aerosol generation by orthopaedic power tools was included. Both English and non-English articles were included. Studies looking at AGPs in specialties other than orthopaedic surgery, conference papers, review articles, expert or personal opinions, and editorials were excluded. Studies using the 'sham surgery' design were also excluded.

3.3. Data extraction

Two authors (SS and RJ) independently screened the titles and abstracts of all the articles identified in the initial search. In the event of disagreement, a consensus was reached by discussion, if needed with the intervention of the senior author (MSD). Articles retrieved during the searches were screened for relevance, and those identified as being potentially eligible were fully assessed against the inclusion and exclusion criteria, and accepted or rejected, as appropriate. The full-texts of all articles selected by either reviewer were obtained and made available to all authors of the review.

3.4. Data items

One investigator (SS) extracted the following data from each included study independently, using a pre-piloted data extraction form: study name, author name, research publication time, study design, study area/country and institute name, number of patients, research information resource, demographic characteristics, subspecialty/surgical procedure investigated, surgical instruments investigated and results/outcomes (including mean number and standard deviation of total and viable particles generated, mean size and standard deviation of particles, particle scatter characteristics, mean particle concentration, microbiological air contamination, contamination of OR personnel, presence of blood in aerosols). This extracted data was entered into a spreadsheet. Two authors (RJ and SP) independently cross checked the article list and data extraction spreadsheet to ensure that there were no duplicate articles, or duplicate information from the same population and also verified the accuracy of the data.

3.5. Risk of bias assessment

The quality of the studies included was appraised using the Risk of Bias in Studies estimating Prevalence of Exposure to Occupational risk factors (RoB-SPEO) tool.[35] The studies were individually rated as: low, probably low, probably high, high or no information based on bias assessment in eight separate domains. Although this tool is relatively new and has limited peer validation, the tool was well-suited for the purposes of this systematic review, has good inter-observer agreement and hence was selected for bias assessment for this systematic review.

3.6. Assessment of strength of evidence

The strength of evidence for key findings of the review was assessed by the GRADE approach.[36]

3.7. Data synthesis

Both qualitative and quantitative analyses were performed. For qualitative analysis, appropriate tables and data visualization diagrams were constructed. The baseline data of included studies as well as all the pre-specified outcome measures were reported. Wherever appropriate, meta-analysis using a random-effects model was used to calculate pooled effect-size estimates; results

Table 1
Search strategy.

SNo.	Search String	Results
A.	**PubMed (Searched on July 21, 2020, updated November 17, 2020)**	
	((((((((((((((((("aerosol s"[All Fields] OR "aerosolic"[All Fields]) OR "aerosolization"[All Fields]) OR "aerosolizations"[All Fields]) OR "aerosolize"[All Fields]) OR "aerosolized"[All Fields]) OR "aerosolizer"[All Fields]) OR "aerosolizes"[All Fields]) OR "aerosolizing"[All Fields]) OR "aerosols"[MeSH Terms]) OR "aerosols"[All Fields]) OR "aerosol"[All Fields]) OR ((((((((((("aerosol s"[All Fields] OR "aerosolic"[All Fields]) OR "aerosolization"[All Fields]) OR "aerosolizations"[All Fields]) OR "aerosolize"[All Fields]) OR "aerosolized"[All Fields]) OR "aerosolizer"[All Fields]) OR "aerosolizes"[All Fields]) OR "aerosolizing"[All Fields]) OR "aerosols"[MeSH Terms]) OR "aerosols"[All Fields]) OR "aerosol"[All Fields])) OR (("droplet"[All Fields] OR "droplet s"[All Fields]) OR "droplets"[All Fields])) OR (((("spray"[All Fields] OR "sprayed"[All Fields]) OR "spraying"[All Fields]) OR "sprayings"[All Fields]) OR "sprays"[All Fields])) OR (("airborn"[All Fields] OR "airborne"[All Fields]) AND (((((((((((((((((((("infect"[All Fields] OR "infectability"[All Fields]) OR "infectable"[All Fields]) OR "infectant"[All Fields]) OR "infectants"[All Fields]) OR "infected"[All Fields]) OR "infecteds"[All Fields]) OR "infectibility"[All Fields]) OR "infectible"[All Fields]) OR "infecting"[All Fields]) OR "infection s"[All Fields]) OR "infections"[MeSH Terms]) OR "infections"[All Fields]) OR "infection"[All Fields]) OR "infective"[All Fields]) OR "infectiveness"[All Fields]) OR "infectives"[All Fields]) OR "infectivities"[All Fields]) OR "infects"[All Fields]) OR "pathogenicity"[MeSH Subheading]) OR "pathogenicity"[All Fields]) OR "infectivity"[All Fields]))) OR ((((((("virology"[MeSH Subheading] OR "virology"[All Fields]) OR "viruses"[All Fields]) OR "viruses"[MeSH Terms]) OR "virus s"[All Fields]) OR "viruse"[All Fields]) OR "virus"[All Fields]) AND (((((((("transmissability"[All Fields] OR "transmissable"[All Fields]) OR "transmissibilities"[All Fields]) OR "transmissibility"[All Fields]) OR "transmissible"[All Fields]) OR "transmissibles"[All Fields]) OR "transmission"[MeSH Subheading]) OR "transmission"[All Fields]) OR "transmissions"[All Fields]))) OR (((("disease transmission, infectious"[MeSH Terms] OR (("disease"[All Fields] AND "transmission"[All Fields]) AND "infectious"[All Fields])) OR "infectious disease transmission"[All Fields]) OR ("infection"[All Fields] AND "transmission"[All Fields])) OR "infection transmission"[All Fields])) OR (("occupational exposure"[MeSH Terms] OR ("occupational"[All Fields] AND "exposure"[All Fields])) OR "occupational exposure"[All Fields])) AND (((((((("orthopaedic"[All Fields] OR "orthopedics"[MeSH Terms]) OR "orthopedics"[All Fields]) OR "orthopedic"[All Fields]) OR "orthopaedical"[All Fields]) OR "orthopedical"[All Fields]) OR "orthopaedics"[All Fields]) OR (((((("orthopaedic"[All Fields] OR "orthopedics"[MeSH Terms]) OR "orthopedics"[All Fields]) OR "orthopedic"[All Fields]) OR "orthopaedical"[All Fields]) OR "orthopedical"[All Fields]) OR "orthopaedics"[All Fields])) OR (((("orthopaedic surgery"[All Fields] OR "orthopedics"[MeSH Terms]) OR "orthopedics"[All Fields]) OR ("orthopedic"[All Fields] AND "surgery"[All Fields])) OR "orthopedic surgery"[All Fields]))	**2272**
B.	**EMBASE (Searched on July 21, 2020, updated November 17, 2020)**	
	(orthopaedics OR (orthopedic AND surgery)) AND (aerosol OR droplet OR 'airborne infection' OR 'virus transmission' OR 'disease transmission' OR 'occupational exposure'/exp OR 'occupational exposure')	**1116**
C.	**SCOPUS (Searched on July 21, 2020, updated November 17, 2020)**	
	((TITLE-ABS-KEY (aerosol) OR TITLE-ABS-KEY (droplet) OR TITLE-ABS-KEY (spray) OR TITLE-ABS-KEY (airborne AND infection) OR TITLE-ABS-KEY (virus AND transmission) OR TITLE-ABS-KEY (infection AND transmission) OR TITLE-ABS-KEY (occupational AND exposure))) AND ((TITLE-ABS-KEY (orthopaedics) OR TITLE-ABS-KEY (orthopedic AND surgery)))	**1453**
D.	**Cochrane Library (Searched on July 21, 2020, updated November 17, 2020)**	
	1. aerosol	**141**
	2. droplet	
	3. spray	
	4. airborne infection	
	5. virus transmission	
	6. infection transmission	
	7. occupational exposure	
	8. #1 OR #2 OR #3 OR #4 OR #5 OR #6 OR #7	
	9. ORTHOPEDICS	
	10. ORTHOPEDIC SURGERY	
	11. #9 OR #10	
	12. #8 AND #11	
E.	**medRxIV & bioRxIV Preprint Servers (Searched on July 21, 2020, updated November 17, 2020)**	
	full text or abstract or title "aerosol orthopaedics" (match whole all)	**12**
F.	**Lancet Preprint Server (Searched on July 21, 2020, updated November 17, 2020)**	
	"aerosol orthopaedics"	**4**
	Total	**4998**

were reported as means with 95% confidence intervals. Forest plots were constructed to visualize the results. Statistical heterogeneity was evaluated by the I^2 test. Analysis was performed by *Stata MP Version 14.0* and the *Open MetaAnalyst Software*.

4. Results

4.1. Literature search

The results of the search strategy have been summarized as per the PRSIMA flowchart (Table 2). The combined searches yielded 4745 records. Full text was obtained for 59 studies, of which 17 were included in the systematic review and 6 studies were included in 5 different sets of meta-analyses.

4.2. Characteristics of included studies

Characteristics of the 19 studies included in this review have been summarized in Table 3. Majority of the studies (n = 9, 47.4%) were prospective human studies; there were 4 cadaveric, 4 animal and 2 experimental studies. Arthroplasty, followed by spine surgery, was most commonly evaluated surgical procedure. Evaluation of aerosol generating devices included electrocautery, cutters, burrs, drills, saws and irrigators. Information on characteristics of individual studies and their salient findings has been presented in Table 4.

4.3. Characteristics of aerosols in orthopedics ORs

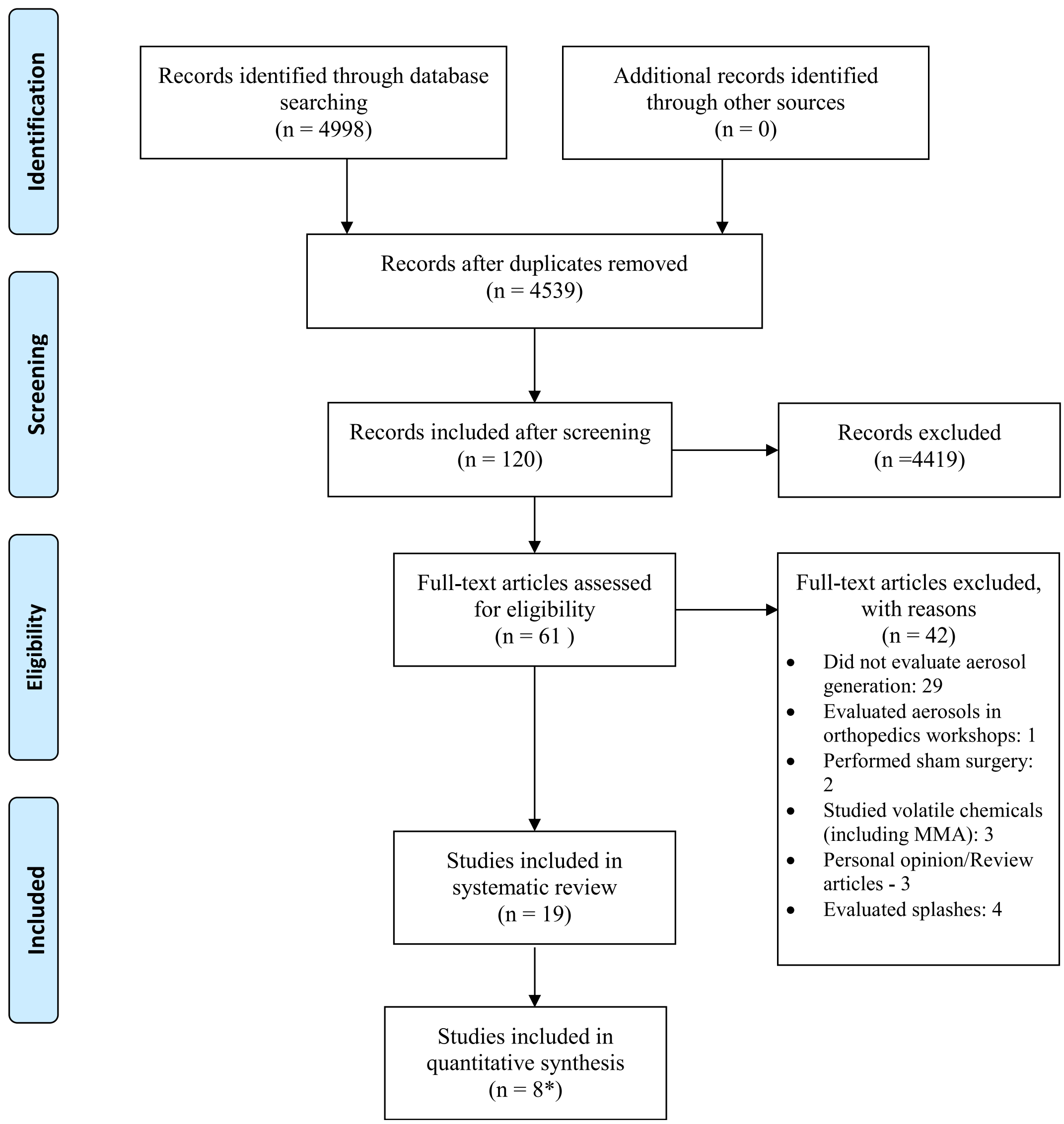
a) Aerosol particle density

Aerosol particle density in human surgeries was reported by two studies[37,38] (Supplementary Table 1). The pooled particle density was estimated to be 390.74 μg/m^3 (95% CI 162.70–618.77 μg/m^3); heterogeneity was high for this analysis (I^2 = 60.3%, Chi Square P Value = 0.001) (Fig. 1).

b) Aerosol total particle counts

Total particle counts (TPC) in human surgeries was reported by

Table 2
PRISMA flow diagram for the study.



two studies.[39,40] The pooled TPC was estimated to be 6.08×10^6 per cubic meter (95% CI, 3.05–9.11 $\times 10^6$ per cubic meter); heterogeneity was high for this analysis (I^2 = 94.9%, Chi Square P Value = 0.000) (Fig. 2).

c) Aerosol particle sizes

Counts of individual particle sizes were reported by five studies.[40–44] Whereas Birgand et al.[41] reported the counts of 3 different particle sizes, the other 4 studies reported the counts of more than 3 different particle sizes. To simplify these results, we categorized particles as *small* (0.3–0.5 μm), *medium* (0.5–5 μm) and *large* (>5 μm) size. Furthermore, in order to determine which particle sizes were most commonly encountered in orthopedics ORs, we determined the ratio of small to medium size particles and small to large size particles (see Supplementary Table 2 for details on how study data was pooled into categories).

The pooled ratio of small to medium sized particles was estimated to be 37.4 (95% CI 25.89–48.87); the heterogeneity for this estimate was high (I^2 = 99.6%, Chi Square P Value = 0.000) (Fig. 3).

The pooled ratio of small to large sized particles was estimated to be 1604.4 (95% CI 1046.68–2162.07); the heterogeneity for this estimate was high (I^2 = 99.9%, Chi Square P Value = 0.000) (Fig. 4).

d) Microbial air contamination

Microbial air contamination (MAC) was evaluated by four human studies.[39–41,43] The pooled MAC was estimated to be 8.08 CFUs per cubic meters (95% CI, 3.36–12.79); the heterogeneity for the estimate was high (I^2 = 96.7%, Chi Square P Value = 0.001) (Fig. 5).

e) Presence of blood in aerosols

The presence of blood in aerosols was evaluated by four studies[22,45–47] (Table 5). Whereas three studies[45–47] used the qualitative Hemastix™ assay, Yeh et al.[22] used ^{51}Cr labelled blood to quantify the hemoglobin content in aerosol. On the basis of data provided by three authors[22,46,47], we estimated that the mean

Table 3
Characteristics of studies included in the systematic review (n = 17).

SNo.	Characteristic	No. of Studies
1.	**Study Design**	9
	•Human study[37–44,54]	4
	•Animal study[45–47,65]	4
	•Cadaveric study[48–50,52]	2
	•Others (Experimental)[51,53]	
2.	**Setting in which aerosol generation was evaluated**	11
	• *Aerosol generation during a specific surgical procedure*o Arthroplasty[38–43,45,48,51,54,65]	4
	o Spine Surgery[38,49,50,52]	1
	o Trauma[38]	1
	o Tenotomy[54]	1
	o Unspecified surgery[44]	5
	• *Aerosol generation by specific power tool(s)*o Burr/Cutter/Ultrasonic devices[47–51]	3
	o Saw[45–47]	3
	o Drill[45–47]	3
	o Irrigator/Hydro-debridement device[52,53]	3
	o Electrocautery[45–47]	
3.	**Aspects of aerosol generation evaluated**	2
	• Aerosol concentration[37,38]	2
	• Total particle counts[39,40]	5
	• Particle counts of different particle sizes[40–44]	4
	• Microbial air contamination[39–41,43]	4
	• Hemoglobin/blood in aerosol[22,45–47]	5
	• Aerosol spread[48–52]	4
	• Contamination of OR personnel[48–50,52]	1
	• HIV in aerosol[53]	1
	• Albumin in aerosol[54]	

HIV = Human Immunodeficiency Virus; OR = Operating Room.

hemoglobin inhaled by a surgeon in an hour can range from 0.04 to 0.68 µg. Johnson et al.[47] estimated that the inhalation risk of virus for surgeons is < 1 HIV virus or 180 Hepatitis B viruses per procedure (Fig. 6).

f) Aerosol spread

Aerosol spread was evaluated by 5 studies[48–52], all of which used similar methodology (Table 6). Saline solution containing *Staphylococcus aureus* was used for irrigation during surgery. Petri dishes with culture media (mannitol salt agar) were placed at regular intervals over a prespecified area to detect the areal spread of microbial contamination. 4 studies[49–52] reported that the aerosol was spread throughout the area under surveillance, evident by bacterial growth in all the petri dishes. One study[48] which evaluated ultrasonic cutter versus Midas Rex cutter in revision hip arthroplasty found a lower aerosol spread with the ultrasonic cutter.

g) Contamination of OR personnel

Contamination of OR personnel was evaluated by 4 studies.[48–50,52] This was done by obtaining surveillance microbial cultures from the face, neck and head of the surgeon, assistant, scrub nurse, anaesthetist and the patient's draped head. The surgeon and the assistant had the maximum contamination; however, all OR personnel, as well as the patient's draped head showed microbial contamination (Supplementary Table 3, Fig. 7).

h) HIV virus in aerosol

To determine whether the Human Immunodeficiency Virus (HIV) could spread via aerosols generated by surgical tools, Johnson et al.[53] performed a laboratory study. Human blood inoculated with the HIV virus was aerosolized by electrocautery, bone saw and a router (instrument similar to burr). The aerosols were then cultured for HIV virus. The authors noted that HIV virus could be cultured from the aerosols of bone saw and router, but not electrocautery.

i) Albumin in aerosols

Hamer et al.[54] studied the levels of albumin in aerosol, and determined whether this could be used as a surrogate to quantify aerosol concentration. The authors found that the albumin levels in aerosol are extremely low and did not change with the use of power tools. Hence, such estimation should not be considered as a reliable method to quantify aerosol levels.

4.4. *Characteristics of aerosols generated by specific orthopedics instruments*

Two studies[45,46] described the characteristics of aerosols generated by different power tools (Table 7, Fig. 8). For the sake of simplicity, we categorized particles as *small* (0.3–0.5 µm), *medium* (0.5–5 µm) and *large* (>5 µm) size.

a) Saw

The oscillating saw was noted to produce 56–68% 'medium' sized particles and 28–40% 'small' sized particles (Fig. 8a).

b) Drill

Jewett et al.[46] investigated aerosol characteristics of two types of drills, i.e. the 'Hall drill', which is a high-speed, air-powered drill (Zimmer, Warsaw, Ind.) and the 'Shea drill', which is a high-speed drill with continuous irrigation (Xomed-Treace, Jacksonville, Fl.) Both drills were noted to produced particles of all sizes. Whereas the Hall drill produced 47% 'medium', 38% 'large' and 17% 'small'

Table 4
Summary of studies included in the review.

SNo	Author	Study Design	Procedure/instrument(s) evaluated	Outcome Parameters	Salient Results
1	Anis 2019[39]	Prospective human study (RCT)	Comparison of C-UVC air filtration Vs no filtration in total joint arthroplasty	TPC, VPC, MAC (CFUs/m^{3})	C-UVC air filtration device significantly decreased TPC, VPC & MAC
2.	Birgand 2015[41]	Prospective multicenter human study	Assessed factors affecting air quality and the effect of air contamination on wound contamination in clean Orthopaedic (TKA and THA) & Cardiac surgery	Particle Counts (0.3, 0.5 & 5 μm), MAC, bacteriological sampling of wound	In turbulent air flow, increasing particle counts were significantly associated with MAC. This effect was not seen in case of laminar air flow. Turbulent air flow, but not MAC, increased wound contamination.
3.	Hamer 1997[54]	Prospective human (case-control) study	Evaluated aerosol generation in 7 hip arthroplasties (cases) and 5 controls (one tenotomy and 4 instances when OR was vacant)	Air albumin levels (in the form of aerosol)	Overall air albumin levels were very low. Air albumin levels were lower in cases as compared to controls (attributed to laminar air flow).
4.	Heinsohn 1991[45]	Animal (bovine) study	Evaluated aerosol generation with electrocautery (on bovine tendon) and different power tools (on bovine bone)	Particle counts and qualitative Hb concentration	Aerosolized blood was detectable in all cases. Bone saw generated particles in 0.07–2.8 μm range. 'Cutting mode' cautery generated particles in 0.07–0.42 μm range. 'Coagulation mode' cautery generated particles in 0.07–4.2 range μm.
5.	Jewett 1992[46]	Animal (bovine) study	Evaluated aerosol generation with electrocautery (on bovine tendon) and different power tools (on bovine bone)	Particle counts and qualitative Hb concentration	Most common particle sizes: a) Shea drill – 14 μm; b) Hall Drill: bimodal (0.42 & 7.9 μm); c) Stryker saw: 0.42 μm; d) Electrocautery, coagulation mode 0.28 μm; e) Electrocautery, cutting mode, 0.07 μm. Aerosol particles >0.28 μm were positive for hemoglobin.
6.	Johnson 1991[53]	Laboratory based	HIV inoculated human blood was aerosolized by electrocautery, bone saw, irrigator and router.	Aerosols were cultured for HIV	Aerosols generated by bone saw and router showed positive HIV cultures.
7.	Johnson 1997[47]	Animal (canine) study	Characterized blood containing aerosols during canine THA	Particle concentration, particle size, hemoglobin content in aerosol.	Mean particle count was $5.45 \times 10^{8} \pm 3.54 \times 10^{8}$. Mass median diameter was 0.89 μm. Mean count median diameter was 0.18 μm. Mean Hb aerosol mass was 133 ng.
8.	Kirschbaum 2020[42]	Prospective human study (randomized cohort study)	Compared air quality in TKAs in laminar air flow (6 cases) and non-laminar air flow (6 cases) ORs	Particle Counts (different sizes), Swabs taken from 'safe air smoke evacuator' for microbial cultures	Laminar air flow group had lower particle concentrations, this was independent of the particle size and measurement location.
9.	Nimra 2015[37]	Human study	Evaluated air quality in different ORs, including orthopedics ORs	Aerosol concentration	Highest aerosol concentration was found in orthopedics ORs. Overall mean particle concentration was 290.5 μg/m^{3}
10.	Nogler 2001/1[51]	Experimental Study	Evaluated aerosol generation with the ROBODOC ball and flat cutter	Macroscopic aerosol spread (nigrosin dye), microbial detection, MAC	The ball cutter resulted in higher macroscopic aerosol spread (4.7 × 2 m) as compared to flat cutter (2.7 × 1.15 m). Mircobes were detected in a maximum radius of 6 × 3 m. After each experiment, the MAC was 1.6×10^{4} CFU/mL.
11.	Nogler 2001/2[50]	Cadaveric study	Evaluated aerosol-based contamination in 3 cadaveric cervical laminectomies with high-speed ball cutter	Contamination of operating room personnel	Contamination detected in 5 × 7 m area. Surgeon, assistant, anesthetist and even the '*patient's*' draped head showed contamination.
12.	Nogler 2001/3[49]	Cadaveric study	Evaluated aerosol-based contamination in one cadaveric lumbar laminectomy with high-speed ball cutter	Contamination of operating room personnel	Contamination detected in 5 × 7 m area. Surgeon, assistant, anesthetist and even the '*patient's*' draped head showed contamination.
13.	Nogler 2003[48]	Cadaveric study	Evaluated aerosol-based contamination in one cadaveric revision hip arthroplasty where ultrasound (US) and high-speed cutters were used.	Contamination of operating room personnel	Contamination from both tools was detected in 6 × 8 m area. The ball cutter resulted in higher contamination than US device. Surgeon, assistant, anesthetist and even the '*patient's*' draped head showed contamination.
14.	Morris 2020[43]	Prospective human study (RCT)	Compared air quality in shoulder arthroplasty with the use of localized laminar air flow device(21 cases) vs control (22 cases)	Particle Counts (different sizes), MAC	Significantly lower CFUs in the localized laminar air flow device group, after adjusting for number of OR personnel and surgical time.
15.	Pereira 2012[44]	Prospective human study	Evaluated aerosol generation in 5 orthopedic surgeries	Particle Counts (six different particle sizes)	13 different aerosol generating activities were identified; each produced different types of particles. Handling of linen, gowns, patient, equipment, room cleaning, use of saw and electrocautery were the most important sources of particles.
16.	Putzer 2017[52]	Cadaveric surgery	Evaluated aerosol-based contamination in one cadaveric spine surgery where hydro-surgical debridement device was used	Contamination of operating room personnel	Contamination from both tools was detected in 6 × 8 m area. Surgeon, assistant, anesthetist and even the '*patient's*' draped head showed contamination.
17.	Stocks 2010[40]	Prospective human study	Evaluated the relationship between particulate air density and density of viable airborne microbes in 22 arthroplasty surgeries (13 THAs and 9 TKAs)	Particle density and MAC	Density of airborne particles >10 μm correlated with MAC. Both particle density and MAC increased with number of staff in OR and with duration of surgery.
18.	Yeh 1995/1[22]	Animal (canine) study	Evaluated the amount of blood-containing aerosols generated in 5 canine THA. ^{51}Cr labelled blood was used.	Aerosol mass and RBC concentration	2.9×10^{5} RBCs or 0.87 μg of Hb is inhaled during a typical orthopedic procedure. 60% RBCs were found to be associated with particles >10 μm in size, only

Table 4 (*continued*)

SNo	Author	Study Design	Procedure/instrument(s) evaluated	Outcome Parameters	Salient Results
					8% with particle <0.5 μm in size. Less than 135 lymphocytes inhaled per surgery.
19.	Yeh 1995/2[38]	Human Study	Evaluated aerosol generation in 10 procedures (5 THAs, 3 TKAs, 1 back fusion, 1 hip reconstruction)	Concentrations of different sizes of particles, at different stages of surgery	Highest amount of aerosol was generated by electrocautery and irrigation-suction. Room clean up did not increase aerosol concentration.

C-UVC: crystalline ultraviolet –C filter, CFU: colony forming unit, Hb: hemoglobin, HIV: human immunodeficiency virus, MAC: microbial air contamination, OR: operating room, RBC: red blood cell, RCT: randomized controlled trial, THA: total hip arthroplasty, TPC: Total particle count, US: ultrasound, VPC: viable particle count.

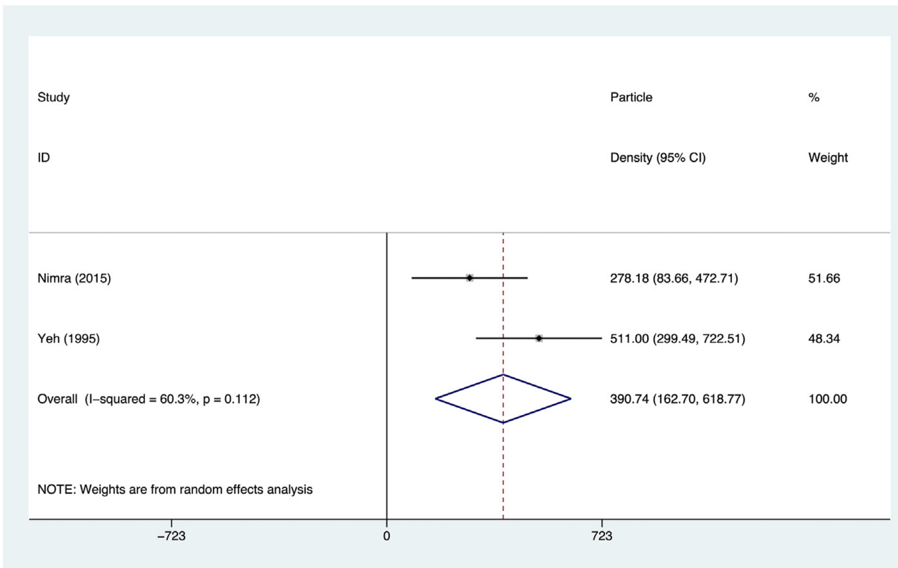


Fig. 1. Forest plot showing pooled estimate of aerosol particle density (random-effects model, all values are in micrograms per cubic meters).

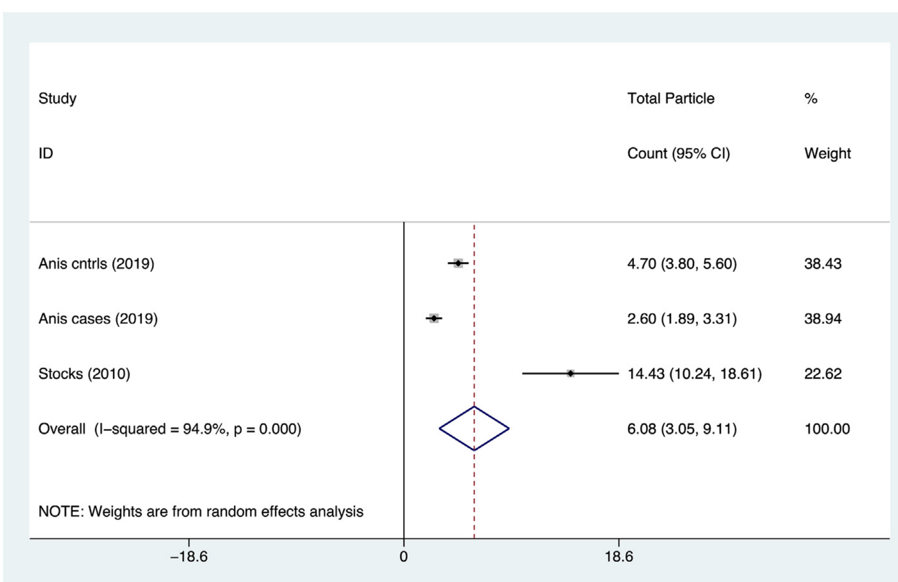


Fig. 2. Forest plot showing pooled estimate of total particle counts (random-effects model, all values are x 10^6 per cubic meters).

sized aerosols, the Shea drill produced 59% 'large', 31% 'medium' and 9% 'small' sized aerosols (Fig. 8b).

c) Electrocautery

Electrocautery was noted to produce aerosols with a

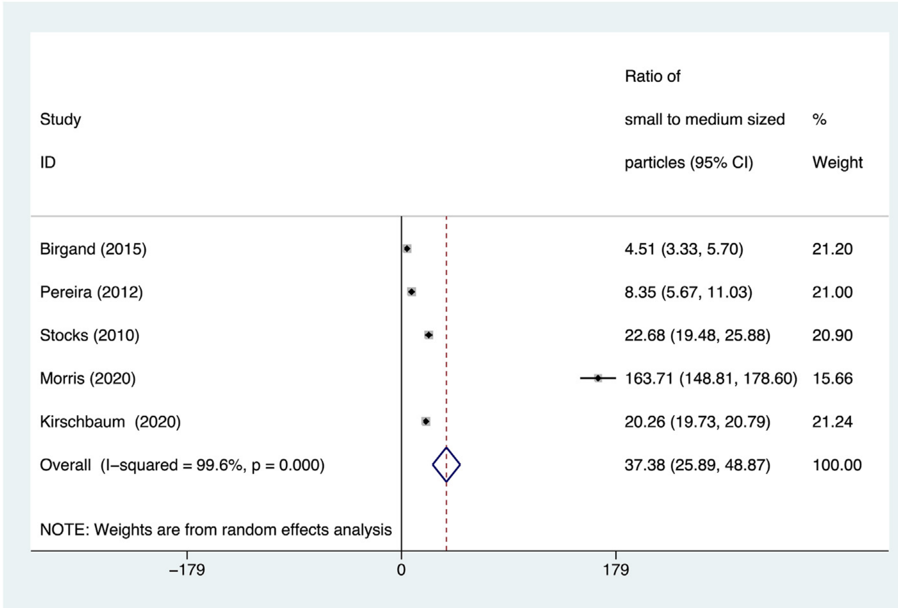


Fig. 3. Forest plot showing pooled estimate of ratio of small (0.3–0.5 μm) to medium (0.5–5 μm) sized particles (random-effects model).

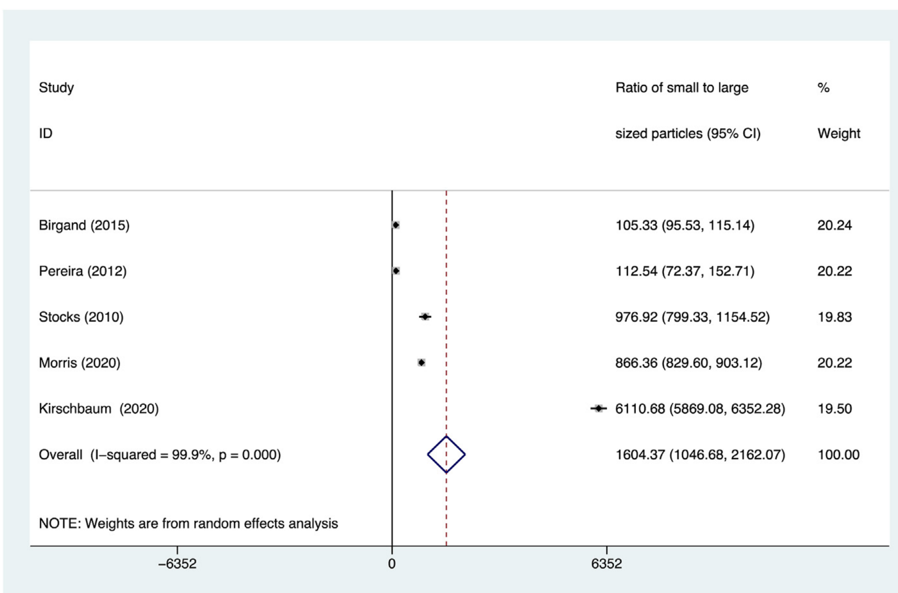


Fig. 4. Forest plot showing pooled estimate of ratio of small (0.3–0.5 μm) to large sized (>5 μm) particles (random-effects model).

predominance of 'small' sized particles. Whereas electrocautery in the 'cutting' mode produced 90–95% 'small' sized particles, the 'coagulation mode' produced 60–78% 'small' sized particles and 20–37% 'medium' sized particles (Fig. 8c and d).

d) Hemoglobin & HIV in aerosols from different power tools

Jewett et al.[46] noted that aerosols from electrocautery, saw and drills contained hemoglobin. Johnson et al.[47] noted that the HIV virus could be cultured from the aerosols of bone saw and router, but not from electrocautery. The authors proposed that the heat of electrocautery may have inactivated the virus.

4.5. Risk of bias

The overall risk of bias was judged to be 'high' for all studies. The domains pertaining to participant selection, non-blinding of study personnel and selective reporting of exposures were noted to have 'high' or 'probably high' risk of bias. On the other hand, the domains pertaining to misclassification, incomplete exposure data, conflicts of interest and differences in denominator and numerator were noted to have a 'low' or 'probably low' risk of bias (Figs. 9 and 10).

4.6. Assessment of strength of evidence

The strength of evidence for parameters pertaining to aerosol

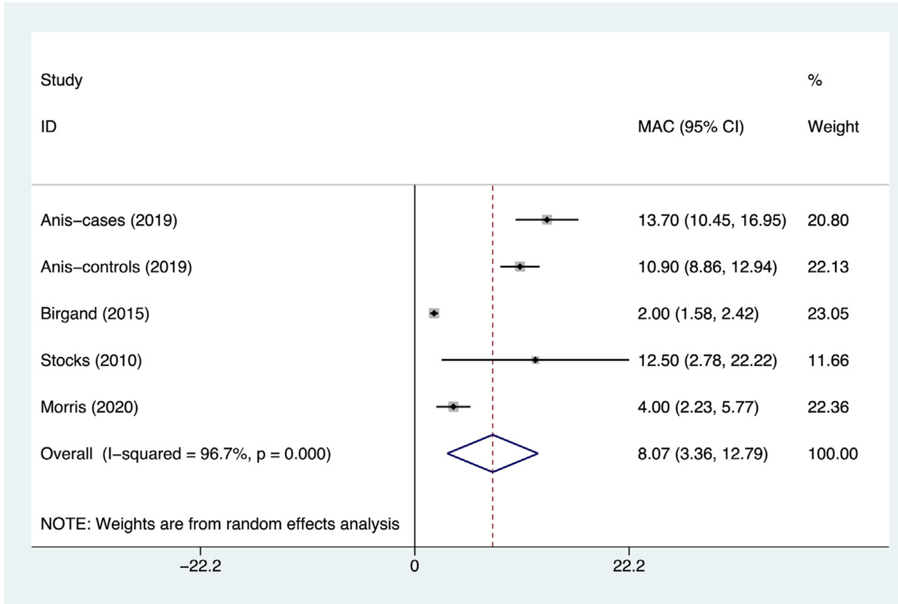


Fig. 5. Forest plot showing pooled estimate of microbial air contamination (random-effects model, all values are in Colony Forming Units per cubic meters).

Table 5
Presence of blood in aerosols.

Study	Type of estimation	Method	Results	Mean Hb Inhaled Per Surgery[a]	Virus Content of Aerosolized Blood
Heinsohn 1991[45]	Qualitative Hb estimation	Hemastix Strip	Hb was detected in all aerosols.	Not estimated	Not estimated
Jewett 1992[46]	Qualitative Hb estimation	Hemastix Strip	Hb was detected in all particles >0.14 μm. Mean Hb concentration 1.4 $\mu g/m^3$	0.5 μg	Not estimated
Johnson 1997[47]	Quantitative	Hb collected on a membrane filter paper & tested with Hemastix Strip	Hb was detected in all aerosols. Mean Hb aerosol concentration = 0.1 $\mu g/m^3$	0.04 μg	Indirect estimates: < 1 HIV virus and 180 HBV viruses per surgery
Yeh 1995[22]	Quantitative. ^{51}Cr Labelled Blood used.	Chemistrip analysis and radiometric counting	Time averaged Hb concentration = 1.9 $\mu g/m^3$	0.68 μg	Not estimated

1 L = 0.001 cubic meters.
Hb = Hemoglobin, HBV: Hepatitis-B Virus, HIV: Human Immunodeficiency Virus.
[a] Assuming an inhaled minute volume of 6 L, for a surgery of 1-h duration. (Hb inhaled = Hb concentration x 0.006 × 60).

density, total particle counts, microbial air contamination, ratio of small to medium and small to large size particles was rated as 'low' as per the GRADE working group grading of evidence[36] (Table 8).

5. Discussion

There is a lot of uncertainty in the literature surrounding aerosol generation during surgical procedures and the associated risk of viral transmission.[21,32] In 2014, the World Health Organization (WHO) defined an aerosol generating procedure (AGP) as *'any medical and patient care procedure that results in the production of airborne particles (aerosols)'*.[55] However, whether such aerosols can potentially transmit disease to healthcare workers is questionable.[56] '*High-risk aerosol generating procedures*' are those that can result in airborne disease transmission from patients to healthcare workers, and therefore require airborne precautions.[56] A situation, background, assessment and recommendations (SBAR) document from the Antimicrobial Resistance and Healthcare Associated Infection (ARHAI) Scotland categorizes high-speed cutting as an 'high-risk aerosol generating procedure' only when it involves the respiratory tract or paranasal sinuses.[56] Hence, the majority of orthopedic surgical procedures would be classified as 'low-risk' on the basis of these recommendations.[56]

Do orthopedic surgical procedures generate bioaerosols? From our review, the answer would be an unequivocal '*yes*'. Our results show that orthopedic instruments and power tools generate aerosols of different sizes, and that majority of these particles are <5 μm in size. Are these bioaerosol concentrations within permissible limits? The International Organization for Standardization (ISO), in its ISO Standard number 14644-1, describes the maximal permissible limit of total particle counts (TPC) in clean rooms.[57] Operating rooms are expected to comply with Class 5 (TPC < 10^5 per cubic meter) or Class 6 (TPC < 10^6 per cubic meter) cleanroom standards.[58] If we considered the pooled estimate of total particle counts (6 × 10^6 per cubic meters) from our meta-analysis, it would be in compliance with an ISO Class 9 (TPC < 35.2 × 10^6 per cubic meter) cleanroom.

Another important determinant of the air quality of an orthopedic operating room is the microbial air contamination (MAC).[59] MAC has been shown to correlate with post-operative wound infection. Many countries use cut-off values based on MAC to assess the air quality of ultra-clean operating rooms, and MAC values of < 5–10 CFU per cubic meters are considered as acceptable.[59] The pooled estimate of MAC (8.08 CFU per cubic meters) from our meta-analysis was noted to be within the upper acceptable limit.

We also noted that the aerosol cloud generated in orthopedic

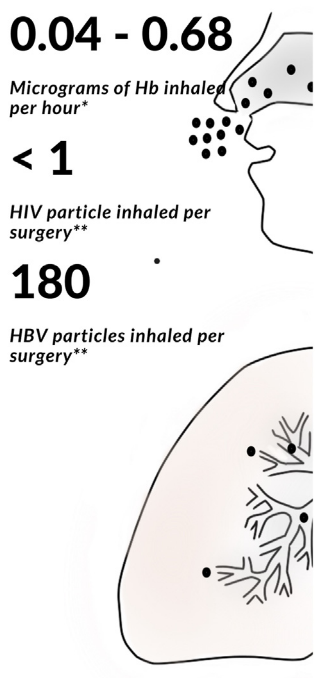


Fig. 6. Key aspects of hemoglobin content and viral transmission by bioaerosols. *([22,46,47], **.[47]

surgical procedures tends to spread out over the entire operating room area and contaminates all personnel within it, with the head and body being the most highly contaminated regions.

Whereas these observations leave little uncertainty on generation of large amounts of bioaerosols in orthopedic procedures, the potential for these aerosols to spread viral infections, including COVID-19 remains debatable. The most important finding of our review in this regard is perhaps the lack of high-quality direct evidence on the infectivity of orthopedic bioaerosols. We could find only one study[53] which showed that the HIV virus can be potentially transmitted through cool aerosols generated by bone saw and burrs. This study was conducted in 1991, and there have be no other studies to validate these observations. Given the fact that the SARS Coronavirus RNA can be found in blood in up to 79% of patients with COVID-19[60], the potential for its spread via aerosols should be given due consideration.

The emergence of this pandemic has exposed many lacunae in the research on bioaerosols in orthopaedic surgical procedures. Most of the published research so far has focused on the role of

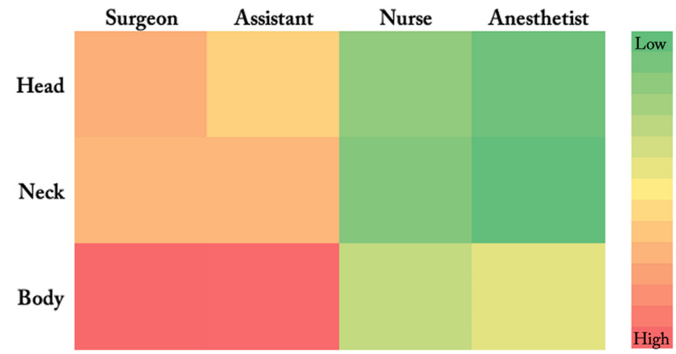


Fig. 7. Heatmap showing contamination of operating room personnel by bioaerosols. Colours represent the number of colony forming units cultured (Note: the colour coding may be considered as an approximate representation only. For details on how the heatmap was constructed, please see Supplementary Table 3).

Table 6
Aerosol spread.

Study	Instrument/Surgical Procedure Evaluated	Whether microscopic or macroscopic areal spread was evaluated	How was spread determined	Microbe Placed in Irrigation Solution	How much area was put under microscopic surveillance (a)	What was the maximum microscopic areal spread (b)	% age of maximal microscopic areal spread (a/b x 100)
Nogler 2001/1[51]	Midas Rex Cutter on a ROBODOC arm; Hip Arthroplasty	Both	Macroscopic spread: detection of nigrosine dye on cloths Microscopic spread: 256 Petri dishes with Mannitol Salt Agar	*Staphylococcus aureus* (ATCC 12600), Concentration = 1.6×10^4 CFU/ml	5×7 m, 35 m^2	3.6×6 m, 21.6 m^2	61.7%
Nogler 2001/2[50]	High speed cutting device with 0.6 mm ball cutter; Cervical Laminectomy	Microscopic	103 Petri Dishes with Mannitol Salt Agar	*Staphylococcus aureus* (ATCC 12600), Concentration = 2-4 x 10^6 CFU/ml	5×7 m, 35 m^2	5×7 m, 35 m^2	100%
Nogler 2001/3[49]	High speed cutting device with 6 mm ball cutter; Lumbar Laminectomy	Microscopic	103 Petri Dishes with Mannitol Salt Agar	*Staphylococcus aureus* (ATCC 12600), Concentration = 2-4 x 10^6 CFU/ml	5×7 m, 35 m^2	5×7 m, 35 m^2	100%
Nogler 2003[48]	High speed cutting device with 6 mm ball cutter & ultrasonic cutter; Revision Hip Arthroplasty	Microscopic	48 Petri Dishes with Mannitol Salt Agar	*Staphylococcus aureus* (ATCC 12600), Concentration = 3.7×10^4 CFU/ml	6×8 m, 48 m^2	6×8 m, 48 m^2 (Higher with ball cutter)	100%
Putzer[52]	Hydrosurgical debridement device; Lumbar spine surgery	Microscopic	103 Petri Dishes with Mannitol Salt Agar	*Staphylococcus aureus* (ATCC 6538), Concentration = 6.4×10^5 CFU/ml	6×8 m, 48 m^2	6×8 m, 48 m^2	100%

Table 7
Percentage of different particle sizes generated by various orthopedic power tools.

Study	% age of particles of small size (<3 μm)	% age of particles of medium size (0.5–5 μm)	% age of particles of large size (>5 μm)
A. Electrocautery – Cutting Mode			
Heinsohn 1991[45]	94.5	4.7	0
Jewett 1992[46]	90.2	6.6	5.7
Mean	**92.35**	**5.65**	**2.85**
B. Electrocautery – Coagulation Mode			
Heinsohn 1991[45]	60.3	37.3	0
Jewett 1992[46]	78.1	20.6	3.8
Mean	**69.2**	**28.95**	**1.9**
C. Saw			
Heinsohn 1991[45]	27.9	67.6	0
Jewett 1992[46]	40.4	56.3	3.03
Mean	**34.15**	**61.95**	**1.515**
D. Drill			
Hall Drill[a] (Jewett 1992[46])	17	47.3	38.1
Shea Drill** (Jewett 1992[46])	9.1	31	59.1
Mean	**13.05**	**39.15**	**48.6**

[a] Hall drill: high-speed, air-powered drill (Zimmer, Warsaw, Ind.); * Shea drill: high-speed drill with continuous irrigation (Xomed-Treace, Jacksonville, Fl.).

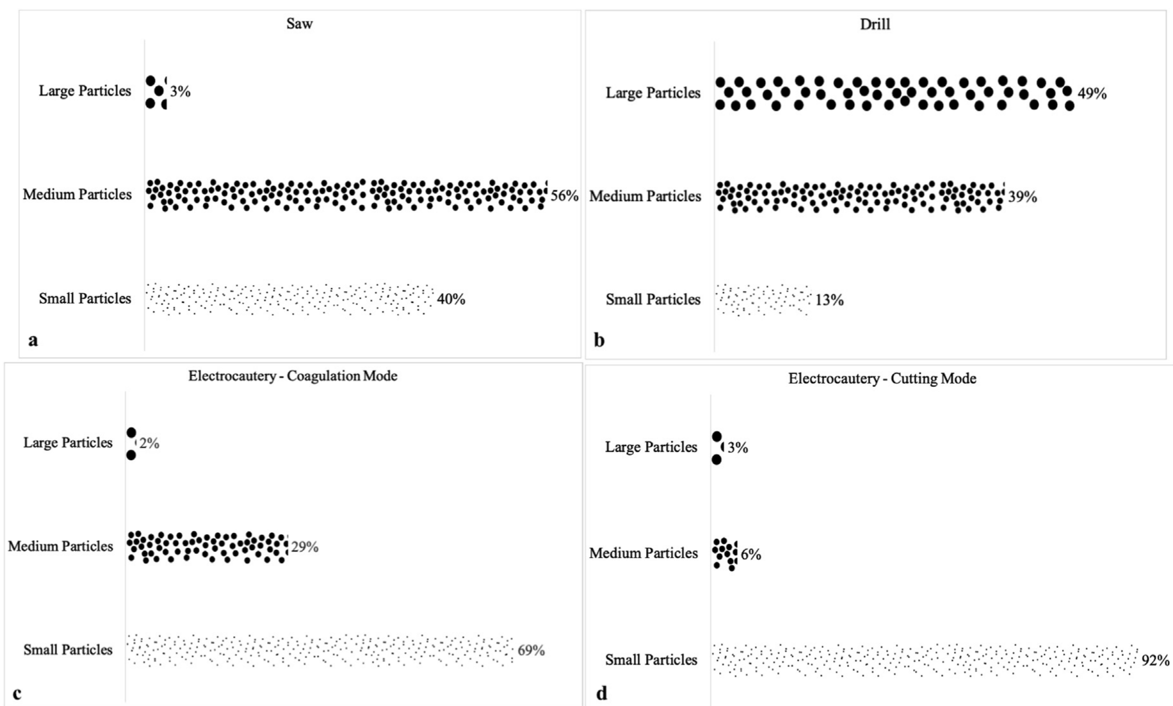


Fig. 8. Bar chart showing comparison of different particles sizes generated by orthopedic power tools. '*Small*' size corresponds to particles 0.3–0.5 μm, '*Medium*' to particles between 0.5 and 5 μm and '*Large*' to particles >5 μm in size. a) Oscillating saw b) Drill c) Electrocautery – '*coagulation*' mode d) Electrocautery – '*cutting*' mode.

aerosols in post-operative wound infection, and measures to control airborne wound contamination. High quality research looking at the infective potential of bioaerosols in orthopedic surgeries and remedial measures is therefore the need of the hour.

The key findings of this review, their implications and the recommendations for orthopedics surgical procedures in COVID-19 patients have been summarized in Table 9. However, these recommendations come with the caveat that the evidence from our review on infective potential of orthopedic bioaerosols can be considered indirect at best.

Since orthopedic ORs have high bioaerosol concentrations, every effort should be made to minimize generation at source. Minimizing the number of OR personnel and traffic, minimizing the number of OR door openings and avoiding unnecessary conversation during surgery are some of the important factors in reducing the aerosol generation from OR personnel. Anis et al.[39] showed that UV-C filters significantly decreased TPC and MAC. Similarly, Morris et al.[43] showed that a localized laminar air flow device decreases the aerosol load in shoulder arthroplasty. However, these are not yet widely in use and their role in decreasing airborne viral transmission needs to be validated before it can be recommended. Since orthopedic power tools generate large amounts of aerosols, they must be used sparing when operating on COVID-19 patients. Raghavan et al.[15] have recommended that power drills, saws and burrs should be used to a minimum, and that hand drills and hand-held saws (like the giglie saw) should be preferred. Also, percutaneous procedures or those that require minimal exposure should be preferred over open surgical procedures.

Another key finding of our review is that aerosols generated during OSPs constitute of predominantly small-sized which tend to

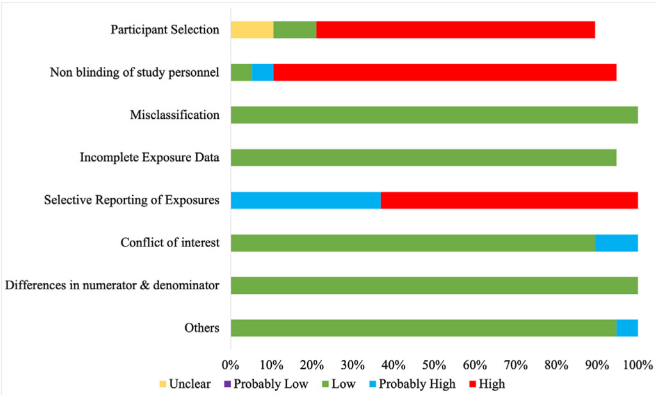


Fig. 9. Risk-of-bias table: review authors' judgments about each risk-of-bias item presented as percentages across all included studies (RoB-SPEO tool).

stay suspended in the air for longer periods.[61] Although they carry smaller number of microorganisms as compared to large-sized particles, their infective potential can be considered as equivalent.[62,63] There is evidence that small particles as less in size as 1 μm can be retained in the respiratory tract; hence the need for respiratory masks.[61] Respiratory masks are classified based on their ability to filter small particles (0.3 μm being the cutoff size). A N95 mask filters 95% of the particles, N99 mask filters 99% of the particles, and N100 mask blocks 99.97% of the particles. Most guidelines around the world recommend N95 masks for orthopedic surgical procedures in patients with COVID-19. Another important factor in decreasing the aerosol load is the OR ventilation. It has been shown that 15 air changes per hour, which is the norm in most ORs, results in removal of 90% of aerosols within 15–20 minutes[20,64] Therefore, limiting the number of personnel to a minimum during intubation, ensuring a lapse of 15–20 min after intubation, as well as after completion of surgical procedure would also be useful in reducing the chances of airborne transmission.[15]

We also noted that bioaerosols tend to spread over a wide area of the OR and tend to contaminate all OR personnel. Hence, thorough disinfection of all OR surfaces with virucidal agents must be performed after each OSP. Furthermore, we agree with the recommendations of using full PPE for OSPs in patients with COVID-19.[15,21] Doffing techniques post-surgery must be deliberate, meticulous and should be performed in a separate room with a single-person attendance at any time to ensure that the aerosols deposited on the gown are not dispersed back into the air.[15,21]

The study has several strengths. To the best of our knowledge, this is the first systematic review and meta-analysis so far, to focus on aerosol generation in OSPs. The protocol for the review was formulated and published *a-priori*.[34] We adhered strictly to PRISMA guidelines[33] (Supplementary Table 4). We performed extensive literature search across multiple databases, and also searched the

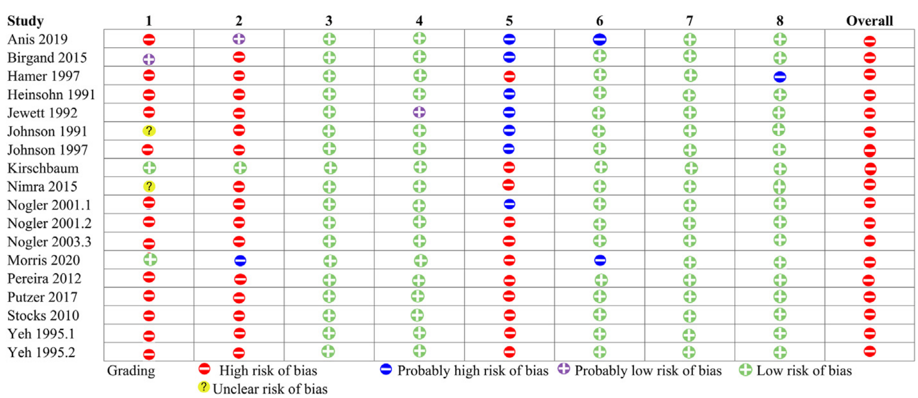


Fig. 10. Risk of bias summary: review authors' judgments for individual studies included in the review. Domains; 1 = Participant selection, 2 = Non-blinding of study personnel, 3 = Misclassification, 4 = incomplete exposure data, 5 = selective reporting of exposures, 6 = conflicts of interest, 7 = differences in numerator and denominator, 8 = others (RoB-SPEO tool).

Table 8
GRADE Summary of findings table.

Outcomes	No. of participants (studies)	Absolute Effect	Relative Effect (95% CI)	Quality of evidence (GRADE)
Particle Density (aerosol density, expressed as micrograms per cubic meter)	22 (2)	390.74	162.70–618.77	Low, due to risk of bias and inconsistency.
Total Particle Count (total number of particles, expressed as million per cubic meters)	72 (2)	6.08	3.05–9.11	Low, due to risk of bias and inconsistency.
Microbial Air Contamination (colony forming units per cubic meters)	175 (5)	9.44	2.4–16.49	Low, due to risk of bias and inconsistency.
Ratio of small to medium sized particles	163 (5)	37.4	25.89–48.87	Low, due to risk of bias and inconsistency.
Ratio of small to large sized particles	163 (5)	1604.4	1046.68–2162.07	Low, due to risk of bias and inconsistency.

CI: Confidence Interval.
GRADE Working Groups Grades of Evidence.[36]
High Quality: Further research is unlikely to change our confidence in the effect of the estimate.
Moderate Quality: Further research is likely to have an important impact on our confidence in the effect of the estimate and may change the estimate.
Low Quality: Further research is likely to have an important impact on our confidence in the effect of the estimate is likely to change the estimate.
Very Low Quality: We are very uncertain about the estimate.

Table 9
Salient findings of this study and their implications for orthopedic surgical procedures in COVID-19 patients.

SNo.	Finding	Implication(s)	What remedial measure(s) can be taken
1.	The pooled total particle count in an orthopaedics OR is 6×10^6 per cubic meters, which corresponds to a ISO Class 9 cleanroom.	Orthopedic ORs have high concentrations of bioaerosols.	Minimize aerosol generation at source. Consider particle filters.
2.	Aerosols in orthopaedics OR consist predominantly of small sized (0.3−0.5 μm or smaller) particles.	Small-sized particles remain suspended in air for longer periods and may be inhaled.	OR personnel should use N-95 respirators when operating on COVID-19 patients. Ensure adequate air-changes in between cases.
3.	Aerosols in the orthopaedics OR tend to spread widely and contaminate a wide area	The entire OR should be considered contaminated after each surgical procedure	Minimize non-essential items in the OR. Thorough disinfection of all OR surfaces should be done after each case.
4.	All OR personnel get contaminated by orthopedic aerosols. The surgeon and the assistant are contaminated the most during surgery; body is the most contaminated part.	All OR personnel should be considered contaminated after each surgical procedure.	PPE should be worn by all OR personnel. Well-established donning and doffing practices should be followed.
5.	Orthopedic aerosols contain variable amounts of blood.	There is a possibility of spread of blood-borne infections via the inhalational route.	Minimize bleeding. Consider use of tourniquet.
6.	Electrocautery produces high volumes of aerosols with very small sized particles.	Small-sized particles remain suspended in air for longer periods and may be inhaled.	Minimize cautery use. Use suction at source.

grey literature to avoid missing unpublished studies. We also assessed the risk of bias and summarized the available evidence by the GRADE approach.

However, there are a number of limitations of this study. We noted a high risk of bias for all the studies included in the review, which can be primarily attributed to weak study design. Furthermore, we noted that the outcome parameters reported were highly variable, we could include only a few studies in the pooled analysis of key variables such as total particle counts and microbial air contamination. A high degree of statistical heterogeneity was also noted in all pooled analyses; this can be attributed to the differences in study populations, variability of measurements of aerosol characteristics. Heterogeneity in ratios of particle sizes may also be attributed to the fact that data from the authors' individual measurements[40,42–44] was pooled into three broad categories. Finally, most of the evidence available is indirect, and high-quality studies on infective potential of orthopedic bioaerosols are missing. These limitations are reflected well in our GRADE assessment of the available evidence.

6. Conclusion

The available literature on bioaerosols in OSPs is sparse, and of low-quality. Whereas there is evidence to suggest that OSPs generate large amounts of bioaerosols, their potential to transmit infectious diseases like COVID-19 from patients to OR personnel is questionable. High-quality research, addressing key issues of study design as well as bioaerosol characteristics, is therefore warranted. Consensus guidelines on the minimum requirements for reporting of studies evaluating bioaerosols in OSPs will go a long in improving the quality of evidence.

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Contributions

SS and RJ conceptualized the review and designed the literature search. SS, RJ, MSD and DN formulated the protocol, including key objectives. SS performed the literature search. SP, DN and KK performed secondary searches. SS, RJ, SP and MSD performed data extraction. SS and KK performed statistical analysis, risk of bias assessment and grading of evidence. SS and RJ wrote the manuscript. MSD and SP edited the manuscript. SS created the artwork. All authors read and approved the final version of the manuscript.

Declaration of competing interest

None.

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None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jcot.2021.03.016.

Abbreviations

AGP	Aerosol Generating Procedure
CFU	Colony forming unit
COVID-19	Coronavirus Disease 2019
GRADE	Grading of Recommendations, Assessment, Development and Evaluation
HBV	Hepatitis B Virus
HCW	Healthcare Worker
HIV	Human Immunodeficiency Virus
ISO	International Organization for Standardization
MAC	Microbial Air Contamination
MERS	Middle East Respiratory Virus
OR	Operating room
OSP	Orthopedic Surgical Procedures
PPE	Personal Protective Equipment
SARS-CoV-2	Sudden Acute Respiratory Syndrome Coronavirus 2
TPC	Total Particle Count
VPC	Viable Particle Count

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