Institution: University of Bristol		
Unit of Assessment: 8) Chemistry		
Title of case study: Aerosol science informs global clinical and public health policy on COVID-19 transmission		
Period when the underpinning research was undertaken: 2000 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Jonathan Reid Bryan Bzdek	Professor of Physical Chemistry Lecturer in Physical Chemistry	03/2004 – present 08/2014 – present
Period when the claimed impact occurred: 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

In July 2020, 241 scientists in an open letter appealed "*to the medical community and to the relevant national and international bodies to recognize the potential for airborne spread of coronavirus disease 2019 (COVID-19).*" To establish this risk, better understanding of airborne transmission and measures of viral aerosol outputs during respiratory activities (speaking, singing, coughing), and importantly medical procedures, was urgent (and economically significant). In 2019, for instance, the West End had 15.3 million audience members and gross revenues of almost GBP800 million. Much of this economic and social activity was lost in early 2020 as the arts and performance sector was forced to close. University of Bristol (UoB) researchers with expertise in Aerosol Science rose to this pressing challenge. Starting work in early July, a team of physical scientists and clinicians developed a robust strategy to accurately measure the concentrations and particle size distributions of aerosols generated during respiratory and medical procedures. An intense six-month collaboration led to the generation of important data crucial for: (I) A public health re-assessment of the risk of medical procedures that generate aerosols, which in late 2020 has begun to inform best clinical practice both in the UK and worldwide. Aerosol generating procedures, which hitherto had been delayed, may soon be able to proceed safely; (II) The rigorous evidence needed for the UK government to re-open the performing arts sector.

2. Underpinning research

The UoB team, led by Prof. Jonathan Reid (JPR) and Dr. Bryan Bzdek (BRB), has over the last two decades pioneered a unique armoury of single-particle analytical tools in aerosol science. These novel techniques have revealed fundamental insights into the underlying physical and chemical processes that characterize *individual* aerosol particles and determine their stability. Scientific achievements, relevant to viral airborne transmission, have included:

- Clarification of the roles played by surfactants [1], and high molecular weight sugars and oligomers [2,3], on the surface and bulk transport kinetics of water loss from drying droplets.
- Development of a novel tool for studying the survival of airborne bacteria (*e.g.* Escherichia coli) and viruses (*e.g.* the mouse hepatitis virus) in small populations of aerosol particles at controlled relative humidity and temperature [4].
- Demonstration, using high time-resolution measurements, that the survival of airborne bacteria depends on aerosol droplet size, particle phase and drying kinetics [5].

This early research informed impacts detailed in Section 4 by developing an appreciation of: (a) the factors that govern the transport of respiratory aerosols and droplets in the environment; (b) the dynamics of water content, particle phase and size distribution of exhaled particles; and (c) the metrology challenges in identifying and measuring expired aerosol particles and droplets which are generated at very low concentrations, are dynamic in size, and contain pathogens.

Building on this science, the UoB team was uniquely positioned at the start of the pandemic to help the medical and public health communities understand the role of airborne transmission in COVID-19. Underpinning research at UoB led to the rapid development of a robust protocol [6], for directly measuring respirable aerosol particle concentrations and size distributions from human activities. Using these techniques, the team showed that [6]:

- Exhaled aerosol particles from a subject coughing (typically with the extremely low concentration of ~1 particle cm^{-3}) can only be directly and unambiguously identified above the ambient aerosol level if the environment is extremely clean ($\ll 0.01\,cm^{-3}$), typical of orthopaedic operating theatres.
- Aerosols from coughs, speaking and from the potential clinical aerosol generating procedures of intubation and extubation, range in size from 0.5 to $> 10\,\mu$m. A direct attribution of the aerosol to the clinical activity may be made from a tight correlation between detection and generation time.
- Aerosols generated from a voluntary cough provide an appropriate metric against which to compare other potential aerosol generating procedures, and thus to evaluate their infectious risk. For example, while tracheal intubation generates very little aerosol, extubation produces quantifiable aerosol but at a much lower concentration than a cough.
- Using the protocol developed, measurements of exhaled aerosols from professional performers (singers and players of wind instruments) were made. This analysis confirmed that singing produced similar concentrations of aerosols to speaking, at the same volume. In addition, aerosols generated by wind instruments were comparable in concentration to the performer's breathing [D1].

The research [6] *was widely read with Altmetric placing it in the top 5% of all articles published in any journal ever (ranked at 6,019 in over 16.6 million research outputs).* The article received over 1,712 tweets from 1,344 users (of which 18% were healthcare professionals), with an upper bound of 2,155,051 followers (25th Jan 2021) and was highlighted in media around the world [C1,C2].

3. References to the research

1. Davies JF, Miles REH, Haddrell AE, **Reid JP.** *Influence of organic films on the evaporation and condensation of water in aerosol*, Proc. Natl. Acad. Sci. USA. 2013; 110: 8807–12. doi:10.1073/pnas.1305277110
2. Marshall FH, Miles REH, Song Y-C, Ohm PB, Power RM, **Reid JP**, Dutcher, CS. *Diffusion and reactivity in ultraviscous aerosol and the correlation with particle viscosity*, Chem. Sci. 2015; 7: 1298–308. doi:10.1039/C5SC03223G
3. Song YC, Ingram S, Arbon RE, Topping DO, Glowacki DR, **Reid JP**. *Transient cavity dynamics and divergence from the Stokes-Einstein equation in organic aerosol*, Chem. Sci. 2020; 11: 2999–3006. doi:10.1039/c9sc06228a
4. Fernandez MO, Thomas RJ, Garton NJ, Hudson A, Haddrell A, **Reid JP**. *Assessing the airborne survival of bacteria in populations of aerosol droplets with a novel technology*, J. R. Soc. Interface. 2019; 16: 20180779. doi:10.1098/rsif.2018.0779

5. Otero Fernandez M, Thomas RJ, Oswin H, Haddrell AE, **Reid JP**. *Transformative approach to investigate the microphysical factors influencing the airborne transmission of pathogens*, Appl. Environ. Microbiol. 2020; 86: 1–13. doi:10.1128/aem.01543-20

6. Brown J, Gregson FKA, Shrimpton A, Cook TM**, Bzdek BR**, **Reid JP**, Pickering AE., *A quantitative evaluation of aerosol generation during tracheal intubation and extubation*, Anaesthesia. 2020; 1–8. doi:10.1111/anae.15292

Major grants

(a) **PI: JPR.** *Centre for Doctoral Training in Aerosol Science*, EPSRC, 2019, GBP6.8 million (A multi-institutional collaboration between the Universities of Bristol, Bath, Cambridge, Hertfordshire, Imperial, Leeds and Manchester supporting 80 PhD students recruited over 5 cohorts. The CDT is supported by a broad range of industrial and public sector partners with additional funding of GBP7 million).

(b) **PI: BRB.** *Comprehensive Investigations of Aerosol Droplet Surfaces and Their Climate Impacts*, ERC (Project 948498, AeroSurf), 2021, GBP2.1 million

(c) PI: Maskell N (Professor of Respiratory Medicine, North Bristol NHS Trust); **co-Is: JPR, BRB**. *AERosolisation And Transmission Of SARS-CoV-2 in Healthcare Settings (AERATOR),* Department of Health & Social Care/UKRI COVID-19 Rapid Response Grant, 2020, GBP433,000

(d) **PI: JPR; co-I: BRB.** *The Investigation of Particulate Respiratory Matter to Inform Guidance for the Safe Distancing of Performers in a COVID-19 Pandemic (PERFORM-2)*, UKRI/EPSRC COVID-19 Rapid Response Grant, 2020, GBP543,000

4. Details of the impact

The work at Bristol had three major impacts:

- Providing a robust measurement strategy to assess the risk of airborne viral transmission during clinical procedures.
- Changing government guidance for the performing arts sector on the risk of pathogen transmission by professional singers and wind instrumentalists.
- Creating public awareness of the transmission of COVID-19 during community singing.

Airborne transmission of COVID-19 in the health sector

At the start of the pandemic, a wide range of common clinical procedures were suspected to be aerosol generating, including anaesthesia (tracheal intubation and extubation), and respiratory interventions such as continuous positive airway pressure (CPAP). Clinical restrictions, to mitigate against aerosol and airborne spread of the coronavirus meant a major reduction, of about 50% [C1], in the UK's health sector capacity for surgical procedures.

UoB research in 2020 delivered a reliable basis to quantitatively assess the risks associated with these aerosol generating procedures (AGPs). Publication of our work [6], instigated a major debate, for instance, on the use of full airborne precaution PPE in operating theatres [A1]. The Editor-in-Chief of the journal Anaesthesia, while cautioning that additional measures were still needed for lung, ear, nose and throat surgery, argued that restrictions could potentially be relaxed for approximately 95% of all surgical operations. "*Other scientists will want to replicate this study, but if the findings are true, it will change policy and the way we conduct surgery completely*" [A1]. The vice-president of the Royal College of Anaesthetists welcomed the research and noted that "*If mask ventilation, tracheal intubation and extubation are not counted as aerosol generating procedures, it will save at least 20 minutes per operation on a patient who has or may have Covid-19". "With more than 3m anaesthetics normally being given for surgery every year in the NHS … I would think that this change might benefit tens of thousands of NHS patients in the next year."*

[C1]. This research is currently informing the UK's *National Institute of Health Research Task and Finish Group* policy on AGPs (of which JPR and BRB are both members) [B]. Future changes in clinical practise could contribute significantly "*to cutting the more than two million"* [C2] people waiting on the NHS list for planned care. There are implications for global healthcare. The Editor-in-Chief of the New England Journal of Medicine, commenting on the UoB study in October 2020 noted that "*because designating any procedure an AGP has profound implications for both healthcare practices and personal protective equipment use it seems highly appropriate, and cost effective for society, that similar quantitative analyses be undertaken to assess the relative risks associated with all procedures now designated as AGPs*" [A2].

Changing UK government policy and guidance for the performing arts sector

The arts play a significant economic and social role in the UK economy, contributing GBP7.1 billion to GVA in 2018 [E]. The sector was particularly badly affected by the pandemic, with over 80% of business closed compared to an average of 30% in other sectors [E]. To mitigate this, the Department of Digital, Culture, Media and Sport (DCMS) and Public Health England (PHE), funded research at UoB in June 2020, with the aim that *"This project would provide the evidence needed to allow us to open up the sector and allow a return to musical performances and sport with the positive benefits that will bring"* [E]. Extensive measurements of aerosol emissions from professional singers and wind instrumentalists were recorded. The PERFORM study was central in providing evidence [D1] to the UK government's Scientific Advisory Group for Emergencies (SAGE). SAGE endorsed the resulting public health guidelines and policy at their meeting on 13th August 2020 and recommended a return to musical performances and sport with the positive benefits that they bring [D2].

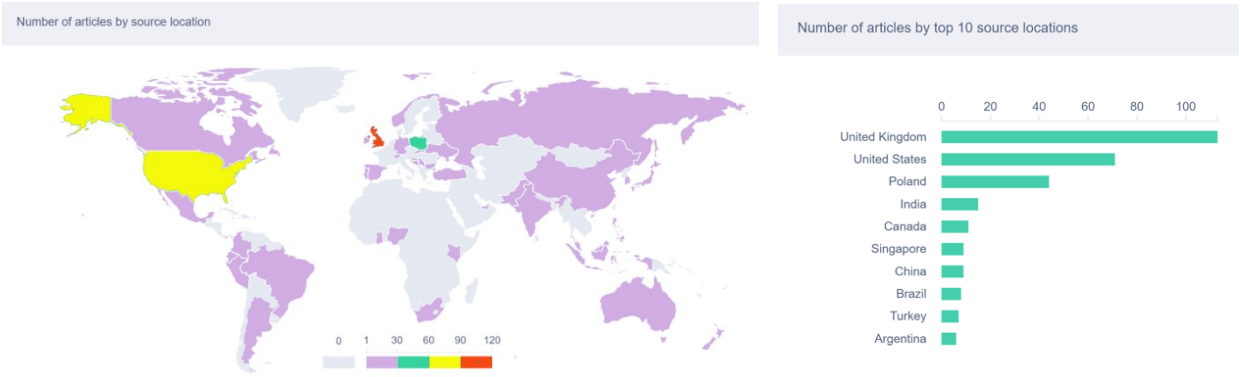

A BBC News film crew reporting on the PERFORM study, (July 2020).

The UoB work led to changes in UK government guidance for the performing arts, published on 14th August 2020 [F]. The Chief Scientific Advisor for DCMS said, "by showing that aerosol concentrations generated from singing are only marginally higher than from speaking at the same volume, and that the volume of the activity was the most crucial factor in influencing risk, PERFORM allowed us to develop guidance for performances allowed indoors and outdoors" [E]. Culture Secretary Oliver Dowden in August 2020 said: "*I know singing is an important passion and pastime for many people who I'm sure will join me in welcoming the findings of this important study. We have worked closely with medical experts throughout this crisis to develop our understanding of COVID-19, and we have now updated our guidance in light of these findings so people can get back to performing together safely.*" [G].

Creating global awareness of the risks of airborne transmission of COVID-19

The PERFORM study had consequences for other indoor settings, in the hospitality sector [F,H] and within faith communities. The UK Government's 'COVID-19: suggested principles of safer singing' published on 20 November 2020 [I], recommended singing only in well-ventilated spaces, at reduced volume or with microphones, with singers spaced two metres apart. Guidance for the hospitality sector limited the volume of music so that customers could talk without shouting or

becoming too close [F,H]. The work received widespread coverage both in the UK and around the world [J1]. JPR, BRB and other members of the project team were interviewed for National and local television (*e.g.* BBC National News, Sky News, CBS News, BBC Points West) and appeared in radio broadcasts (*e.g.* BBC Radio 4 Front Row, BBC Radio 3, PBS in the US, 15 local BBC radio stations). The results were reported widely in print media throughout the world (all UK national daily newspapers [J2,J3] and newspapers in USA [J4], Brazil, Japan, India, Australia, and Canada) and online (*e.g.* the BBC website). Altogether more than 389 articles appeared [J1-4] citing the work performed at UoB (as of October 2020), with an estimated global reach of 6.64 billion people (in excess of 80% of the global population).



Summary of the global media reports of the PERFORM study [J1].

5. Sources to corroborate the impact

[A] 1. Nestor et al, Anaesthesia, 76, 151-155, 2021 and #TheAnaesthesiaPodcasts - No 4, Oct. 2020 (downloaded over 500 times).
2. Ellison RT (Oct 2020). New England Journal of Medicine commentary: *Are Intubation and Extubation Aerosol-Generating Procedures?* and Twitter post (427 retweets and 600 likes).

[B] NIHR (2021). Supporting letter – Medical Director, NIHR Clinical Research Network and Chair, Clinical Research Network AGP Research Group

[C] 1. *Covid: unnecessary precautions causing NHS surgery backlog*, Guardian, 6th October 2020.
2. *New research paves way for cuts to surgery waiting lists*, Times, 7th October, 2020.

[D] 1. SWI Working Group (2020). Report: Aerosol and droplet generation from Singing, Wind Instruments (SWI) and performance activities.
2. 51st SAGE meeting minutes on COVID-19, 13th August 2020.

[E] Letter of support from Chief Scientific Advisor in Department for Digital, Culture, Media and Sport, 13th January 2021.

[F] Guidance change for the Performing arts, UK government, 14th August 2020.

[G] *Singing is no more risky than talking finds new COVID-19 study*, UoB press release, 20th August 2020.

[H] *Singing and dancing now illegal in pubs with landlords facing £10,000 fines*, Daily Telegraph, 29th September 2020.

[I] *COVID-19: suggested principles of safer singing*, UK government, 20th November 2020.

[J] 1. Mentions of Bristol work in world media (UoB Media office, January 2021).
2. *Coronavirus: Singing 'no more risky than talking'*, BBC News, 20th August 2020.
3. *Sing into the funnel please: inside the COVID-19 lab hoping to declare singing safe*, Guardian, 22 July 2020.
4. *Singing Is No More of a COVID-19 Risk Than Talking but Volume Matters, UK Study Finds*, New York Times, 20th August 2020.