Update:
Bioaerosol Emissions and Exposures in the Performing Arts: A Scientific Roadmap for a Safer Return from COVID19

NASM - 20 May 2021

John Volckens
Department of Mechanical Engineering
School of Biomedical Engineering
Colorado School of Public Health

Kristen Fedak, Dan Goble, Nick Good, Amy Kiesling, Christian L’Orange, Emily Morton, Rebecca Phillips, & Ky Tanner
Why don’t we have more answers here?

• For every 1,000 doctors that graduate from US medical schools, we see ~1 new PhD granted in aerosol science

• There are probably fewer than 5,000 aerosol PhDs actively working in the U.S.

• 80% of those PhDs work outside of academia

• Probably less than 5% study bioaerosols and public health

• Not everything you read on the internet is true…
Questions we hope to answer

1. What is the rate (and size) of bioaerosol emitted by performers of varying age and gender when engaging in music, voice, and dance?

2. How effective are active and passive control measures at reducing bioaerosol emissions and exposures?
   - isolation and distancing
   - room ventilation and filtration
   - use of homemade masks, respirators, shields or other barriers

3. Can the risks of co-exposure be reduced to “acceptable levels” using these active and passive controls?
Some Sizes and Sources of Airborne Particles

- Flour Dust
- Pollen
- Spray
- Smoke

Particle Size, µm

- Breathing
- Sneezing & Coughing
- Musical and Vocal Arts?
- Talking
Human bioaerosol spans a huge size range (and not all particles behave the same)

- 0.1 µm
- 1 µm
- 10 µm
- 100 µm

If this particle were the size of a baseball

Then this particle would be the size of a baseball stadium
Size of Bioaerosols from the Human Respiratory Tract

Proportion of particles

Aerosols

Large Respiratory Droplets
(reason for 6’ distancing rule)

Breathing

Laryngeal

Oral

Morawaska et al. https://doi.org/10.1016/j.jaerosci.2011.07.009
Breathing mode:
Wall collapse & film separation within compliant bronchioles

Kubáň et al. https://doi.org/10.1016/j.aca.2013.07.049
Breathing: Many Opportunities for Tube Collapse & Separation

<table>
<thead>
<tr>
<th>Generation</th>
<th>Number per generation</th>
<th>Diameter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1.8</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1.22</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>0.83</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>0.56</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>0.45</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
<td>0.35</td>
</tr>
<tr>
<td>6</td>
<td>64</td>
<td>0.28</td>
</tr>
<tr>
<td>7</td>
<td>128</td>
<td>0.23</td>
</tr>
<tr>
<td>8</td>
<td>256</td>
<td>0.186</td>
</tr>
<tr>
<td>9</td>
<td>512</td>
<td>0.154</td>
</tr>
<tr>
<td>10</td>
<td>1024</td>
<td>0.13</td>
</tr>
<tr>
<td>11</td>
<td>2048</td>
<td>0.109</td>
</tr>
<tr>
<td>12</td>
<td>4096</td>
<td>0.095</td>
</tr>
<tr>
<td>13</td>
<td>8192</td>
<td>0.082</td>
</tr>
<tr>
<td>14</td>
<td>16384</td>
<td>0.074</td>
</tr>
<tr>
<td>15</td>
<td>32768</td>
<td>0.066</td>
</tr>
<tr>
<td>16</td>
<td>65536</td>
<td>0.06</td>
</tr>
<tr>
<td>18</td>
<td>260,000</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Laryngeal mode:
Vibration (100-300 Hz) of your vocal cords sheds particles

Top view

Oral Mode:
Saliva from tongue & lip movement (large droplets)

Side view
(slow motion)

https://en.wikipedia.org/wiki/Vocal_cords
https://www.flickr.com/photos/mirsasha/26545332340/
Mask Testing Results
CSU Mask and Respirator Testing Program

- Shortage of N95 respirators for healthcare workers across Colorado
- Supply of domestic and international respirators of unknown quality / performance
- On March 25th, Colorado Governor Jared Polis asked our lab to provide respirator testing & performance verification for State of Colorado COVID-19 Task Force
N95 means >95% removal efficiency for particles that flow into the mask.

CSU testing program follows modified* NIOSH protocol for particle collection and “breathability”

“Looks” can be deceiving!

Only CDC/NIOSH can certify masks to bear the “N95” label.

PASS  PASS  FAIL  FAIL

* https://www.cdc.gov/niosh/nptl/respirators/testing/default.html
Anonymous Donor:

“Please test these 24 different masks, each made with popular mask material, and make the data publicly available”

N95s are great if you can get them - they are hard to find - so what about cloth masks?
Most N95 masks remove ~99% of all particle sizes
(provided they don’t leak air around the edges!)
What about “Singer’s Masks”?

http://jv.colostate.edu/masktesting/

Cloth Mask Performance

Want to learn more? Watch our free webinar on mask design  https://col.st/Wq2Bu
Mask efficacy is determined by four primary factors:

1. **Fit**
   - Does the air flow through the mask or around the mask?

2. **Filtration**
   - How efficient is the mask at removing particles that flow though it?

3. **Breathability**
   - How easy is it to draw air through the mask?

4. **Compliance**
   - Are you doing what was asked of you?
Protection Factor (PF) = \frac{\text{Mass of aerosol flowing towards the mask}}{\text{Mass of aerosol that gets past the mask}} = \frac{\dot{M}_{\text{in}}}{\dot{M}_{\text{out}}}

\int \left[ \text{Aerosol} \times \text{Large Respiratory Droplets (historical 6' distancing rule)} \right] \times f(\text{behavior})
Protection Factor tells you: “By how much is your exposure (or your release of aerosol) reduced from wearing this mask”?

Leith et al. https://doi.org/10.1021/acs.est.0c07291
Real-World: Vary the key factors that control Protection Factor

These results account for variation in breathing rates, mask leakage (fit), time spent talking, etc.
Reducing Bioaerosol Emissions and Exposures in the Performing Arts: A Scientific Roadmap for a Safer Return from COVID19
Take Home Messages

• You were right to apply the precautionary principle in 2020 and that choice saved lives.

• Brass instruments emit more aerosol than woodwinds.

• Singing emits more aerosol than speaking.

• Men emit more aerosol than women.
  • This difference can be explained by physiology.

• Adults emit more aerosol than children.
  • This difference can also be explained by physiology.

• Masks and bell covers help…when used appropriately.

• In the absence of “herd immunity” a layered strategy will be needed.
Experimental Design

• 100 volunteers over 3.9 months (~2/day)
  • Open to ages 12 and up; all genders
  • ~28 singers, actors, dancers
  • ~72 instrumentalists: bassoon, clarinet, euphonium, flute, oboe, piccolo, saxophone, French horn, trombone, trumpet & tuba

• Everybody speaks, sings and “does their thing”
  • With and without control technologies in place
    • Masks, bell covers, and screens to be tested
    • “BYOM” approach to testing

• Particle sizes from 0.01 to 100 micrometers
Cameron Peak Fire: August 13 – December 1, 2020

Photo credits: CSU SOURCE, Erik Hardy
SET Facility: A Musical Class 100 Cleanroom
SET Facility: A Musical Class 100 Cleanroom
Lower (~100 counts)

Highest (2,500+)

Higher (~500)

below
background

none_no_free
none_yes_break
saxophone_no_free
saxophone_no_scales
saxophone_yes_nine
voice_no_happy_birthday
voice_no_passage
voice_yes_happy_birthday
voice_yes_passage
<table>
<thead>
<tr>
<th>Participants (n)</th>
<th>Age Range (years)</th>
<th>Female [male] (n)</th>
<th>Minor [adult] (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>12-63</td>
<td>42 [45]</td>
<td>40 [50]</td>
</tr>
</tbody>
</table>
Instrument Results
(particles 0.3 - 30 µm)
Instrument Emissions (particles 0.3 - 30 µm)

Relative Particle Emissions

- highest
- higher
- lower
- below background
Instrument Emissions (particles 0.3 - 30 \(\mu m\))

Relative Particle Emissions

- highest
- higher
- lower
- below background
Instrument Emissions (particles 0.3 - 30 µm)

Woodwinds ← Brass

Relative Particle Emissions

- highest
- higher
- lower
- below background

Vocal emissions

- bassoon
- flute
- clarinet
- oboe
- piccolo
- saxophone
- french horn
- talking
- happy birthday
- singing
- tuba
- trumpet
- trombone
To Bell Cover or Not to Bell Cover?

A steep line means a stronger effect (this one is about a 70% reduction in emissions). A flat line means no effect seen.

No bell cover using a bell cover

Higher emissions

Lower emissions
To Bell Cover or Not to Bell Cover?

**Woodwinds**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>FALSE</th>
<th>TRUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>bassoon</td>
<td>31%</td>
<td></td>
</tr>
<tr>
<td>clarinet</td>
<td>28%</td>
<td></td>
</tr>
<tr>
<td>oboe</td>
<td>18%</td>
<td></td>
</tr>
</tbody>
</table>

**Brass**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>FALSE</th>
<th>TRUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>saxophone</td>
<td>35%</td>
<td></td>
</tr>
<tr>
<td>trombone</td>
<td>76%</td>
<td></td>
</tr>
<tr>
<td>trumpet</td>
<td>56%</td>
<td></td>
</tr>
</tbody>
</table>

*Higher emissions*

*Lower emissions*
• Results suggest that brass instruments tend to have higher particle emissions than woodwinds…
  BUT the “player effect” is likely larger than the “instrument effect”…
  Meaning that almost ALL instruments have the potential for high emissions.
• Bell covers on brass instruments (single air exit) make sense.
• Bell covers on woodwinds (multiple exit paths for air besides the bell) show mixed results.
Vocal Results

(particles 0.3 - 30 μm)
Note: We “see” lots of big droplets emitted from voice, instruments, too.
Singing *happy birthday* tends to produce more particles than talking *(The Caterpillar)*

https://doi.org/10.1044/1058-0360(2012/11-0134)
Singing *(happy birthday)* tends to produce more particles than **talking** *(The Caterpillar)*.
Adults tend to produce more particles than minors (18 and under)
Men tend to produce more particles than women.
The differences in bioaerosol emissions between men & women and minors & adults are explained by two factors: voice volume and lung capacity.
Particle emissions are correlated with voice volume
Adults (& men) tend to speak, sing louder than minors (& women)
Men tend to have larger lungs (and thus exhale more air) than women.
If we account for voice volume and exhaled $\text{CO}_2$ in our models of vocal emissions, then the differences between men & women and adults & minors become negligible.

This means that monitoring volume and CO$_2$ levels indoors will provide a decent indicator of exposure risk for infectious aerosol.

- Ventilation, masking, distancing will remain part of the “layered” approach for risk reduction
- Vaccination $>>$ all these interventions
Closing thoughts

1. Our data collection is complete; we continue to study our results and plan to publish these data (open access) this Summer.

2. We still do not know (as a scientific community) how many COVID19 virions it takes to produce an infection in humans.
   • This is not really a single number. It likely varies with the mode of transmission, your genetics, health status, etc.
   • Until we have a better idea of this number (and the proportion of particles that carry active virus), we cannot define your absolute risk.

3. Although we cannot define absolute risk, we can define relative risk. Look for continued guidance from our group and others in the coming months.
   • Absolute risk: In this setting, you have a 25% chance of becoming infected
   • Relative risk: If you do this, you can lower your chance of infection by 50%

4. Get vaccinated!
Thank you to those who made this work possible!

Major Supporters:
Yamaha Corporation
United States Institute for Theatre Technology (USITT)

Lead Supporters:
American Bandmasters Association Foundation
American Choral Directors Association
American Guild of Musical Artists (AGMA)
Auburn University
Big Ten Band Directors Foundation
CSU School of Music, Theatre, and Dance
Mill City Church
National Association of Teachers of Singing
National Band Association
University of Kentucky
Wenger Corporation

Supporters:
Association of Concert Bands
Community Foundation of Northern Colorado
Conn-Selmer Corporation
Diana Anderson
Gayle Treber
O'ahu Band Directors Association
Texas A&M University Bands
Women Band Directors International Foundation

Valued Donors:

Advisory Board:
Dan Goble, CSU
Allen Henderson, Ga Southern
Emily Morgan, CSU
Rebecca Phillips, CSU
Heather Pidcoke, CSU
Timothy Rhea, TAMU