Effects of surgical masks on aerosol dispersion in professional singing

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BACKGROUND: In the CoVID-19 pandemic, singing came into focus as a high-risk activity for the infection with airborne viruses and was therefore forbidden by many governmental administrations.

OBJECTIVE: The aim of this study is to investigate the effectiveness of surgical masks regarding the spatial and temporal dispersion of aerosol and droplets during professional singing.

METHODS: Ten professional singers performed a passage of the Ludwig van Beethoven’s “Ode of Joy” in two experimental setups — each with and without surgical masks. First, they sang with previously inhaled vapor of e-cigarettes. The emitted cloud was recorded by three cameras to measure its dispersion dynamics. Secondly, the naturally expelled larger droplets were illuminated by a laser light sheet and recorded by a high-speed camera.

RESULTS: The exhaled vapor aerosols were decelerated and deflected by the mask and stayed in the singer’s near-field around and above their heads. In contrast, without mask, the aerosols spread widely reaching distances up to 1.3 m. The larger droplets were reduced by up to 86% with a surgical mask worn.

SIGNIFICANCE: The study shows that surgical masks display an effective tool to reduce the range of aerosol dispersion during singing. In combination with an appropriate aeration strategy for aerosol removal, choir singers could be positioned in a more compact assembly without contaminating neighboring singers all singers.

Keywords: Aerosol dispersion; Choir singing; Surgical mask; Airborne virus transmission; SARC-CoV-2 pandemic

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INTRODUCTION

Person-to-person transmission of CoVID-19 mainly proceeds by direct contact or transmission of droplets with diameters ≥5 μm and smaller aerosol particles with diameters ≤5 μm within a range of 0.001–500 μm [1] within a range of 0.001–500 μm [2, 3]. Whereas virus-laden droplets are only received when a person is in close proximity to the emitter, aerosol particles remain hovering in the air and convectively spread in the environment distributing within large regions and rooms. Therefore, the infection with SARSCoV-2 can potentially take place via reception of expelled droplets and aerosol particles from an infected person, or by inhalation of accumulated aerosol particles in closed rooms without appropriate ventilation.

According to the super-emitter theory [4], the expulsion of a much larger amount of droplets and aerosol particles owing to exhalation activities such as extensive and loud speaking, singing, sneezing, or coughing poses the highest risk for CoVID-19 transmission. Especially singing turned out to be a high-risk activity for aerosol and droplet production [5–7] resulting in fatal infectious events during choir singing as documented in Amsterdam, Berlin, and Skagit Country (WA, USA) [8–10].

Speaking is thought to produce about three times the absolute amount of aerosol compared to breathing [11] and the particle emission rate during different spoken text passages increases for phrases that include a higher number of vowels [12]. Singing with its exaggerated articulation, as defined by the sustained vocalization of a vowel, is associated with a much higher rate of aerosol emission, showing ten times higher values than breathing and about three times higher values than speaking [11]. Furthermore, the exaggerated articulation produces a larger amount of ballistic droplets. In recent studies, an even higher production of aerosol was observed with a 4 to 100 times greater amount produced by singing compared to speaking [13–15]. Thereby, the directly expelled aerosol cloud has the highest density of potentially virus-laden aerosol particles and ballistic droplets constituting a high risk of infection for people staying in that region. This region is located directly in front of the singer up to a distance of 1.5 m to
As a consequence, in scientific and administrative evaluations, singing has become associated with a much higher risk for person-to-person transmission of infectious diseases, such as CoVID-19. Consequently, in certain countries across the globe, singing in choirs and at religious services was restricted or prohibited [17, 18] because especially in choirs, the singers stay in close proximity to each other which is essential for the quality of the performance.

Beside social distancing, wearing masks and face shields are the most effective arrangements to lower the risk of airborne transmission of viruses such as Influenza, SARS-CoV, MERS-CoV, and SARS-CoV-2 [19, 20]. In fact, aerosol particles and ballistic droplets were found to be reduced if the emitter wore a mask [21] and overall transmission could further be reduced if both the emitter and receiver wore masks [22] especially for surgical and KN95 mask types. However, leaks at the cheeks and nose bridge were found in experimental [23, 24] as well as in numerical studies [25, 26] through which especially aerosol particles escape with the leakage flow. In contrast, the droplets with ballistic behavior especially those generated by coughing and sneezing are effectively filtered out [27] as long as the face mask is composed of three layers as common medical masks (surgical, N95, KN95) [28].

With regard to droplets, the distance from the mouth depends on many factors, such as loudness [29, 30] or the type of activity such as just vocalizing or speaking especially by articulating consonants. For coughing, droplets have been detected at distances up to 8 m from the mouth [29]. After being expelled, these droplets follow ballistic trajectories and descend to the ground quickly [30–32]. For the investigation of the dispersion of expelled aerosol particles and droplets, qualitative, and quantitative flow visualization techniques as smoke visualization with bright light or laser light-sheet illumination, Particle Image Velocimetry [33] (PIV, with derivates as Particle Tracking Velocimetry) or Schlieren visualization [34, 35] have been applied using mostly manikin models [36, 37] or single human subjects [38, 39].

Although singing turned out to be highly critical [5–7], the respiratory activities that were mainly studied are breathing, coughing, sneezing, and speaking. Furthermore, the distances reached by the aerosol particles and droplets were only measured in the main expulsion direction [23, 39] without taking into account all three spatial directions.

Thus, the aim of this study is to analyze the spatial and temporal dispersion of aerosol particles during professional singing with a surgical mask in comparison with singing without masks. In a second experiment, we detected ballistic droplets in front of the singer with and without mask to prove the filtering efficiency. The experiments were performed in a studio of the Bayerischer Rundfunk (BR: Bavarian public-service radio and television broadcaster) with ten professional singers of the BR choir (five males and five females) serving as subjects. With the study, we contribute data to answer the question were the region with the highest aerosol concentration is localized and whether and how a surgical mask influences the dispersion of expelled aerosol particles and the ballistic droplet during professional singing.

The goal is how the application of these masks could contribute to develop strategies to maintain and support choir rehearsals and performances during an airborne spreading virus pandemic as CoVID-19.

**METHODS**

After approval from the local ethics committee (20–395), ten professional full-time singers from the BR Choir, all nonsmokers and without pulmonary symptoms, were included in the study (five female, five male, age 44 ± 11 years). All subjects practice western classical singing and had completed their vocal studies at music conservatories. No subject complained of dysphonia: normal values (mean 2 ± 3) were obtained for a German version of the singing-voice-handicap-index-12 [40].

**Singing tasks**

All subjects were asked to perform a part of the melody from the fourth movement “Ode of Joy” of Ludwig van Beethoven’s 9th symphony to the original text, Freude schöner Götterfunken, Tochter aus Elysium” written by Friedrich Schiller, in the key of D major, thus starting on F#3 for the male (fundamental frequency \( f_0 \approx 185 \text{ Hz} \)) and F#4 (\( f_0 \approx 370 \text{ Hz} \)) for female voices, respectively. The duration of singing task lasted approximately 6–10 s depending on the individual speed of the single singer. In a second task, the singers were asked to perform the task again while wearing a standard surgical mask. During the experiments, the singers were frequently encouraged to drink water in a comfortable amount.

**Aerosol measurement**

All aerosol measurements were performed in a studio of the BR with the approximate dimensions: 27 m × 22 m × 9 m (width × length × height). The singer stood on a lifting platform to lift them to the correct height. A mark at the singer’s forehead was used as a point of reference to adjust the height of the platform to the singer’s height. The platform was shifted 5 m to the left of the platform. To the right and in front of the platform, the walls were more than 7 m away. Three measuring rods for each spatial direction were mounted onto the lifting platform to convert the pixel dimension of the recorded pictures into metric dimensions. The rods were assembled in a cross configuration and had a 0.02 m and 0.1 m scale, respectively. A picture of the setup is shown in Gantner et al. [41].

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Droplet particle detection and tracking

The laser-illuminated particles were tracked by an in-house software tool written in Python. In a first step, all particles were detected in each frame based on a grayscale threshold method. In a second step, tracking was initialized by assigning an identity marker to all particles in a frame. For each particle, a distance matrix was calculated to allocate those particles in the consecutive frame that have a distance of maximum 50 pixels. Subsequently, a deviation score was calculated for each allocated particle based on parameters as particle size, direction of motion and velocity. The particle with the lowest deviation score is then assigned as being identical with the particle of the preceding frame. Furthermore, this algorithm also allows a temporarily disappearance of particles if particles are moving in the boundary regions of the laser light sheet with lower laser intensity.

Owing to the environmental conditions in the television studio, the air was not free from dust particles which were also illuminated by the laser light sheet. Thus, a post-processing step of the identified particle data was performed to exclude those particles that did not originated from the singer. The following rules were defined to identify potential dust particles that hover in the air not originating from the singer’s respiratory tract:

- The particles have to occur in at least 11 frames.
- The particles have to move at least 1 pixel between the first and last frame of occurrence.
- The mean velocity of a particle has to be at least 2 pixels per frame.

The post-processing was performed in Matlab (The MathWorks Inc., Natick, MA, USA) and the statistics in IBM SPSS version 24 (IBM, Armonk, NY, USA).

RESULTS

Aerosol cloud visualization

Figure 3 exemplarily shows two singers who emitted the inhaled aerosol cloud during singing with and without surgical masks (see bright skin of the singer’s face, neck, and arms. Those outliers were removed by a moving median filter with a fixed window length of 30 time points and subsequent cubic spline approximation performed in Matlab (The MathWorks Inc., Natick, MA, USA). More details about the post-processing procedure are shown in Westphalen et al. [47].

Segmentation of aerosol cloud

A coordinate system was defined to segment the video footage in three directions with the origin at singer’s mouth with x-direction to the front, y-direction transversely from the left to the right, and z-direction vertically from the bottom to the top, as shown in Fig. 2. To evaluate the temporal evolution of the exhaled vapor, the video footage of cameras 1 and 3 was converted into grayscale and the singer was covered with a black mask to avoid the segmentation of bright features such as skin or hair. The aerosol cloud was then segmented in each video frame which was performed with an in-house software tool using a threshold-based region-growing algorithm yielding the area of the cloud and its contour as a function of time. The dimensions of the ROI are $\text{ROI}_x \times \text{ROI}_y \times \text{ROI}_z = 260 \text{ cm} \times 270 \text{ cm} \times 180 \text{ cm}$ for camera 1 and $190 \text{ cm} \times 270 \text{ cm} \times 180 \text{ cm}$ for camera 3. Based on the cloud contour, the maximum dimensions of the cloud ($d_x, d_y, d_z$) as indicated in Fig. 2 in each frame were computed. Thus, the $d_x$ and $d_z$ dimension were calculated from side view (camera 1) and $d_y$ from top view (camera 3).

Based on the segmented aerosol cloud, its dispersion was computed in each spatial direction. Several outliers occurred when non-vapor regions were segmented if the cloud reached a region with similar grayscale value as e.g., the white sectors of the measuring rods or remaining areas of

Fig. 1 Principle of the droplet visualization with a laser light sheet placed in front of the singer. The particles were recorded by a highspeed camera within the region of interest (ROI).

Fig. 2 Pictures of camera 1 (top) and camera 3 (bottom) views with the defined coordinate system. Based on the segmentation of the cloud, its maximum dimensions $d_x$, $d_y$, and $d_z$ were computed in each frame.
all singers in Supplementary Figs. 1, 2). During singing without mask, the aerosol cloud is majorly expelled into the region in front of the singer with a forward-downward direction of motion. In contrast with a mask, the cloud is located around the singer's head extended in majorly upward (see side view) and both transverse directions as shown in front and top view at the end of the task. The reason for the different dispersion pattern is that the aerosol cloud escaped through mask leakages at the cheeks and the nose as Fig. 3 shows. As a result, the cloud extent in x-direction is reduced compared to singing without mask.

Temporal devolution of aerosol cloud dispersion

After the segmentation of the aerosol cloud in the video footage, the temporal devolution of the cloud dispersion was determined in x- (to the front), y- (transversely to the sides), and z-direction (vertically upright) according to the coordinate system shown in Fig. 2. The quantitative dimensions of the aerosol cloud in all directions are shown for the time point 0 s (end of task) and 10 s after the end of task in Table 1.

In the top row of Fig. 4, the temporal aerosol cloud dispersion to the front $d_x$ is shown for all singers with and without surgical mask. The median devolution indicates the median cloud expansion over all singers at every time point. The singers’ individual curves reveal a smaller expansion of aerosol cloud to the front $d_x$ when the singers wore a mask. This is also shown by the two median curves representing the two tasks. Moreover, the further expansion of the cloud at the time point 10 s after the end of task is also smaller if a mask was worn. However, there are large individual differences between the individual singers in both tasks. Even two singers reached a maximum distance to the front with masks that is slightly smaller than the median distance for singing without mask at the end of task. In the further progress at 10 s after the end of task, there is a slight increase in median $d_x$ for both tasks as shown in Table 1.

Regarding the transverse direction to the sides, the diameter of the cloud $d_y$ was found to be larger with mask at the end of task as depicted in Fig. 4 middle row. Note here, that the diameter $d_y$ is the difference between the upper (red curves) and the lower margin (black curves) for each individual singer. In the further progression to time point 10 s after the end of task, the diameter $d_y$ almost doubled for the task with the mask worn, whereas without mask, the diameter only slightly increased as shown in Table 1.

Another trend could be observed for the cloud expansion in vertical upright (z-) direction as shown in Fig. 4 bottom row. In contrast to the transverse direction, the cloud diameter in vertical upright direction $d_z$ decreases as shown in Table 1 if a mask was worn. Furthermore, the cloud moved in upward direction reaching higher levels up to $z = 1$ m above the singer’s mouth compared to $z = 0.77$ m for singing without mask. Similar to the further progression to the front $d_x$, only a slight increase in median $d_z$ occurred for singing with and without mask.

For all three directions, there are individual devolutions which decrease in distance after the corresponding singer has stopped singing without mask.

Table 1. Expansion of the aerosol cloud at (a) time point 0 s (end of task) and (b) time point 10 s after according to the spatial dimensions introduced in Fig. 2.

| Time point | $d_x$/m | $d_y$/m | $d_z$/m |
|------------|---------|---------|---------|
| t = 0 s    | Median  | Min     | Max     | Median  | Min     | Max     | Median  | Min     | Max     |
| Without mask | 0.85    | 0.63    | 1.28    | 0.66    | 1.12    | 1.06    | 0.83    | 1.29    |
| With mask  | 0.37    | 0.15    | 0.78    | 1.24    | 1.69    | 0.69    | 0.43    | 1.08    |
| t = 10 s   | Median  | Min     | Max     | Median  | Min     | Max     | Median  | Min     | Max     |
| Without mask | 1.11    | 0.61    | 1.39    | 1.20    | 0.65    | 1.98    | 1.21    | 0.91    | 1.38    |
| With mask  | 0.43    | 0.00    | 1.06    | 1.45    | 0.05    | 1.82    | 0.91    | 0.005   | 1.53    |

The dimensions correspond to the diameter of the aerosol cloud in the basic direction introduced in Fig. 2: $d_x$ axial diameter to the front (x-direction), $d_y$ transverse diameter to the sides (y-direction), and $d_z$ vertical diameter in upright (z-)direction. All dimensions in m.
singing at time point 0, as shown in Fig. 4. This decrease is caused by vanishing of the vapor at the borders of the cloud due to dilution and evaporation. As the visibility of the vapor cloud is a function of the density of aerosol particles, the decrease in distance caused an uncertainty in the exact location of the border. However, during the relevant period of active singing until time point 0, this uncertainty is estimated to be small owing to the high contrast between cloud and no cloud regions.

Droplet particle expulsion

In a second experiment, the ballistic droplets were detected within a laser light sheet and subsequently tracked in the region in front of the singer’s head. It has to be mentioned here that although potential dust particles were excluded from the analysis of the high-speed video footage as described above, it cannot be guaranteed that dust particles were completely excluded. Thus, the results show the relative difference of counted particles between the singing task with and without mask.

Figure 5 shows the total number of droplets tracked (left diagram) and the number of those particles which moved exclusively to the front (right diagram). The total number of droplets was found to be significantly reduced by on average 47% for singing with a mask in comparison to singing without mask (Wilcoxon rank test \( z = -2.497, p = 0.013, n = 10 \)). Furthermore, the number of particles fluctuated for both singing cases, especially for the task singing with mask with singer #4 even more particles than singing without mask. If considering only particles which were emitted through the mouth and therefore assuming that they moved to the front away from the singer, the reduction of particles for singing with mask even significantly increased on average to 86% (Wilcoxon rank test \( z = -2.803, p = 0.005, n = 10 \)). Furthermore, the number of particles less fluctuates and for eight of the ten singers the number was <100 particles. Again for singing without mask, the fluctuation of the number of particles that only moved to the front (in positive \( x \) direction) is much larger.

DISCUSSION

The aerosol particles and ballistic droplets are mostly generated during breathing, talking, coughing and sneezing [11, 48]. Thereby, coughing and vocalization produce a much higher amount of particles than breathing [11]. Recently, several studies additional
analyzed the aerosol particle generation during the sustained phonation or singing [13–15, 49] and found an enhancement of aerosol production by the 3-fold to 300-fold compared to breathing. As consequence, the aerosol particles and droplet expulsion during singing states a high risk to transmit airborne viruses and resulted in several outbreaks of CoVID-19 worldwide [8–10]. All these studies measured the particle count or concentration and did not account for the local distribution of the aerosol particles around the emitter. However, for choir singing this information is critical to define the distances between the singers and between the choir and the audience. Echtenerach et al. [16] showed that the expelled and highly concentrated aerosol clouds are able to reach distances up to 1.3 m achieved by professional singers. Thus, face masks play an important role not only in relation of their filtering properties but also with regard to their ability to decelerate and deflect the primarily expelled aerosol cloud as previously shown for coughing [50]. The number of studies about the effectiveness of face masks increased since the COVID-19 pandemic has started in late 2019 [20, 51]. These studies show, that face masks are an effective tool to disturb the transmission of an airborne virus by aerosol particles (size 0.1–10 μm) and larger droplets (size ≥10 μm). The number of transmitted viruses could be reduced by 50 and 90% depending on the type of face masks and who is wearing the mask, the emitter and/or the receiver [22].

In our experiments with a laser sheet technique, the amount of tracked droplets was reduced by 47% in this ROI if the singer wore a surgical mask. Especially the reduction of droplets moving in the ejection direction was reduced by 86% on average. Those droplets behave as ballistic particles mainly in the ejection direction and the gravity force [27, 33, 52]. Similar reduction values were observed for surgical masks for the entire size range of particles (aerosol particles and droplets) [12, 53, 54] although these studies only investigated breathing, speaking and coughing.

Kolewe et al. [53] confirmed in general the effective filtering capabilities of masks. However, they also found a large portion of the expelled particles escaped through leakages at the sides (cheeks) being not filtered out by the mask.

These leakages are critical for the smaller aerosol particles which possess a diameter in the range of 0.3–10.0 μm [5, 6, 37] and thus, hover and follow the air flow in the environment. Similar observations were reported for breathing, coughing and sneezing by using human subjects [24, 33, 50], manikin model [22, 23, 39, 53] or CFD models [26]. Furthermore, leakages were also found for KN95 or N95 masks [25, 42, 55, 56]. Especially in closed rooms without effective ventilation, exhaled aerosol particles can accumulate and develop a critical concentration if single persons are infected.

In this context, our measurements showed that surgical masks reduce the primary momentum and deflect the direction of expulsion as similarly reported for coughing [50]. Thus, at the end of the singing task, the aerosol particles were mainly located in the near-field above and around the singer’s head. In contrast, singing without mask produces an aerosol cloud spreading in front of the singer with far higher distances. Furthermore, the aerosol particles are shifted majorly to higher regions around and above the head with a median distance of ~0.5 m in all directions. This basic principle seems to also hold for other types of masks (community, silk cloth scarfs, FFP2) as Westphalen et al. [47] showed in single subject experiments. Additionally, the aerosol particles being in this near field of the emitter showed a tendency to move further upwards owing to the thermic convection flow due to the in general higher temperature of the emitting person compared to the environmental temperature [36, 57].

In large meeting rooms or e.g., concert halls which are critical regarding infectious scenarios, this condition of the thermal upward drift of the aerosol [36] becomes important because those rooms are mostly equipped with air conditioning and ventilation systems. The ventilation outlets are commonly placed at the ceiling to remove the used air with a high concentration of CO₂ generating a vertical upward flow direction of the expelled aerosol.

The typical surgical mask is not optimized for professional singing. Whereas the usage of surgical masks and typical community masks constitutes an option for layman singers and choirs, the masks might become less effective and hindering due to the exaggerated articulation in professional singing. Hence, special masks for singing should enable large movements of the mouth without increased leakage openings by possibly less influencing the acoustic signal.

**Limitations**

The aerosol cloud consisted of the vapor generated from the basic liquid of e-cigarettes. In contrast to the naturally generated and emitted aerosol particles, the vapor consists of a much larger amount of aerosol particles and is, thus, visible. As the contour of the cloud was determined with a threshold-based segmentation algorithm, the exact dimensions of the cloud rely on the intensity of the illumination of the particles and the accuracy of the light-sensitive sensor in the camera. As a consequence, this visualization technique does not allow the detection of aerosol particles in regions where the cloud vanished due to evaporation and/or dilution. For this purpose, other measuring techniques based on particle counting [5–7] have to be applied which, however, deliver the particle count and size only at specific point in the room and thus are not applicable to acquire the spatial and temporal dynamics of an aerosol cloud.

Another limitation of this study is the restricted reproducibility owing to the human singer subjects with their individual expulsion flow characteristics and the unforeseeable nature of...
unconfined flows. Although the measurements were performed with 10 singers under a strict measuring procedure as described above, differences of the singers’ individual expulsion characteristics cannot be excluded.

In the second experiment, only the relative droplet reduction could be evaluated because the measurements were also performed in the television studies that did not provide a filtering system for the environmental air. Thus, as we mentioned above, dust particles in the air were also recorded which did not originate from the singer’s respiratory tract. As only droplets could be detected and tracked, that were illuminated by the thin laser light sheet in front of the singer’s head, it also cannot be excluded that some droplets escaped through the leakages of the masks or moved outside the laser sheet. Thus, the presented numbers do not present the total number of expelled particles but are rather an indicator for the mask filtration ability by comparing the task with and without mask.

Furthermore, although the setup for droplet detection allowed to detect droplets down to a size of 10 μm, the size of droplets being smaller than the pixel resolution of 60 μm/pixel, could not be determined.

SUMMARY AND CONCLUSIONS
In this work, the effects of surgical masks were investigated during professional classical singing with the focus on the droplet and aerosol particle expulsion originating from the respiratory tract. Two different experiments were performed with ten professional singers of the BR choir who sang the “Ode of Joy” of Ludwig van Beethoven’s 9th symphony with and without a surgical mask. In the first experiment, the singers inhaled the vapor of e-cigarettes that consists of aerosol particles before they started to sing. The analysis of the video footage showed that the aerosols escaped from the mask through leakages at the cheeks and the nose. However, the aerosols stayed in the singer’s near-field around and above the head in contrast to singing without mask for which the aerosol cloud spread far in front of the singer with distances of over 1 m. Thus, the masks kept the aerosol particles near the emitter and deviated the aerosol cloud in larger heights above the singer being less critical to be inhaled by other persons. However, this effect is useless without an effective ventilation concept or an automated ventilation system as the aerosols remain still in the environment becoming especially critical in closed rooms after a certain time period.

In the second experiment, the ballistic droplets were detected within a laser light sheet that was located in front of the singer with the ROI immediately at the singer’s mouth. The particles were recorded by a high-speed camera and subsequently detected and counted for the two tasks of singing with and without mask. For singing with mask, the number of droplets largely decreased. Assuming that those droplets were kept by surgical masks, they were prevented from spreading in large distances from in front of the emitter.

As conclusion, the surgical mask is an effective tool to reduce the emission of potentially virus-laden particles over large distances with the potential risk to infect other singers or the audience. However, surgical masks are not optimized for singing as they are too small to tightly cover the singer’s mouth owing to his/her excessive articulation typical for professional singing. Nevertheless, these masks will certainly be an option in layman singing, e.g., in churches and layman choirs.

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AUTHOR CONTRIBUTIONS

SK: study concept, principal investigator, and paper writing; PS: methodology and data analysis particle tracking; GP: data analysis video segmentation; CW: performing video segmentation; BJ: particle tracking and statistics; RV: data analysis video segmentation; AMK: methodology particle tracking; MD: validation statistics particle tracking; SG: performing video segmentation; LK: performing video segmentation; TB: study concept, interpretation; MS: interpretation, review of paper; ME: study principal investigator, study concept, and review of paper.

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COMPETING INTERESTS

The authors declare no competing interests.

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