Quantitative High-speed Assessment of Droplet and Aerosol From an Eye After Impact With an Air-puff Amid COVID-19 Scenario

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Purpose: To quantify aerosol and droplets generated during non-contact tonometry (NCT) and assess the spread distance of the same.

Methodology: This was an experimental study on healthy human volunteers (n=8 eyes). In an experimental setup, NCT was performed on eyes (n=8) of human volunteers under normal settings, with a single and 2 drops of lubricant. High-speed shadowgraphy, frontal lighting technique, and fluorescent analysis were used to detect the possible generation of any droplets and aerosols. Mathematical computation of the spread of the droplets was then performed.

Results: In a natural setting, there was no droplet or aerosol production. Minimal splatter along with droplet ejection was observed when 1 drop of lubricant was used before NCT. When 2 drops of lubricant were instilled, a significant amount of fluid ejection in the form of a sheet that broke up into multiple droplets was observed. Some of these droplets traversed back to the tonometer. Droplets ranging from 100 to 500 μm in diameter were measured.

Conclusions: There was no droplet generation during NCT performed in a natural setting. However, NCT should be avoided in conditions with high-tear volume (natural or artificial) as it would lead to droplet spread and tactile contamination.

Key Words: aerosol, droplet, noncontact tonometry, COVID-19, SARS-CoV-2

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The World Health Organization (WHO) declared coronavirus disease 2019 (COVID-19) as a “Public Health Emergency of International Concern” in late January. The pandemic is escalating at an alarming rate despite numerous outbreak control measures.2 The transmission of the novel coronavirus (2019-nCoV) occurs predominantly through direct contact3 or through droplets when an infected individual coughs or sneezes. Medical staff are at high risk as social distancing is difficult to maintain amidst their work environment and several patients may be asymptomatic. Aerosols and droplets generated during diagnostic and surgical procedures pose a concern to health care workers because they may become airborne and are not easy to track. Precise measurement of intraocular pressure (IOP) through tonometry is an essential practice in an ophthalmology clinic.5,7 The ideal device must be easy to use, fast, safe, and precise, irrespective of patient posture, age, patient compliance, and operator bias.8 The Goldmann applanation tonometry is a widely used method for measuring IOP.9,10 However, noncontact tonometer (NCT) (air-puff tonometry) uses an air puff to flatten the cornea and no topical anesthetic or risk of corneal abrasion is involved compared with Goldmann tonometry.10,11

There is some evidence of tear film dehiscence and aerosol formation during NCT.12 The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) virus may reside in the tears and conjunctival secretions of symptomatic patients with COVID-19.13 Hence, there is concern regarding the usage of NCT during the COVID-19 pandemic.14 Based on their size, droplets may be subgrouped as large (>10 to 20 μm) and small (<10 to 20 μm) droplets. The larger droplets settle quickly and hence do not get deposited in the lower respiratory tract.15,16 By definition, aerosols are suspensions in the air (or in a gas) of solid or liquid particles and small enough to remain suspended in air because of low settling velocity. Particles with a diameter <3 μm do not usually settle.17 Most particles of size >6 μm can get trapped in the upper respiratory tract.16 To quantify aerosols and droplets, shadowgraphy is a visualization technique in which the object to be imaged is inserted between the light source and the camera. Because of the density difference between the medium (air) and object (aerosol and droplet), light rays naturally bend and create a shadow that defines the boundary of the object. Shadowgraphy is the preferred technique for high-speed imaging where the sensitivity is low at high frame rates (number of images acquired per second).18 We have previously used this technique to quantify the spread of aerosols and droplets during phacoemulsification and flap cut with a microkeratome, which revealed the generation of droplets of large sizes that had minimal risk of aerosolization.19,20 Frontal lighting is another imaging technique in which light is directly shone upon the device to be imaged. The aim of this study was to quantify the spread of aerosol and droplet generation during NCT using shadowgraphy and frontal imaging.

METHODOLOGY

This experimental study was approved by the institutional research and ethics committee of Narayana Nethralaya Multispeciality Hospital, Bangalore, India and conducted in...
accordance with the tenets of the Declaration of Helsinki. The study was performed in collaboration with the Department of Mechanical Engineering of the Indian Institute of Science, Bangalore, India. First, NCT was performed on one eye of each subject under normal settings (no eye drop instilled before NCT). Then, 1 drop of lubricant was instilled and NCT was repeated immediately (Systane Ultra lubricant eye drop, Alcon Laboratories, Fort Worth, TX). Then, 2 drops of lubricant were instilled and NCT was again repeated immediately. A 10-minute interval was maintained between each NCT measurement. The above process was repeated in 8 subjects who volunteered for the study. The inclusion criteria were healthy eyes and age between 18 and 39 years. The exclusions criteria were dry eyes, contact lens wearers, previous history of any intraocular or extraocular surgery, diagnosed case of any ophthalmic pathology, history of usage of any topical, or systemic medication. The Shin-Nippon NCT-200 (Rexxam Co, Ltd, Osaka, Japan) was used for all the experiments.21

The shadowgraphy technique involved the use of a high-speed camera, the Mini- UX100 (Photon USA Inc, San Diego, CA) coupled with a macro lens (ATX 100, 100 mm, f2.8D; Kenko Tokina Co, Ltd, Tokyo, Japan) for imaging. The resolution of the camera was 1280×1024 pixels. The aperture was set to f/32 for a maximum depth of field. The continuous illumination of the setup used a high-power light-emitting diode (LED) source (Constellation 120, Veritas) positioned opposite to the camera. The NCT device was placed between the light and camera for high-speed shadowgraphy (side lighting setup in Fig. 1A, B). The camera was manually triggered to acquire images before the NCT was triggered. For the frontal lighting setup of shadowgraphy, the

![FIGURE 1. Experimental setup. A, Shadowgraphy setup with a high-speed camera and light-emitting diode (LED) opposite to one another with an object to be imaged in between. B, Shadowgraphy setup with the subject. C, Frontal lighting setup with an LED light source placed behind the camera. D, Frontal lighting setup with the subject. E, Fluorescein analysis setup with a blue LED light and a bandpass filter attached to the camera. F, Fluorescein analysis setup with the subject. Figure 1 can be viewed in color online at www.glaucomajournal.com.](image-url)
illumination was placed in front of the NCT device so that the light fell directly on it (Fig. 1C). The LED light source was placed behind the camera to image the tear droplets distinctly (Fig. 1D) because the normal morphology of the human face, location of the eyes, and tilt of the human head sometimes impeded the shadowgraphy technique. By placing a white translucent tape on the subject’s nose, enough backlighting was possible to make the cornea seem like a shadow that allowed sharper imaging of the indentation of the cornea during applanation. The white tape blocked light partially from reaching the cornea to enable adequate contrast for its imaging.

For the fluorescein dye analyses, we stained the conjunctiva of the volunteers with a sterile ophthalmic fluorescein sodium strip (Fluo Strips, Contacare Ophthalmics & Diagnostics, Vadodara, India) after moistening the tip with a lubricant drop and 1 mg of sodium fluorescein. The volunteers were requested to blink repeatedly following a period of eye closure after the application of the strips. Then, tonometry was performed. The fluorescein absorbed wavelengths between 460 and 480 nm (blue) and emitted fluorescence in the range of 530 to 560 nm. To capture these emissions from the illuminated eye, we used a 30-W blue LED as an excitation source and imaged with a bandpass filter (527 nm) placed on the camera. We used 3 different cameras for the fluorescein dye analyses. First, we used a 16-megapixel smartphone camera (Realme 3 Pro-Realme Mobile Telecommunications Private Limited, Haryana, India) for external video filming in a darkly lit room. Videos were captured in 4K resolution and at 30 frames per second (fps). Second, a Nikon D7200 digital single-lens reflex (DSLR) camera was used to capture high-resolution images (24 megapixels) at a shutter speed of 2.5 seconds. Videos on the same camera were acquired at 25 fps. Third, the Mini UX100 was used at a low acquisition rate (50 fps) to check for aerosol and droplet generation. The lens used for all the experiments was the ATX Pro 100. Figures 1E and F show the fluorescein setup.

A simple 1-dimensional analysis of the aerosol and droplet spread was performed similar to our earlier works.\textsuperscript{19,20} Assume that a droplet of diameter ($D$ $\mu$m) was ejected with a velocity ($u_{\text{jet}}$ (horizontal component)) during the course of air-puff tonometry. Our out-patient departments do not have controlled air-conditioning and a natural air velocity ($u_{\text{air}}$) $\sim$0.1 to 0.2 m/s in the room was considered assuming that the room was closed from inside. This was considered as a low airflow condition. However, the presence of an air-conditioning (ac) unit or a table fan can enhance $u_{\text{air}}$ to as much as 1 m/s.\textsuperscript{19,20} This was considered as a fan/ac condition in subsequent figures. The appropriate governing drag equation for the droplet can be written as:

\[
\frac{d u_{\text{rel}}}{d t} = \frac{9}{2 r^2} \left( \mu \rho_l u_{\text{rel}} - u_{\text{jet}} \right) \rho_g, \quad \text{(1)}
\]

where $u_{\text{rel}} = \sqrt{(u_{\text{jet}} - u_{\text{rel}})^2 + \frac{r}{2}}$, $r = D/2$, $u_{\text{jet}}$ was the settling rate of the droplet, $\mu_l$ was the viscosity of air, $\rho_l$ was the density of air, $\rho_g$ was the density of droplet, and $g$ was the acceleration because of gravity. The droplets evaporated and settled because of gravity simultaneously.\textsuperscript{22} The evaporation timescale was estimated from the $D^2$ law,\textsuperscript{23} whereas the appropriate settling rate ($v_t$ in m/s) was estimated from the Stokes equation:

\[
v_t = \frac{(\rho_l - \rho_g) g D^2}{18 \mu_t} \quad \text{(2)}
\]

The calculation assumed that the human eye was positioned $\sim$50 cm from the tabletop on which the NCT was placed. Thus, the timescale of droplet settling was obtained from Equation 2 as follows:

\[
t_s = \frac{1}{v_t} = \frac{18 \mu_t}{(\rho_l - \rho_g) g D^2} \quad \text{(3)}
\]

The final horizontal distance ($x$) traveled by the droplet was determined from the smaller of the 2 quantities, the evaporation timescale, and settling timescale. Additional details about the properties of air and droplet used for these calculations were provided in our earlier study.\textsuperscript{19,20} The droplet sizes were measured using custom algorithms as described in our previous works.\textsuperscript{19,20}

**RESULTS**

Unlike our previous studies, shadowgraphy was difficult to perform as the anatomy of the human face and the setting of the human eye obstructed distinct imaging of the cornea and conjunctival surfaces. The cornea appeared as a thin white film and deformed upon the impact of the air puff. Figures 2A–E shows a sequence of frames captured with shadowgraphy. Some deformation was evident in Figure 2C. After applying 1 drop of lubricant, a large droplet of diameter $\sim$470 $\mu$m was observed originating from the eye (Fig. 2E). On superimposition of the sequential images, we could chart the trajectory of the same (Fig. 2F).

To overcome the shortfalls of shadowgraphy imaging, we repeated the measurements using frontal lighting. The images were acquired at a rate of 2000 fps and a shutter speed of 1/20,000 second. We first imaged without the instillation of any eye drop. We observed the presence of a tear film with minimal pooling of tears in the lower meniscus before NCT. No formation of any droplet or aerosol was observed during the procedure (Fig. 3). On instillation of a drop of lubricant in an eye, we witnessed pooling of fluid in the lower meniscus, along with tear drops on the lower eyelashes before tonometry (Fig. 4). Impingement of the air puff caused the deformation of the cornea that caused the fluid film on the ocular surface to be displaced. In one instance, ejection of a tear drop was noted that traversed toward the lashes of the upper lid. The drop was seen as suspended from the upper lashes after the return of the cornea to its normal state (Figs. 4C, D). In another eye after corneal deformation, the fluid from the lower meniscus moved along the meniscus laterally up to the lateral canthus of the eye and was evidently imaged (indicate by white circle in Fig. 5). On repeating the test on a third eye, we observed break-up of the fluid film and ejection of 2 droplets (Fig. 6). Thus, each eye had a different outcome.

On instillation of 2 drops of lubricant, there was excessive fluid in the lower meniscus of the eye along with the presence of droplets in the lower lashes (Fig. 7). On impingement of the air puff and after corneal deformation, the tear film was pushed away from the ocular surface. A sheet of fluid was initially noted that disintegrated into droplets (Fig. 7). The diameters of these droplets were in the range of 100 to 500 $\mu$m among all subjects (Fig. 7). In all the
FIGURE 2. Shadowgraphy imaging with 1 drop of lubricant. A, Human cornea before applanation ($t = 0$ s). B, Impingement of the air puff leading to sliding down of the tear film and subsequent formation of a bulge near the lower lid ($t = 3$ ms). C, Maximum applanation (deformation) of the cornea ($t = 11$ ms). D, Cornea regaining its original shape ($t = 14.5$ ms). E, Ejection of a single droplet $\sim 470 \mu$m from the lower fornix formed from the displaced tear film ($t = 28.5$ ms). F, The trajectory of the ejected tear droplet is illustrated by the superimposition of sequential frames. The scale bar in black equals 5 mm, whereas the one in grey equals 2.5 mm. The white arrow shows the time point at which the cornea was applanated.

FIGURE 3. Frontal lighting imaging under normal eye condition. A, Human cornea before applanation ($t = 0$ s). B, Impingement of the air puff led to the deformation of the cornea ($t = 34$ ms). C, Cornea regaining its normal shape after maximum deformation ($t = 44$ ms). D, Cornea returned to its original shape ($t = 56$ ms). No droplets were noted in any frame. The scale bar in black equals 5 mm.
FIGURE 4. Frontal lighting imaging on an eye instilled with one drop of lubricant. A, Human cornea before applanation \((t=0\,\text{s})\). Droplets noted on lower eyelashes. B, Impingement of the air puff led to the deformation of the cornea \((t=14\,\text{ms})\). The minimal movement of the droplets on the eyelashes was noted. C, Corneal deformation \((t=24\,\text{ms})\). Droplet being ejected from the cornea traveled upwards toward the upper eyelashes. D, Cornea returned to its original shape \((t=56\,\text{ms})\). An ejected droplet was observed trapped on the upper eyelashes.

FIGURE 5. Frontal lighting imaging on an eye instilled with one drop of lubricant. The cornea seemed out of focus as the plane of focus was on the lateral bulbar conjunctiva. A, Human cornea before applanation \((t=0\,\text{s})\). B, During air impingement, the droplet was noted near the lower lid at the lower meniscus \((t=8\,\text{ms})\). C, Movement of the droplet along the lower lid toward the lateral canthus \((t=20\,\text{ms})\). D, Further movement of droplet toward the lateral canthus noted \((t=28\,\text{ms})\). The scale bar in gray equals 5 mm.
subjects, we noted that the droplets originated from the fluid lake along the lower lid margin. On air impingement, a redirection of air impulses from the center of the cornea toward the conjunctival fornices occurred that led to the separation of eyelid margin from the sclera. If pooling in the lower fornices was present, then NCT caused an excursion of fluid. As the smallest detectable droplet diameter was $\sim 100 \mu m$, the process was controlled primarily by the settling timescale. To compute the distance traversed by these droplets, we used the drag Equation 1 taking into consideration 2 settings of room air velocity, $\sim 0.1$ and $1$ m/s. Figure 8 shows the estimated distance traversed by the droplets as a function of diameter. This distance would be traversed by the droplet if its path of the traverse was left unobstructed. The initial value of droplet’s horizontal velocity ($u_h$) was calculated as $1$ m/s from the sequential images shown in Figure 7. The distance between the point of contact of the human eye and the pneumatic port of the tonometer was $\sim 11$ mm.21 Hence, droplets smaller than 300 $\mu m$ can settle on the device even in case of low room air circulation velocity of 0.1 m/s (red circles in Fig. 8). The spread distance increased with a greater air velocity of 1 m/s (blue circles in Fig. 8). The simple calculation presented here did not account for the clustering effect observed in sprays.24 The fluorescein experiments confirmed the observations from our frontal imaging experiments. No aerosol production in a natural eye setting (Fig. 9A) (without the instillation of eye drop) was seen on either smartphone imaging (Fig. 9B), DSLR camera (Fig. 9C) or high-speed imaging (Fig. 9D). When one drop of lubricant was instilled, we noted the supplementary volume of fluid in the lower fornix (Fig. 10A) and minimal aerosol production on tonometry. The smartphone (Fig. 10B) and DSLR camera (Fig. 10C) picked up droplets being emitted from the ocular surface on air impingement, which seemed to settle on the nose bridge of the subject. High-speed photography revealed emission of droplets from the lower tear meniscus that were emitted initially as a sheet and subsequently disintegrated (Fig. 10D). When 2 drops of lubricant eye drop were instilled, we observed pooling of fluorescein stained tears in the lower fornix with some spillage toward the medial and lateral canthi (Fig. 11A). Via the nightscape smartphone videography, there was a generation of droplets observed (Figs. 11B, C), which traversed back up to the NCT contaminating it (Fig. 11D, E). The DSLR (Figs. 11F, G) and high-speed imaging (Figs. 11H, I) too demonstrated ample dispersion of droplets. Droplet size and trajectory in fluorescein analysis could not be computed because of the halo around the droplets obtained and the low speed (50 fps) of acquisition.

**DISCUSSION**

The fact that aerosols and large droplets can transmit viruses is well known.17 Therefore, it is possible for COVID-19 to be transmitted through respiratory droplets.25 – 28 Thus, the mucosa (mouth or nose) or conjunctiva is at risk of being exposed to the infected respiratory droplets.13 Another mode of transmission of the COVID-19 virus is through fomites in the environment around the infected person.29 Airborne transmission differed from droplet transmission as it denoted the presence of aerosols that were smaller than 5 $\mu m$ in diameter. These have the potential of surviving in the air for longer periods of time and also travel greater distances.30 Thus, the air or the objects around an infected person may be a potential source of infection. The
procedures or treatment modalities that generate aerosols could result in airborne transmission of COVID-19.

Current recommendations indicate that NCT should be avoided. Some bodies suggested the use of single-use disposable tonometer tips as cleaning of the tips with 70% alcohol did not provide adequate disinfection. Because of these guidelines, many eye clinics may have discontinued the use of NCT and moved on to contact tonometry (Goldmann applanation tonometry). The goal of this study was to precisely determine if there was a risk of aerosolization from the NCT measurement. We observed no aerosolization from the eye of the subjects without the instillation of eye drop. This was a critical finding. On instillation of a single lubricant drop, we observed the accumulation of fluid in the lower fornix. On air impingement, dispersion of this fluid was observed. Most of the fluid was either drained along the lower meniscus into the lake near the lateral canthus or a small amount of fluid was ejected in the form of droplets. However, these droplets only traveled up to the lashes and were not emitted outside the eye. Only in one of the subjects did we observe droplets being ejected that traversed back up to the pneumatic port of the tonometer. This could possibly be a source of infection if the infected patients had ocular symptoms of COVID-19. The pneumatic port once infected may act as a reservoir for the virus and could transmit the same to the successive patients undergoing tonometry. In our final set of experiments, instilling 2 drops of lubricant resulted in a significant splash of fluid from the ocular surface relative to the 1 drop of lubricant or normal setting. These drops may remain suspended in air until they settle and contaminate the surfaces on which they land. It should be noted that the size of the droplets did not change between the 1 eye drop versus 2 eye drops condition. Only the
number of droplets were more in the 2 eye drops condition. Thus, results showed in Figure 8 were independent of the number of eye drops.

As long as the eye was in its natural condition, the droplet generation was nonexistent. Conditions such as epiphora, dry eye, and allergic conjunctivitis that result in pooling of the lacrimal lake could result in the dispersion of potentially infectious droplets from the ocular surface. As epiphora is common after phacoemulsification, pterygium surgery, refractive surgery, lacrimal apparatus surgery, squint correction, and trabeculectomy, NCT should not be performed until epiphora resolves. The use of a protective shield on ophthalmic equipment such as slit lamps, optical coherence tomography, and fundus cameras was recommended. However, the use of a shield on a NCT between the pneumatic port and the eye would prevent the air puff from reaching the eye. To our best knowledge, only 1 previous study evaluated the dispersion of aerosols during NCT. Britt et al used fluorescence photographic technique to study the presence of aerosols. A major drawback of this method was the inability to gauge the size of the aerosols, chart their trajectory, and spread. Contrary to our findings, they reported the dispersion of aerosols and droplets on NCT in most eyes. This could be explained by the fact that they used a drop of fluorescein to stain the ocular surface in every subject. Hence, we used a moistened fluorescein strip instead of fluorescein drops in all conditions.

FIGURE 9. Fluorescein analysis under normal eye condition. A, Normal eye condition is captured in the nightscape mode of a smartphone. B, No ejection of any droplets noted on noncontact tonometry. Video captured with 4K resolution in the nightscape mode of a smartphone. C, Images captured on Nikon DSLR. No generation of droplets was noted. D, No production of droplets captured by ultra-high-resolution Mini UX 100 camera. Figure 9 can be viewed in color online at www.glaucomajournal.com.
subjects to replicate the state of the normal human eye. The observation of excessive splatter on the addition of a drop of methylcellulose was akin to our findings. They also used 2 different NCTs, the American Optical NCT II (Cambridge Instruments Inc, Cambridge, MA) and Keeler Pulsair (Keeler Instruments Inc., Broomall, PA) tonometer. The AO NCT used a piston generated air impulse that linearly increased over the first 8 milliseconds after which it progressively decayed. The Keeler Pulsair used an electrical pump to create a pressure gradient and a ramped air impulse for applanation. It consisted of a sub-30 mm and a supra-30 mm mode based on the IOP of the patient. The supra-30 mm mode created a more forceful impulse that in turn would lead to more splatter. In comparison with this, we used the Shin-Nippon NCT-200 that used a newly developed Smart Puffing Controlled system. This system had an integrated algorithm to adjust air-puff pressure instantly based on the patients’ IOP. Although we did not use an adjustable triggering device for the synchronization of the camera (for shadowgraphy and frontal imaging) with the tonometer, we tweaked the frame per seconds rate of the cameras to ensure that we capture the entire video of the air puff indenting the cornea up until the droplets being emitted.

By using 3 different imaging setups (shadowgraphy, frontal lighting, and fluorescein), we were able to image the fluid dynamics of splatter from the eye during NCT.

It is important to note the stochastic nature of droplet creation from the fluid splatter. Atomization of the fluid depends on several factors, for example, air-puff pressure, duration of air-puff, thermophysical properties of the fluid, angle of inclination of the eye to the puff, and centration of the eye. Nonetheless, our experiments showed that the droplet diameters were bounded up to 500 µm (Fig. 8) in all the captured frames of the side lighting videos. For each eye, as many as 100 frames were captured over a 50 millisecond second period during shadowgraphy and frontal imaging. However, the distribution of the droplet sizes between the frames differed sharply because of the stochastic (random) nature of droplet creation in such experiments. This is a well-known phenomenon in the field of droplet fluid mechanics. Thus, assessing repeatability between frames or between the eyes was physically unrealistic. We focused on the frames that yielded the smallest droplet diameter. Based on our detailed experiments, we concluded that NCT did not lead to droplet or aerosol generation when the eye was in its natural state. However, any condition that could lead to watery eyes (natural or artificial) should be an exclusion criterion for performing NCT. In the clinic, there is no standardized method available to quantify the threshold tear production beyond which droplet or aerosol spread will be critical. At the same time, we were not able to quantify the same in this study. Therefore, a standardized effective method for device disinfection and protection of the operator needs to be
deliberated upon in future studies. For example, a protective shield on the operator’s face and adequate ventilation (such as open windows with airflow) may be useful in preventing contact with droplets.

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