Transparent antifouling material for improved operative field visibility in endoscopy

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Camera-guided instruments, such as endoscopes, have become an essential component of contemporary medicine. The 15–20 million endoscopies performed every year in the United States alone demonstrate the tremendous impact of this technology. However, doctors heavily rely on the visual feedback provided by the endoscope camera, which is routinely compromised when body fluids and fogging occlude the lens, requiring lengthy cleaning procedures that include irrigation, tissue rubbing, suction, and even temporary removal of the endoscope for external cleaning. Bronchoscopies are especially affected because they are performed on delicate tissue, in high-humidity environments with exposure to extremely adhesive biological fluids such as mucus and blood. Here, we present a repellent, liquid-infused coating on an endoscope lens capable of preventing vision loss after repeated submersions in blood and mucus. The material properties of the coating, including conformability, mechanical adhesion, transparency, oil type, and biocompatibility, were optimized in comprehensive in vitro and ex vivo studies. Extensive bronchoscopy procedures performed in vivo on porcine lungs showed significantly reduced fouling, resulting in either unnecessary or ∼10–15 times shorter and less intensive lens clearing procedures compared with an untreated endoscope. We believe that the material developed in this study opens up opportunities in the design of next-generation endoscopes that will improve visual field, display unprecedented antibacterial and antifouling properties, reduce the duration of the procedure, and enable visualization of currently unreachable parts of the body, thus offering enormous potential for disease diagnosis and treatment.

antifouling materials | endoscopy | surface wetting | biopsy

Camera-guided instruments are extensively used in a variety of applications such as oil field and marine exploration, sanitation inspections, robotics, optical sensors, and medicine. However, their operation is heavily compromised in highly contaminating environments where oil, sewage, marine fouling, or body fluids permanently disrupt the visual field. Clearance methods developed for these applications are insufficient in keeping the operative field functional and periodically cleaning the surfaces of these cameras for their continued effective performance is time consuming, costly, and often ineffective. The primary means used to clear lenses is mechanical wiping, in which case contours or curvature are particularly difficult to clean. Mechanical wiping can also damage and wear the lenses over time, and in scenarios involving a need to maintain attention to detail, damage can distort the view. Another approach to lens cleaning is to combine a camera with additional channels through which irrigation or spraying can be applied, significantly increasing the size of the instrument. Engineering a novel, antifouling, transparent material that can be applied to the surface of lenses may obviate contamination-induced vision loss, render cleaning procedures unnecessary, and allow miniaturization of the instrument for use in previously unreachable environments and confined spaces. Perhaps most significantly and more than in any industrial application, these challenges manifest themselves in medical procedures such as endoscopy.

Endoscope operators use the device to inspect interior regions of the human body and, in the case of flexible endoscopes, to obtain samples for diagnostic studies and to provide minimally invasive therapy via instruments passed through the working channel (1, 2). All these procedures bring the camera lens in close contact with body fluids, which adsorb onto the lens and compromise the visual field, risking imprecise or undesired movements of the device that damage the surrounding tissue and harm the patient. Traditionally, the lens is cleared via suction, vigorous saline irrigation, or rubbing against the tissue walls (3–6). Often, the endoscope needs to be retracted and manually cleaned, which is more likely to occur during the most crucial points in a procedure, for example, during excessive blood flow caused by a biopsy. Rigid endoscopes do not have a working channel through which irrigation or suction can be performed, so rubbing or withdrawal to wipe clean are the only recourses. All these measures impose risks to the patient's health. Of particular concern are procedures in flexible bronchoscopy (7, 8), where wiping against the delicate tissue in the lungs can cause lens reocclusion, coughing reflexes, or even tissue damage. Suction in narrow airways can lead to luminal collapse, and saline irrigation brings liquids into airways and can dislodge previously formed clots leading to bleeding. Retracting the endoscope and wiping it clean results in periodic, highly undesired interruptions contributing to longer and potentially riskier procedures. Conversion to open surgery may even be required when complications arise from procedures performed while visually impaired (3).

Significance

Inspection devices are frequently occluded by highly contaminating fluids that disrupt the visual field and their effective operation. These issues are particularly striking in endoscopes, where the diagnosis and treatment of diseases are compromised by the obscuring of the operative field by body fluids. Here we demonstrate that the application of a liquid-infused surface coating strongly repels sticky biological secretions and enables an uninterrupted field of view. Extensive bronchoscopy procedures performed in vivo on a porcine model shows significantly reduced fouling, resulting in either unnecessary or ∼10–15 times shorter and less intensive lens clearing procedures compared with an untreated endoscope.

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To address these problems, it is important to design a material that exhibits a set of critical properties that are difficult to achieve in combination: not only should it satisfy the general requirements for coatings of medical devices (i.e., to be conformal, mechanically robust, biocompatible, and antimicrobial), it additionally has to display high transparency, extreme resistance to fouling by body fluids, and antifogging properties that will allow the maintenance of a clear visual field throughout the procedure. The last decade has witnessed significant development in the design of Lotus leaf-inspired superamphiphobic surfaces, which show repellency of various liquids (9, 10). However, the requirements to sustain repellency throughout an endoscopic procedure are extremely challenging because (*i*) direct contact with proteins, cells, and bacteria, as well as the formation of blood clots upon contact with an abiotic surface, compromise the performance of superhydrophobic surfaces (11, 12), and (*ii*) their transparency is not easily achievable. Recently, liquid-infused coatings, consisting of a porous structure infiltrated with a lubricant, have emerged as a new, alternative strategy for repellent materials (11, 13–17). The formation of a stable lubricant overlayer on the surface creates a dynamic slippery barrier that protects the underlying substrate from direct contact with polluted media, thus drastically lowering the adsorption of various serious contaminants including bacteria (18, 19) and proteins (20–22). This new, non-fouling material can be designed to perform under flow (23, 24), provide enhanced damage tolerance (15, 16) and self-healing capabilities (11), or be integrated with a vascularized network that secretes the lubricant to repair the interface (25, 26).

The characteristics of liquid-infused coatings may provide a potential solution to mitigate the performance concerns in endoscopes, especially because methodologies have been developed to create transparent coatings with efficient liquid repellency (16, 20–22, 27). Here, we design and explore the function of a liquid-infused coating applied on a bronchoscope lens during clinically relevant procedures. We extensively test the repellency and operative field view of the coated endoscopes in contact with blood, mucus, and airway secretions, optimize the physico-chemical properties of the lubricant and its interface with the underlying solid to maximize antifouling properties, and characterize the performance of the coating in vivo in a porcine animal model whose lungs are subjected to a set of widely applied bronchoscopy procedures. In our study, the coated endoscopes significantly outperformed the unmodified instruments, showing either no fouling or minor, transient lens occlusion, retaining sufficient field of view, and requiring at least ~10–15 times shorter lens cleaning procedures.

Results

We adopted a layer-by-layer deposition (28–30) protocol using 20-nm silica particles and poly(diallyldimethylammonium chloride) to create mechanically robust porous 100-nm-thick silica network on glass (21). The coating is strongly adhered to the substrate showing no delamination during adhesion tape tests (21). The feature sizes and porosity of the silica network render the material antireflective, and when infused with a liquid, it displays increased transparency compared with the underlying plain glass (21). This porous silica network infiltrated with varying oils was first characterized for performance in vitro and ex vivo using a 5.5-mm-diameter Eggsnow USB Borescope Endoscope Pipe Inspection Camera (*SI Appendix*, Fig. S1 A and B), similar in size to an Olympus Bronchoscope (EXERA BF-160) used in our subsequent clinical in vivo experiments (*SI Appendix*, Fig. S1C). We developed a protocol to create a disposable endoscope attachment by fixing a coated glass coverslip onto the endoscope lens via a polydimethylsiloxane (PDMS) adhesion layer (Fig. 1*A* and *SI Appendix*, Fig. S1). For in vivo studies, a 6-mm glass coverslip was cut in the shape of a crescent to fit over the lens while leaving the working channel exposed (Fig. 1 *A* and *B*). This strategy (*i*) maintains transparency, (*ii*) seals the endoscope lens from contaminating liquids, (*iii*) allows the use of the working channel for various procedures (e.g., suction, irrigation), and (*iv*) enables removal of the attachment after experiments, making multiple repeats possible.

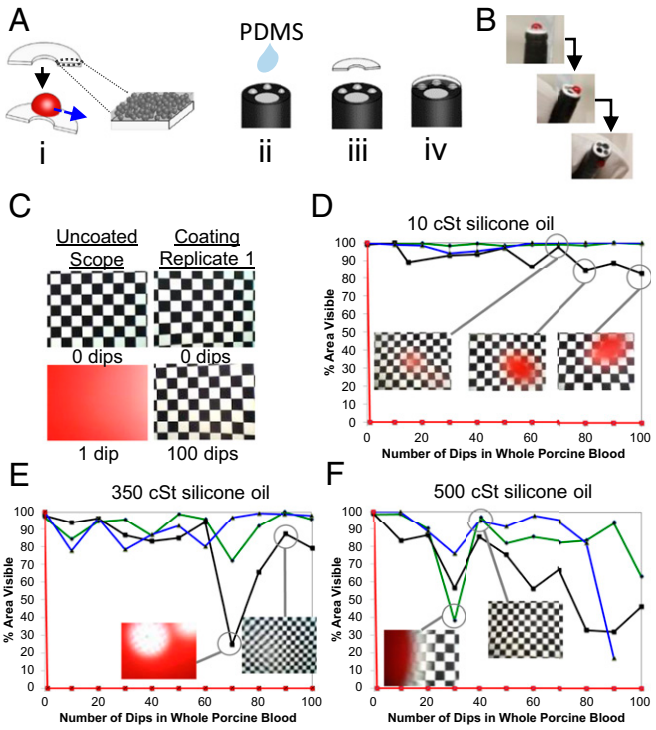

Fig. 1. Schematic of the coating process and subsequent characterization of the visual field during blood-dipping experiments with coated and untreated endoscopes. (*A*) An endoscope is modified with a disposable, glass coverslip (*i*) coated using previously described procedure (21). A drop of PDMS was added to the tip of the scope (*ii*) before fixing the coated glass on the endoscope lens (*iii*). The PDMS was cured securing the coverslip to the surface of the lens (*iv*) while exposing the working channel. (*B*) The coated endoscope repels a droplet of blood. (*C–F*) The following experiments were performed in triplicates. (Scale bar, insets in the plots are ~2 mm in width.) (*C*) The uncoated endoscope fails immediately after one dip in whole porcine blood (*Left*), whereas the 10-cSt oil allows for repellency up to 100 dips with no fouling (*Right*). (*D–F*) Evolution in the reduction in visible area as a function of the number of dips for endoscopes coated with silicone oils of varying viscosity: (*D*) 10 cSt; (*E*) 350 cSt; and (*F*) 500 cSt. The red lines correspond to the uncoated endoscopes. Replicates = 1 (green), 2 (blue), and 3 (black) correspond to each coated scope tested. *Insets* in *D* demonstrate visualization of field of view at 70, 80, and 100 dips for the poorest performing sample. The droplets of blood on the 350- and 500-cSt silicone oil surfaces are not as mobile due to viscous dissipation in the lubricant layer and temporary visual aberrations become more pronounced once they are shed from the surface. This contributes to the oscillatory behavior in visibility.

The reduction in performance for liquid-infused coatings is expected when the contaminating liquid comes into contact with and is irreversibly pinned on the underlying solid substrate. This contact can either happen catastrophically, when the liquid displaces the lubricant inside the silica network due to incompatible chemistry, or slowly with time, as the lubricant becomes depleted due to the formation of a wrapping layer around the repelled liquid and by shear force (23, 31). In the challenging environment in which endoscopes are used, highly adhesive body fluids will then contaminate the lens resulting in a reduction of the field of view and a necessity to clear the lens through extensive irrigation and suction. To estimate the duration of uncompromised lens performance in such conditions, we repeatedly immersed the endoscopes in and withdrew them from porcine blood and mucus and characterized the loss of visibility arising from the lens occlusion. We tested two classes of commercially available lubricants: silicone oils (Momentive or Gelest polydimethylsiloxanes) and perfluorinated fluids [perfluoroperhydrophenanthrene, or Vitreon, and perfluoropolyethers

(PFPEs): DuPont Krytox series]. These choices were dictated by the physical properties of these liquids (low surface energies and broad range of viscosities and volatilities), their chemical inertness, and prior US Food and Drug Administration (FDA)-approved applications of some of them in clinical settings, such as ophthalmic surgeries (32). The silicone oils of different viscosities (10, 350, and 500 cSt) showed stable performance and maintained a remarkably clear field of view after multiple dips of the endoscopes in fresh porcine blood (Fig. 1 *C–F*). In contrast, the untreated controls failed immediately after the first contact with blood (Fig. 1 *D–F*, red lines). The lowest viscosity silicone oil tested (10 cSt) consistently maintained a visual field close to 100% clarity for up to 100 dips in blood for all tested endoscopes (Fig. 1 *C* and *D*) (image analysis is described in *SI Appendix*, Fig. S2; Movie S1 presents an additional view of the resulting repellency properties).

Although there is natural variability among the different replicates (blue, black, and green lines in Fig. 1 *D–F* represent individual experiments performed with different samples), several observations can be made: the best sample (green line) demonstrates 100% clarity for all 100 dips (Fig. 1*D*), whereas the poorest performing sample (black line) only slightly fouls the lens (reduction in visibility by ∼20%). However, this fouling is found to be dynamic and transient in nature: droplets of size on the scale of millimeters are occasionally observed on the surface (Fig. 1*D*) but do not stay pinned; rather, they appear randomly in different areas and are easily removed by repeated dipping, bringing the field of view to the original 100% visibility. Importantly, we find that following contamination, after a gentle water wash and relubrication, the coating continues to maintain clarity for at least another 100 dips (*SI Appendix*, Fig. S3). We measured the force required to remove a 2-μL (millimeter-sized) blood droplet using a cantilever-based force sensor (*SI Appendix*, Fig. S4). For a silicone oil-based coating, it was found to be <10 μN, i.e., the weight of the droplet (∼20 μN) can easily overcome any pinning force leading to droplet self-removal (*SI Appendix*, Fig. S4). This low pinning force explains the mobility of the blood drop on the lens and the oscillatory nature of the experimentally measured field of view (Fig. 1*D*). Analogous oscillatory behavior in visualization is also found for the higher viscosity lubricants (Fig. 1 *E* and *F*), but temporary visual aberrations become more pronounced because the contaminating liquid is less mobile due to viscous dissipation in the lubricant layer (23, 33).

Perfluorinated lubricants, including FDA-approved Vitreon, were also investigated as alternatives to silicone oil. The pinning force for a droplet of blood measured on a force sensor for Vitreon-infused coating was >40 μN, exceeding the weight of the droplet by at least a factor of 2 (*SI Appendix*, Fig. S4). These results were further supported by optical observations and contact angle (CA) measurements of a blood droplet on these surfaces: the light passes through the interface between the blood droplet and the silicone oil-based coating indicating the presence of a stable lubricant film beneath the droplet and thus the absence of the direct contact between the contaminating medium and the substrate (CA = ∼180°); in contrast, for a Vitreon-based coating, the blood droplet is in direct contact with and pinned on the silica network, preventing any light from passing through (CA = ∼170°; *SI Appendix*, Fig. S4). Therefore, although perfluorinated liquid-based coatings show improved repellency compared with that of the unmodified scopes, they display reduced droplet mobility and tend to fail faster than their silicone oil-based analogs (after ∼5, 20, and 30 dips for Vitreon, 80-cSt PFPE, and 550-cSt PFPE, respectively; *SI Appendix*, Fig. S4–S7). Thus, moving forward we chose to focus on the silicone oil coating due to its superior performance in these tests.

Similar to the blood dip experiments, we immersed the silicone oil-coated endoscopes into porcine mucin solutions with a concentration (17 wt./vol%) typically found in cystic fibrosis patients: a patient population known to have an excess of extremely sticky lung secretions (34, 35). Fig. 2 clearly shows that the mucus is more easily shed from the surface lubricated with 10-cSt oil compared with the one lubricated with 350-cSt oil, surviving on average ∼20 dips before loss of visual field. Both coating types significantly outperform the uncoated control, which consistently loses visibility after the very first exposure to mucus solution (Fig. 2 *A* and *B*, red lines). Interestingly, in some cases, even with such a sticky contaminant, both the 10- and 350-cSt oil display an oscillatory behavior in vision reduction. We note that mucus is a viscoelastic liquid that cannot be easily shed from the lens surface from gravity alone, which results in some noise in the data between different coated samples. Importantly, however, up to ∼10 dips neither replicates of 10-cSt lubricated scopes lose more than ∼25% of the visual field, providing sufficient level of visualization. The field of view can also be restored after initial fouling by applying continued solution contact (*Insets* in Fig. 2*A*).

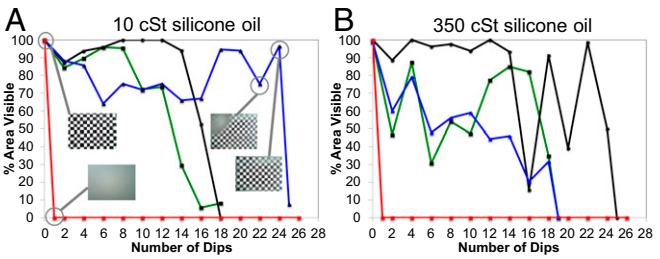

Fig. 2. Characterization of the visual field during mucus exposure. All experiments were performed in triplicates. Replicates = 1 (blue), 2 (green), and 3 (black) and correspond to each sample tested; red dots illustrate the performance of an uncoated control that fails after the first exposure. Dipping was performed in 17 wt.% mucin solution using endoscopes coated with 10-cSt silicone oil (*A*) and 350-cSt silicone oil (*B*). Note an oscillatory behavior in clearance, mostly pronounced for the higher viscosity oil.

To minimize the reduction in visual clarity due to lubricant trail formation and slower clearance that is observed for higher viscosity silicone oils while maximizing their possible contribution to longevity, we studied the performance of the coatings lubricated with the mixture of high and low viscosity oils. As an example, *SI Appendix*, Fig. S8 shows the results for the coating infused with a 10- and 350-cSt silicone oil in a 1:1 volume ratio. The mixed lubricant has a viscosity of 72 cSt and leads to approximately four times longer performance compared with the 10-cSt control (*SI Appendix*, Fig. S8*A*), showing that the performance can be further optimized by the application of a mixed-oil system.

To assess potential toxicity of the components of the coating, we subjected mouse mesenchymal stem cells in two separate sets of experiments to the two key components of the coating, i.e., 20-nm silica particles and lubricants (silicone or fluorinated oils). Fig. 3*A* shows live/dead stains of cells incubated with varying concentrations of silica nanoparticles. We quantify toxicity by evaluating the area coverage of cells (Fig. 3*C* and *SI Appendix*, Fig. S9). At the lowest concentration studied, 0.003 wt.%, that is more than four times higher than in the hypothetical worst case scenario in which the entire coating delaminates from the substrate (corresponding to $\sim 7 \times 10^{-4}$ wt.% of silica particles), we observe minimal dead cells and a live-cell coverage similar to the control, indicating no toxic effects from the silica particles (this concentration falls in the regime indicated by the dotted box in Fig. 3*C*). Toxicity begins to manifest itself only at a silica particle concentration ∼35 times higher than that available from the fully delaminated coating. It is noteworthy that the assembled coating provides a very strong bonding of the particles to the substrate (21), making any removal of nanoparticles from the coating due to mild abrasions with soft tissue extremely unlikely. Cells were then grown on a plain glass substrate and on the silicone oil-infused coating for 4 d to assess toxicity of the lubricant (Fig. 3 *B* and *D*). Although cells on the liquid-infused coating show lower

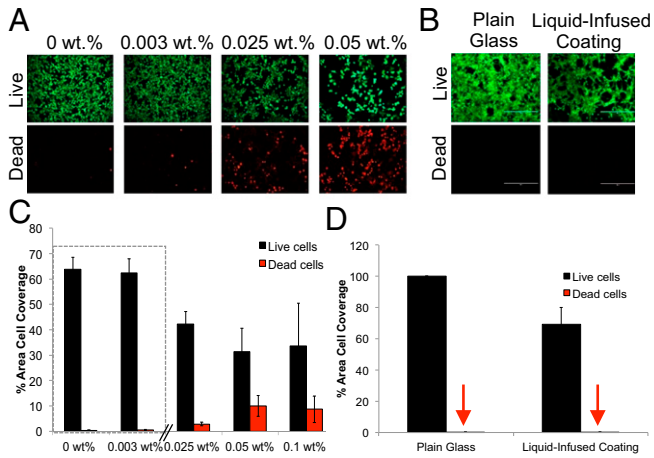

Fig. 3. Assessing the potential toxicity of the two components of the coating: silica nanoparticles and silicone oil. (*A*) Mouse mesenchymal stem cells were grown in tissue culture wells in the presence of varying concentrations of 20-nm silica particles and stained for live/dead cells. (*B*) The cells were grown on plain glass and on the silicone oil-infused coating and stained for live/dead cells. There are no visible dead cells on the control and the coating. (*C*) Quantification of area coverage with live (black) and dead (red) cells. In the concentration regime of interest (indicated by dashed box), no toxicity is detected, and coverage remains equal to the control. The coverage of dead cells increases to a measurable quantity only at concentrations that are 35 times higher than the regime of interest. (*D*) Similar quantification is also performed for cells grown on plain glass surfaces versus liquid-infused surfaces. The number of dead cells is negligible on the coating, as well as on the plain glass control.

cell coverage (as expected from the compromised adhesion to the repellent coating), the number of dead cells are negligible (Fig. 3*D*). The effect of the PFPE oil was also evaluated and found to be nontoxic (*SI Appendix*, Fig. S10).

Subsequent microbial adhesion tests in which *Escherichia coli* was grown for 24 h on a coated glass slide show significantly reduced bacterial film overgrowth compared with an uncoated control (*SI Appendix*, Fig. S11). The 24-h incubation time is much longer than any anticipated endoscopic procedure; therefore, we are confident that our coating can prevent bacterial attachment in procedures performed in a shorter length of time. We also evaluated vision loss after contact with cellular debris (*SI Appendix*, Fig. S12), in low pH conditions (*SI Appendix*, Fig. S13), and after scratching (*SI Appendix*, Fig. S14), which are scenarios often encountered in various endoscopic procedures, and found no substantial reduction in performance.

To determine the efficacy of the surface coating in maintaining a clear operative field, we performed bronchoscopy in ex vivo and in vivo porcine lung models. The porcine model is frequently used in pulmonary research due to its similarities to humans in size and bronchial structures (36). First, we used an explanted porcine lung to test the function and resistance of a coated endoscope against lung surfactant, present to preserve lung compliancy (37). Due to its interfacial activity lung surfactant may compromise the coating's stability and contribute to impaired vision and fouling. After contact with airway secretions in the explanted lung, the uncoated endoscope was unable to retain a clear field of vision, whereas the coated scope maintained complete clarity (Fig. 4*A* and Movie S2). This encouraging result strongly indicates that the antifouling liquid-infused coating may indeed offer significant advantages in clinically important in vivo procedures, which we investigated next.

For this part of our study, we evaluated the performance during typical bronchoscopy procedures, such as airway inspections, endobronchial biopsies, and transbronchial biopsies, performed by pulmonologists in vivo on porcine lungs. The results are presented in Movies S3–S5 and extracted as images in Fig. 4. In all of the procedures, the likelihood of vision loss of a coated endoscope after contact with biological material is reduced by at least a factor of 2 compared with the uncoated reference (the control lost vision in ∼50% of all contacts, the coated endoscope in less than 20% and the vision loss in the latter case was partial and often transient). Moreover, these experiments are likely to have overestimated the quality of the uncoated control because residual silicone oil present in the intubation tube at entry points from the previous experiments with coated endoscopes may have deposited on the control in subsequent experiments, improving its operation.

The most striking difference in performance between the liquid-infused coating and the uncoated bronchoscope is observed during endobronchial biopsies where forceps are used to sample the carina. After withdrawal of the forceps, contact of the bronchoscope with the bleeding carina induces complete vision loss. Fig. 4*B* summarizes the results comparing the coated and uncoated instruments when both bronchoscopes were exposed to similar levels of bleeding. Of the three times that the biopsy was performed, the uncoated bronchoscope lost visibility all three times (Fig. 4*B* and Movie S3). Clearance on average took more than 1 min. In two instances, visibility was not completely retained even after intermittent rubbing and suction, leading to blind operation for more than 2 min. In contrast, the bronchoscope coated with the liquid-infused material maintained a clear field of vision (biopsy 1) or, if partial vision loss had occurred, visibility was restored rapidly (on average, in just 4 s) and with minor efforts (short contact with the wall or short suction to remove pooled blood) (Fig. 4*B* and Movie S4).

After a transbronchial biopsy (Movie S5) with the coated bronchoscope, significant bleeding necessitated the performance of a wedge; a procedure in which the bronchoscope is pressed against the bleeding site to form a plug that stops the blood flow and facilitates clotting to induce hemostasis. After two submersions in blood for ∼5 s, the field of vision remained completely clear (Fig. 4 *C*, *i*). Extensive suction (∼20 s) applied to remove the blood from the surrounding area before the wedge resulted in ∼50% fouling of the lens area and partial loss in vision (Fig. 4 *C*, *ii*). However, clarity was sufficient to allow the operator to visualize the airway, guide the bronchoscope to the site of bleeding, and perform the wedge in this critical situation involving bronchoscope exposure to a substantial amount of blood and to shear conditions imposed by the suction procedure. After 3 min, the bronchoscope was withdrawn from the bleeding site, and remarkably, more than 50% of the visual field remained clear, with occlusion occurring exclusively at the edge of the lens (quite likely due to edge effects whereby blood adherence starts on the uncoated sides of the endoscope). Short contact with the airway wall and suction completely clears the lens within seconds (Fig. 4 *C*, *ii*). This exceptional performance of the coated endoscope during extensive bleeding demonstrates the potential of the coating in one of the harshest environments encountered in bronchoscopy.

Beyond medical endoscopy, we demonstrate that the coating preserves full transparency on exposure to crude oil, sewage mimetic, and algae (*SI Appendix*, Fig. S15), showing its potential in camera-guided instruments used in sanitation, marine, and oil exploration.

Discussion

We demonstrated that liquid-infused repellent coatings can be used in camera-guided instruments to protect the lens from contamination and obstructed visibility. Such coatings applied on endoscope lenses provide unprecedented clarity of visual field after contact with a range of highly contaminating body fluids. In particular, a coating infused with 10-cSt silicone oil is shown to consistently repel blood when repeatedly submerged in it losing not more than 20% visibility, whereas the uncoated scope loses 100% of the field of view immediately after submersion. The former also drastically improves the repellency of mucus and lung surfactant. In vitro toxicity tests do not indicate any adverse effects. This coating was therefore tested in multiple bronchoscopies performed in vivo on porcine lungs. A range of clinically relevant procedures (endobronchial

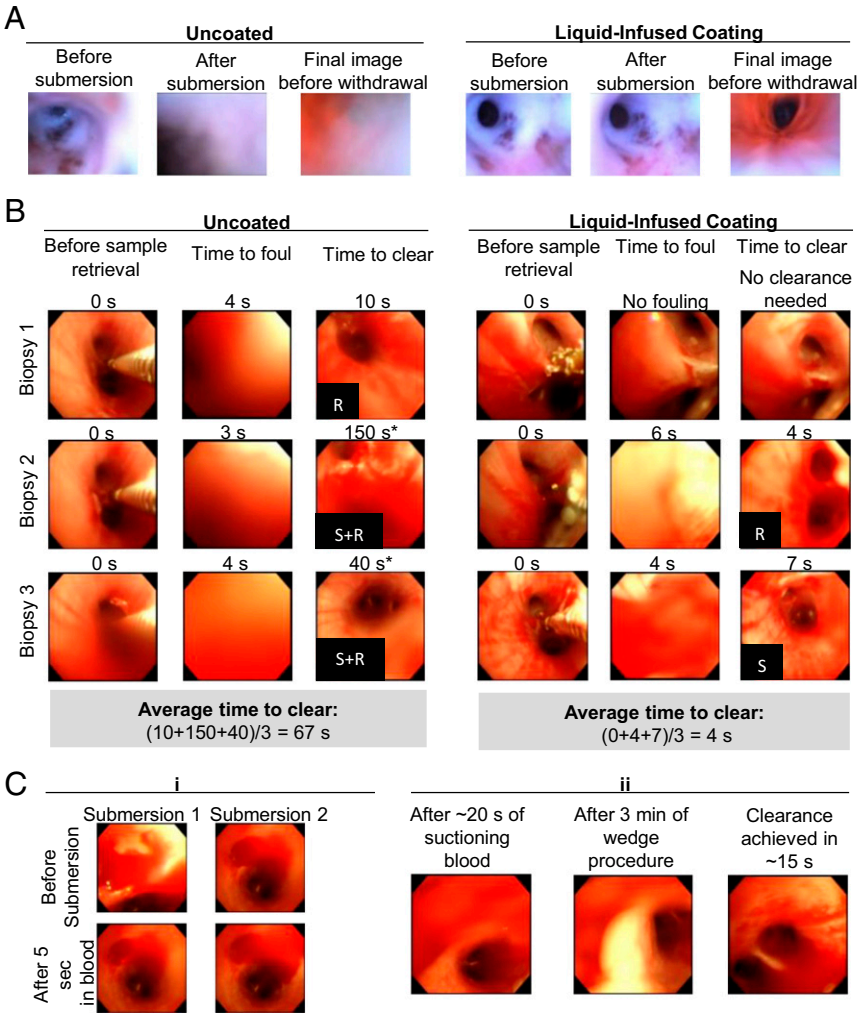

Fig. 4. Ex vivo and in vivo bronchoscopy procedures. (*A*) Contact of the endoscope with lung secretions in an ex vivo lung. (*B*) Endobronchial biopsies using an uncoated bronchoscope were performed in the right lung of a pig, whereas the liquid-infused coated bronchoscope sampled the left lung of the same animal. Methods used for the lens clearance are indicated on the bottom-left of the image: R, rubbing against airway walls; S, suction. The control endoscope fouls for all three biopsies with extensive suction and rubbing required for biopsies 2 and 3 (the symbol * in the "time to clear" indicates that even after intense clearance complete visibility was not regained). The average time for clearance for all three procedures was 67 s. The liquid-infused coating did not foul after the first biopsy and was quickly cleared using either suction or rubbing after the second and third biopsy with an average clearance time of 4 s. (*C*) Images obtained after performing a wedge. Visualization was entirely retained after two submersions in blood (*i*) and partially obstructed (~50% of clear field remained) after performing a 20-s blood suction and a 3-min wedge (*ii*).

biopsy, transbronchial biopsy, and transbronchial brushing) demonstrate that these antifouling liquid-infused coatings prevent loss of vision from blood occlusion and considerably reduce the clearance time needed to completely regain visibility, even in harsh environments involving strong bleeding. In contrast, the visual field of the uncoated endoscopes in both ex vivo and in vivo procedures are immediately compromised under the same experimental conditions and require extended (10–15 times longer) clearance times.

Solving lens fouling with a repellent, transparent surface coating has much broader implications in medicine, far beyond the improvement of visibility presented in this study. One particular consideration is that liquid-infused surfaces significantly reduce bacterial adhesion (18, 19, 24, 25, 38), which is a key advantage in endoscopy, considering the magnitude of the tragedy at the University of California, Los Angeles Medical Center, where seven patients were infected after the procedure with Carbapenem-resistant *Enterobacteriaceae* due to a lack of sufficient sterilization (39). More recently, outbreaks have occurred in hospitals in Seattle, Pittsburgh, and Chicago (40). We envision that in the future design of endoscopes, this coating can be applied directly to the endoscope lens or on a disposable cover. Direct application on the lens would require a simple relubrication after standard sterilization protocols, which would reduce bacterial adhesion and therefore possibility of infection.

Another potential consideration is the reduction in the duration of the procedure, with associated decrease in health care costs, and the increase in the number of treatments that could be performed. To put our results in perspective, for example, the time required for sample collection during a biopsy when no fouling occurs is only ~20–25 s. Therefore, the cleaning time after a fouling event in an uncoated bronchoscope (on average 67 s) is approximately two to five times the length of the sample collection duration, whereas in a coated endoscope, the cleaning time (on average 4 s) contributes only ~1/5th to the sample collection time. The total duration of one endobronchial biopsy from entry into the intubation channel to exit is ~1 min. These values indicate that physicians spend approximately equal time cleaning the lens as the total procedure in an uncoated bronchoscope, whereas in a coated instrument the cleaning adds merely 5–10% to the total procedure time and in many cases is not needed at all.

We have chosen bronchoscopy as one of the most challenging cases of medical endoscopy, in which highly delicate lung tissue with complex air/liquid interfaces is involved and thus common approaches of lens wiping, irrigation, and suction can lead to serious complications, including tissue injury, lung collapse, or dislodging of clots in the irrigated airways. Therefore, minimizing the use of the cleaning procedures, as shown in this study, will result in potential improvement in safety by decreasing the probability of tissue damage and associated complications, as well as of patient discomfort. The lubricated surface of the instrument is likely to further reduce discomfort during insertion and removal of the endoscope. There are also additional corner cases where this coating may be used, such as low pH environments encountered in gastroenterology.

Finally, it is important to emphasize the growing interest in miniaturized endoscopes that may enable the visualization of the most inaccessible regions of the human body. Further miniaturization of currently used scopes is impossible, as it will necessitate the elimination of the working channel, leaving doctors without the recourse of suction and irrigation to clear the visual field. Our results show that immersion in blood, mucus and secretions enable an uninterrupted airway inspection with the coated scope. The presence of such a coating may thus offer an unprecedented opportunity to design a flexible instrument without working channels, reducing its size to 2–3 mm, approximately the diameter of unimaged small airways. We believe therefore that liquid-infused coatings may provide a strategy to significantly expand the limits of the areas of the human body that physicians can currently image, offering enormous potential for improving disease diagnosis and treatment.

Although we chose to focus on a medical application, the findings of this study extend to the use of these coatings in other industries. The exceptional antifouling performance of this class of transparent materials has the potential to mitigate the effects of vision loss from highly contaminating liquids on inspection cameras in sewers for sanitation systems, oil field and underwater exploration, robotics, surveillance cameras, solar panels, and optical sensors. All these scenarios benefit from the improved visibility, reduction in cleaning times, and therefore decreased overall cost and enhanced functionality.

Materials and Methods

A 5.5-mm Eggsnow borescope was used to perform all blood and mucus dipping experiments. The toxicity studies were performed with OVA D1 mesenchymal stem cells. The in vivo bronchoscopy procedures were completed using an Olympus Bronchoscope (EXERA BF-160). The large animal study was approved by the Institutional Animal Care & Use Committee of Beth Israel Deaconess Medical Centre under Protocol 022-2015 (Performance of SLIPS-Bronchoscope in Swine Study). Detailed materials and methods are described in *SI Appendix, SI Materials and Methods*.

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