Rapid Fabrication of Sterile Medical Nasopharyngeal Swabs by Stereolithography for Widespread Testing in a Pandemic

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1. Introduction

The challenge of the local and global supply chain to respond to potential catastrophes is very high, as shown by the Federal Emergency Management Agency (FEMA) Supply Chain Resilience Guide.[1] Responses to natural disasters, such as hurricanes, have shown that even with historical analyses that prefigure response strategies, there remain a lack of readiness, awareness, and organization between governmental relief and private-sector supply networks in solving logistical bottlenecks, surges, and restoration.[2] The lack of preparedness is even greater when facing a pandemic, such as that of COVID-19, as unprecedented catastrophe development means that we rely only on a small subset of data from past events whose scale is not comparable to the current event, such as past epidemics like SARS and MERS, to come up with ideal solutions. To meet supply chain demands, mass production pipelines need time to ramp up their efficiency to provide a reliable flow of provisions. To bridge this time gap and solve this tactical problem, local communities can support and provide to supply chain resilience strategies through classical rapid prototyping. As FEMA recommends, community lifelines can effectively be repurposed for “maintaining or restoring the most critical services or infrastructure.”[1] In a matter of weeks, a local rapid short-term response can be made possible through fast design and fabrication methods provided by rapid prototyping. Over a series of months, the industrial mass production methods can scale up to respond to a global demand of resources. For example, shortage in ventilators was addressed by enthusiast communities who developed cost-effective, rapid prototyping-based, open-source designs of mechanized bag valve masks,[3,4] all in a matter of few single weeks from the state-of-emergency announcement on March 13, 2020, immediately resulting in an National Institutes of Health approval pipeline.[5] Any person with basic mechanical engineering skills could implement and troubleshoot such a ventilator in a day, enabling one to tactically meet immediate local needs. Later, in a more global and strategical approach to the shortage of ventilators, Ford Motors adopted its production line for an approved third-party commercially available design. Ford’s production of ventilators started on April 20 first with 500 units, continued into May with 10,000 units, and has an expectation to produce 30,000 units per month moving forward.[6] It should

The 3D printing of nasopharyngeal swabs during the COVID-19 pandemic presents a central case of how to efficiently address a break in the global supply chain of medical equipment. Herein a comprehensive study of swab design considerations for mass production by stereolithography is presented. The retention and comfort performance of a range of novel designs of 3D-printed swabs are compared with the standard flocked-head swab used in clinical environments. Sample retention of the 3D swab is governed by the volume, porosity density, and void fraction of the head as well as by the pore geometry. 3D-printed swabs outperform conventional flock-head swabs in terms of sample retention. It is argued that mechanically functional designs of the swab head, such as corkscrew-shaped heads and negative Poisson ratio heads, maximize sample retention and improve patient comfort. In addition, available designs of swab shafts for an optimized sample collection procedure are characterized. The study is conducted in vitro, using artificial mucus, covering the full range of human mucus viscosities in a 3D-printed model of a nasal cavity. The work sets the path for the resilient supply of widespread sterile testing equipment as a rapid response to the current and future pandemics.
be noted that to enable the maker communities to fill the gaps in supply chains of medical equipment effectively, an emergency approval process needs to be developed. While technology to close these gaps is available, the policy awaits optimization.

The natural capability of rapid prototyping to incorporate quick change in functional designs over a series of iterations, along with the recently increased use of digitalized technology and 3D printing in biomedical devices and biocompatible material application, makes rapid prototyping the obvious short-term response method of fabrication to meet supply chain needs.\(^ [7,8] \) In the current pandemic, the need for early widespread testing of COVID-19 has yielded a significant demand for nasopharyngeal swabs (NPS) and other testing materials. Additive manufacturing is increasingly used in biomedical applications in recent years.\(^ [7,9–11] \) Specifically, in test swabs production, it is capable of meeting the market needs while significantly simplifying the supply chain.\(^ [12] \) This paper details 3D-printed NPS as an alternative to existing mass produced equipment and compares our original designs to other open-source, computer-aided designed swabs developed by the online biomedical engineering community.

### 2. Comparative Design Review of NPS

Many comparative studies have been conducted prior to the COVID-19 pandemic to evaluate the performance of conventional specimen extraction methods in clinical studies. Efforts toward the development of new swab designs should base themselves first and foremost on the existing standards. Even so, imitation and innovation are not mutually exclusive processes. The different methods of specimen sampling, shown in Table 1, vary in terms of design parameters, including comfort, safety, accuracy, ease of self collection, and the ability to mimic these standard biomedical tools in rapid fabrication. The following discussion covers benefits and drawbacks of using nasal or nasopharyngeal wash, nasal aspirate (NA), oropharyngeal swab (OPS), nasal swab (NS), and NPS. The types of FDA-approved NPS for SARS-CoV-2 sampling are shown in Figure 1.

#### 2.1. Conventional Swabbing Tools

This section offers a comparison of the different approved methods for the detection of the SARS-CoV-2 virus. Background information about each method is available in Supporting Table 1.

| Parameters       | Conditions                                                                 |
|------------------|-----------------------------------------------------------------------------|
| **Constraints**  |                                                                             |
| Dimensions       | Head diameter, \( D_{\text{head}} = 3.0 \) mm                               |
|                  | Neck diameter, \( D_{\text{neck}} \approx 1.0 \) mm                         |
|                  | Handle diameter, \( D_{\text{handle}} = 2.5 \) mm                         |
|                  | Total swab Length, \( L_{\text{swab}} \geq 150.0 \) mm                    |
|                  | Head length, \( L_{\text{head}} \geq 15.0 \) mm                           |
|                  | Breakpoint from head, \( L_{\text{score}} = 70.0 \) mm                    |
| **Function**     | Swab must be compatible with specimen preparation for RT-PCR.              |
|                  | Swabs should withstand storage under freezing temperatures.               |
|                  | Swabs should be easily breakable at their score.                          |
|                  | Swabs should be autoclavable for complete sterilization.                   |
|                  | Swab should bend but not deform.                                           |
| **Safety**       | Swab features must not break off during use.                              |
|                  | Swabs should be sterilized before use.                                     |
|                  | Residual uncured liquid resin from 3D-printed swabs must be removed, through isopropyl alcohol or ethyl alcohol, and germicidal ultraviolet light, following exposure timescales that do not damage the material properties of the swabs. |
|                  | Designs should be optimized for mass production and limit random and systematic errors such that it does not affect the functionality and any potential harm to its user. |
|                  | Ecological concerns associated with fabrication, material, and disposal methods should be handled as appropriate. |

| **Objectives**   | Tip surface area should be maximized.                                      |
|                  | Surface features should be smooth and rounded, close to flocked swabs.     |
|                  | The experience should be comfortable when inserting, swabbing around, and withdrawing the head. |
|                  | Easy to use for self-collection.                                           |
|                  | A minimum production yield of thousands of swabs per day.                 |
|                  | The swab should be easy and comfortable to break off into the transport vial. |
|                  | Length of the swab head submerged in vial transport solution is about 30 mm. |

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Information. Virus detection from NA samples was shown to be superior to NPS samples.\textsuperscript{[16]} However, aspirate methods require additional suction equipment that does not make this tool cost effective, scalable, and easily implementable for widespread testing, unlike the range of different NS and NPS which are easy and safe and can be done anywhere without the need for additional devices.\textsuperscript{[17]} One study showed that patients found the nasal wash (NW) more comfortable, in addition to being a more effective method than NPS in pathogen detection by culture, but with reverse transcription polymerase chain reaction (RT-PCR), both methods were comparable.\textsuperscript{[18–20]} On the contrary, another comparison between self-administered foam NS versus staff-collected NW showed that the former was comfortable, easy, and preferred by patients over the latter.\textsuperscript{[20]} The adequate detection sensitivity when using NS for a wide range of respiratory viruses has been proven in previous clinical work,\textsuperscript{[17]} as well as for NPS,\textsuperscript{[21]} where it was shown that NPS sampling is more effective than OPS sampling, but NW is more sensitive than NPS sampling. Another study observed that although NPS was more reliable than OPS, it was not optimal and that the combination of the two had a better detection yield.\textsuperscript{[22,23]} However, data sensitivity must be balanced by the cost of additional swab fabrication, patient comfort, and compliance, hence why the additional use of OPS is unnecessary. A solution is to combine swab collection with saline spray, which showed to provide more sensitive results and was recommended as a better alternative to the high sensitivity of NW for conducting respiratory virus inspection.\textsuperscript{[20]}

Midturbinate swabs are designed to come into contact with a larger nasal surface area and for self-collection, as shown in Figure 2. Compared with other swabs, midturbinate swabs have an additional collar at the handle to guide the maximum insertion depths of 55 mm, tolerated for adults. The study showed that self-collected flocked midturbinate NSs were equivalent to staff-collected NS or NPS and more efficient than rayon NPS.\textsuperscript{[24]} Midturbinate swabs have shown to be less invasive and better suited for self-collection due to the safety collar, as well as similarly comfortable compared with NSs and at least as sensitive as standard NPSs.\textsuperscript{[23,26]} The longer conical flocked head maximizes mucus contact, enabling better collection of specimens while offering a safe method of respiratory cell collection.\textsuperscript{[27]} The major drawback of the collar in midturbinate swabs is in its rapid fabrication. Its structure takes more
volumetric space, thus reducing the number of swabs that can be printed in a batch when using stereolithography (SLA). Under noncrisis conditions, this is not an issue, but under current conditions, fast-paced production and item count are of the utmost priority.

Self-collected swabs have been proven to be a reliable alternative to healthcare worker-collected swabs, because self-swabbing is feasible without any necessary prior training.[20,24,25] Specifically, self-administered collection has proven to be useful in community-oriented research.[28] This could be a key facilitator of widespread testing of quarantined individuals during a pandemic outbreak and allow healthcare workers to allocate time to urgent treatment rather than testing. Furthermore, patients seem to prefer self-collection.[25] In a comparison of flocked nylon fiber swabs versus polyurethane foam swabs, as shown in Figure 1, it was found that the former had a larger interacting surface area, held more fluid volume, and could release the fluid more readily into the testing medium than the latter. However, the latter is better in performance when it comes to anterior nares swabbing.[29] Flocked nylon fiber swabs have been shown to collect more respiratory epithelial cells from the posterior nasopharynx.[30] Flocked swabs also have the advantage of preserving samples at its extremities, allowing for easy sample separation during specimen testing preparation.[25]

Another study showed that different swab material and head or bristle designs impact sampling differently based on the collection site. This same study claimed however that the design of the swab seemed to matter less than the location of the virus in the respiratory tract.[23]

This history of swab-type comparisons provides benchmarks for specimen volume collection, respiratory virus detection, comfort of use, flexibility, fabrication and scalability, cost effectiveness, and widespread implementation, as shown in Table 1. A variety of materials, beyond the polymers discussed here, have been used for swab designs in the past, including wood,[31] which suggests that using nontraditional materials for swab fabrication, such as dental photopolymers, is not far-fetched. Although dental photopolymers are not cost effective due to the chemical complexity of the polymer composite, their rapid production ability using affordable widespread precise equipment, in addition to their comparable functionality and efficiency, renders them an attractive possibility.

2.2. Open-Source Collaborative Designs

Countless additive manufacturing companies across the world have joined the COVID-19 response efforts through...
the fabrication of biomedical equipment such as swabs, ventilators, face shields, and more. Many universities have transitioned their courses online, and research has been limited to essential work, leading to the emergence of new collaborations between laboratories, manufacturers, and healthcare institutions, in part, yielding important considerations for swab design, fabrication methods, and validation protocols. These, combined with those that have resulted from our team’s collaborators—namely, Indiana University (IU) Protolab, IU Health, Eskenazi Health, and Deaconess Health—and previous assessments of regular manufactured swabs discussed in the previous section, have been listed in terms of constraints and objectives in Table 1.

2.3. Design Requirements

Designs must adhere strictly to requirements and avoid mass production printing errors, as the nasopharyngeal space is very sensitive and prone to tissue damage, bleeding, and irritation. Institutions seeking to develop their own designs should use these parameters as a reference for their work and should seek local partners for production and testing. Methods for assembling swabs with more conventional polymers, such as polypropylene (PP), polytetrafluoroethylene (PTFE), polydimethylsiloxane (PDMS), and more, safe adhesives, and wicking substrates have been reviewed.[15] However, this fabrication process is hardly scalable for high throughput and requires significant labor if not automated, meaning that this solution should be left to contributors with existing industrial capabilities to that effect. The design fabrication should not depend on the labor of untrained students, researchers, and other members of the local community, even given the crisis conditions. While some have suggested that only immunocompromised patients need sterilized swabs, and that all other swabs can simply be disinfected,[15] this is too low of a standard, especially when dealing with such a novel and dangerous virus. Further, as swabs are produced in mass, making sterilization the base requirement, as opposed to making separate batches of sterilized and disinfected swabs, is more efficient and eliminates the risk of caregivers, giving immunocompromised patients the wrong swab. Safety and efficiency are not only important to those producing swabs, but also to the frontline healthcare workers dealing with an already overwhelming workload.

2.4. Design Selection for Testing

At the Fibers and Additive Manufacturing Laboratory (FAMES Lab), we developed a variety of designs that meet the constraints and objectives of Table 1, as shown in Figure 1. These were designed to optimize specimen collection. They are printed out of biocompatible dental resin by SLA and their assessment is covered in the next sections. We include here designs X and XIV from Abiogenix and the University of South Florida, respectively. These parallel design efforts have been picked due to their high accuracy and precision, excellent surface finish, biocompatibility, thermal resistance, flexibility, and functionality. The hardened resin is a collection of low-molecular-weight monomers bonded by covalent bonds into a solid crosslinked unit. As polymerization is an ongoing reaction that is never fully complete, it often involves required postprocessing steps in the process. Photopolymers are slow to dissolve and instead swell and soften when absorbing a solvent.[33-35] Among light-activated composite resin types, dental resins have a history of flexibility, and functionality.

3. Rapid Prototyping and Fabrication

Rapid prototyping creates functional systems or part representation before the release of a commercial product. This process usually involves additive manufacturing, an automated, simple method of producing an object with complex geometry with speed, precision, limited resources, and processing steps, often from a computer-aided design. Rapid prototyping proves its efficiency also in times of crisis, such as the COVID-19 outbreak, where biomedical equipment needs to be available to caregivers with haste, with little time to optimize the otherwise robust traditional manufacturing processes such as injection molding. Rapid prototyping equipment also has the advantage of being available in many fabrication spaces, from research laboratories to industrial centers to community-operated collaborative workspaces, enabling the engagement of many toward the resolution of the present pandemic. SLA is used here as the additive manufacturing solution, as opposed to fused-deposition modeling, selected laser sintering, laminated object manufacturing, or digital light processing due to the requirements for high accuracy and precision, excellent surface finish, biocompatibility, thermal resistance, flexibility, and functionality.

3.1. Stereolithography

SLA is one of the oldest methods of 3D printing, invented by Hideo Kodama in 1981 as an automated fabrication of 3D objects through layers of hardened polymers by ultraviolet exposure.[32] Rapid prototyping through SLA enables us to 3D print objects with arbitrarily complex geometries and with critical demands on precision and accuracy. SLA is a 3D vat polymerization printing process that involves the change of properties of light-activated resin polymers when exposed to ultraviolet or visible light, namely photopolymerization. The polymer composition involves a variety of chemical components such as photoinitiators, absorbents, precursors, additives, and fillers. The hardened resin is a collection of low-molecular-weight monomers bonded by covalent bonds into a solid crosslinked unit. As polymerization is an ongoing reaction that is never fully complete, it often involves required postprocessing steps in the process. Photopolymers are slow to dissolve and instead swell and soften when absorbing a solvent.[33-35] Among light-activated composite resin types, dental resins have a history of...
use in dentistry, making it well suited to invasive human specimen sampling.

3.2. Autoclavable Dental Resins

In dentistry, the use of biocompatible photopolymers as an oral restorative biomaterial dates back to 1960s.[36,37] Dental resins are generally based off vinyl, polystyrene, or acrylic resins to be used as relining, die, impression, crown, and with other oral care applications.[48] Although biocompatibility resists precise definition in areas like tissue engineering,[39] in dentistry, an extended history of biocompatibility tests and protocols have been designed for local (mucosal and pulp toxicity) and systemic (allergic, estrogenic, mutagenicity, and more) adverse reactions in vitro, in animals, in clinical studies, as well as occupational cyclic exposure.[40–44] One notable biocompatible acute toxicity assessment test is performed on fish embryos, where their stages of development are observed for chemical effects from exposure to the material over time.[45] Furthermore, the effects of the photo-hardening transition from liquid to solid resin have also been studied for a variety of conditions, such as shrinkage, irradiation, or cure depth effects.[46–49]

Dental SG Resin (Formlabs, Inc.) as a photoactive resin is a light-yellow translucent liquid and contains toxic elements. It has a viscosity between 800 and 1500 mPa s and an approximate composition of 90% methacrylic oligomers,[50] a standard monomer group used in dental resins,[41] and 3% phosphine oxides[50] used for material color stability.[51] As the liquid resin holds toxic properties—causing possible irritation if ingested, inhaled, or through skin and eye contact—its curing process has to be followed strictly, especially for clinical applications.[52] Dental SG Resin has a type D durometer hardness value of 80 according to standard ISO 868:2003 and a Carpy impact strength of 2 according to standard ISO 20795-1:2013. In terms of flexibility, the material has a flexural strength greater or equal to 50 MPa and a flexural modulus greater or equal to 1500 MPa, according to standard ISO 20795-1:2013.[53] However, material properties can vary depending on the print geometry, temperature, and orientation. To address this concern, three-point bending tests done on swabs by Formlabs will be discussed in a later section of this paper.

The autoclave was first invented by Denis Papin in 1679 and is now a standard for sterilization used in biological and medical research and industry, hospitals, mortuaries, and waste disposal. Its cycle of operation combines saturated steam loaded with latent heat, elevated moist heat up to 134 °C or dry heat up to 180 °C, and pressure and clean water to create a germicidal environment and induce protein denaturation, within its sealed chamber. This standard process must be used for cleaning surgical tools and any implantable or intrusive medical equipment, such as swabs. The cured dental resin must therefore be stable both against heat and humidity in the autoclave process. Dental SG Resin has been designed in its proprietary chemical composition for that purpose, unlike Dental LT Resin by Formlabs. However, it has been observed that once autoclaved, the brittleness of the material increases requiring a further look into the properties of autoclaved dental resins.

4. Preclinical Swab Design Testing

In a preliminary step, certain observations of the mechanical performance of the selected swab designs were done, as shown in Figure 3. The roughness of the head designs was assessed to see what potential damage they could do to nasal tissue surfaces, by vigorously applying the design head onto a flat surface coated with wax. The head was first moved in an upward and downward direction and then rotated ten times. Although the head designs were not very rough overall, designs II, IV, and XIV showed the worst outcomes. The break-off of the swab head into transport vials was assessed by snapping each of the four types of shafts present among the selected designs. Design X was the only one showing resistance which can lead to frustration for a caregiver swiftly packing up collected specimen into a vial. The different neck bending capabilities of the four shaft types were also tested both before and after sterilization. It was observed that sterilization seems to make the dental resin more brittle. A simple test, shown in Figure 3, suggests that the angle of curvature barely changes. Formlabs ran a comparative study on the tensile (ASTM D638) and torsional tests of swab Design XIV, Puritan swabs, and Copan swabs, which met the dimension requirement of Table 1, included in Supporting Information. Snapped swab heads holding a viscous xanthan gum and Milli Q water solution (4.0 W V−1) were placed in 15 mL Falcon tubes in a centrifuge for 5 min at 3000 RPM and showed that collected samples were easy to extract from all head designs. Leaching of the artificial mucus was successful for every design, which is required for RT-PCR sample preparation. This viscous solution will be further discussed in the next section as a good model to mimic mucus properties. In terms of fabrication, using Form 3B (Formlabs, Inc.), a batch of 400 swabs can be printed with a reasonable large-print software processing time. In a calculation of a mass print of swab design V, the 400 swabs, arranged in a square array, representing 3196 layers of 50 μm-thick layers and a resin volume of 265.23 mL, would require 69 h and 23 min to print, 2–3 h of post-process, 45 min sterilization cycle, and cost about $113.07 to produce, that is 28 cents per unit swab, taking into account material, equipment operation energy consumption, and the hourly labor of a makerspace technician. More information on the printing parameters are provided in Supporting Information.

4.1. Artificial Mucus

Xanthan gum is a commonly used biopolymer, acting as a thickening agent for applications such as food, pharmaceutical, and cosmetic formulations.[54] The xanthan gum solution prepared from Xanthomonas campestris (Sigma-Aldrich, G1253) to mimic mucus with different viscosity properties will be hereinafter referred to as artificial mucus. Human mucus viscosity varies based on many factors, including the specific disease a patient is affected with, such as respiratory track diseases like rhinitis, chronic sinusitis, and chronic bronchitis.[55] A wide viscosity range was achieved by altering the percentage weight to volume of the xanthan gum powder, as shown in Figure 4, effectively covering a broad range of viscosity behaviors. Homogeneity of the artificial mucus highly depends on mixing method.
Highly viscous artificial mucus which is above 1% W/V needs more mixing time until the gum is dissolved homogeneously without any clumping. Xanthan gum powder should be mixed directly when exposed to Milli Q water. Xanthan gum powder may stick to the bottom of the beaker, though this can be prevented by a glass stirrer to collect all agglutinate powders from the bottom. Mixing with a magnetic stirrer caused air bubbles in the solution which were eliminated by the desiccator before the viscosity measurement of each concentration of the artificial mucus to obtain accurate viscosity data.

4.2. Mucus Retention Dipping Test

Printed NPS were dipped 30 mm deep according to design requirements in 50 mL conical Falcon tubes. During each test, swabs were introduced without touching the inside of the Falcon tube, which was necessary to keep the contact area with the artificial mucus consistently sterile for each trial. Shaft design and the head of the volume did not affect the retention rate because the dipping motion was directed vertically, straight down within the confinement of the diameter of the 50 mL falcon tube, which was wide enough for the manipulation of the head volume of all NPS designs. This consistency is shown in general by the amount of small error bars (see Supporting Information) for each of the concentrations of the artificial mucus, resulting in a more coherent visual comparison of the different selected NPS designs.

Five trials of the 11 dipping tests for the 10 different NPS swab designs were conducted across 7 different concentrations of artificial mucus, as shown in Figure 4. When overall results from all the artificial mucus concentrations were considered with the normalization by the total head volume of the NSP, the highest retention was found in design II and design VIII. These have a similar design that heavily relies on the surface tension of the collected liquid to hold itself in the hollow reservoir of the head. Design II has higher head volume than design VIII, enabling it to hold a greater volume of sputum. A dramatic increase in retention was observed with design VI and VII past a threshold off 2% W/V concentration of artificial mucus, as the latter’s viscosity increases. The dimension of the honeycomb structure affected the amount of artificial mucus collected by the NPS head in design VI and VII, suggesting that the larger honeycomb gaps result in better sample collection. NPS design II was designed alike Archimedes screw involving a specific rotational direction which helps withdraw sputum as the head is rotated during sample collection. Due to the direction-specific nature of this design, two dipping tests were administered clockwise and counterclockwise for design III. The results show that there is a slightly better retention rate when rotating the swab in the counterclockwise direction as expected.
We have compared the performance of 3D-printed designs to that of standard swabs (FLOQSwabs 503CS01, Copan Diagnostics). The result of those trials is shown in Figure 4, labeled as design XXI, where the flocked swab performed fine for low viscosities but surprisingly bad for higher viscosities, in terms of both average retention and its random variation, reflected by the larger error bars (see Supporting Information).

4.3. Nasal Model for Swab Behavior Analysis

The nasal model consists of a 3D-printed support structure, a 10 mL narrow mouth Erlenmeyer flask, and a plastic tube with an inner diameter of 6.35 mm, which was used to mimic the confined nose canal of the nasal cavity, as shown in Figure 5. The model simulated the nasal cavity, wherein the NPS has to be inserted to reach the nasopharynx, and was based on computed tomography measurements done on an asymptomatic adult-sized nasal air space. NPS designs with different shafts and different head volumes and the viscous behaviors of the artificial mucus both affected retention rates significantly. Due to the slight bend in the nasal pathway featured in the model, NSP with a rigid shaft design (designs V–VIII, X, and XIV) had a tendency to break while turning inside the 10 mL narrow-mouth Erlenmeyer flask. The flexible shaft performed much better with the nasal model. Large NPS heads (designs I–V) were not very efficient in the confined space of the tube. During the swab withdrawal step, a significant amount of the collected artificial mucus, especially the mucus with low viscous behavior, was lost. This loss invited instability in retention measurements for each trial with artificial mucus with same viscosity.

Taking these results into account and normalizing them in terms of volumetric flow when withdrawing the head out of the tube, the highest retention was found in design III (with both...
The volumetric flow equation is based on Stokes drag flow, shown in Equation (1), for which its derivation is provided in Supporting Information, where $V_{\text{out}}$ is the total volume withdrawn from the nasal model, $D_{\text{Tube}}$ is the tube diameter, $D_{\text{Head}}$ is the maximum head diameter, $L_{\text{Head}}$ is the length of the head, $V_{\text{out}}$ is the total volume withdrawn from the nasal model, and $V_{\text{Head}}$ is the volume of the swab head (see Figure 3).

$$V_{\text{out}} = \pi \cdot \left( D_{\text{Tube}}^2 - D_{\text{Head}}^2 \right) \cdot L_{\text{Head}} + V_{\text{Head}}$$

Equation (1): Volumetric flow of the withdrawn head with collected specimen, to which swab performances in the nasal model are normalized.

It is interesting to point out that in this test the clockwise direction of swab III performed better despite expectations. Design IV was created with a negative Poisson ratio, such that it would radially contract upon application of compressive stress along the head axis to maximize the patient’s comfort during insertion and would radially expand upon application of tensile stress along the head axis to maximize sample retention during extraction. Indeed, the geometric shape of the head provided better retention among most of the other NSP designs. To address the lack of rigid shaft performance in the bent confined model, a comparison between the performance of a flexible handle and a rigid handle for the same head design II and VIII was conducted, as shown in Figure 5. The results show that the difficulty in maneuverability of the shaft barely affects the retention capabilities of the head designs.

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The trials ran for the flopped swab, design XXI, shown in Figure 5, had a similar outcome as the dipping test. The flexibility of the industrial swab made the collection as easy as it was for designs I–IV, which have a flexible shaft. However, its retention
of artificial mucus with high viscosity was suboptimal, unlike its efficiency with lower viscosity behaviors which were adequate. All performances for both the dipping and nasal model tests are shown in Table 2.

5. Conclusion

Some preliminary results have suggested that conventional swabs outperform new prototypes. Our study highlights exactly which design factors may be responsible for these differences and thus offers insights into precisely how prototypes should be designed so as to improve upon the conventional swab design. In comparing a variety of original designs, we have demonstrated the efficiency of various surface porosity, geometries, and volumetric space optimizations. We have provided direction regarding the appropriate design for the shaft ability to snap easily swabs with collected specimen from their sacrificial handle, surface roughness comfort levels, and head and shaft dependence in confined airspaces. In our study we have provided a protocol for preclinical trials to observe mucus retention through an anatomical model and mimic the tenderness of human tissue in comfort level trials. In addition, we created a xanthan gum-based artificial mucus that covers the range of human mucus viscosity and can be used for future applications as a semisynthetic mucus model. Rapid prototyping and fabrication by SLA is an attractive option to consider for NP swab production. Especially given the current crisis, rapid prototyping offers the capability for quick, precise design and manufacture, which will in turn enable widespread, reliable testing for COVID-19. Widespread, reliable testing is necessary for the prompt diagnosis and treatment of the disease and ultimate management of the pandemic. Though not cost effective, dental photopolymers are an appealing material for a possible NP swab design given that they enable fast, precise fabrication and are conducive to the design constraints discussed in this paper. Importantly, the history of swab design and a comparison of existing designs provide a basis for future innovation.

6. Experimental Sections

3D Printing: A CAD model was printed by SLA in Dental SG Resin or Castable Wax, using a Form 3B printer (Formlabs, Inc.). Parts were then washed for 15 min in an isopropanol bath to remove leftover uncured resin. The parts were left to dry for 1 h. Unless the component was printed in castable wax, the parts were then cured under both ultraviolet and blue light of wavelength 400–500 nm (Dulux L BL 18 W/71 and Dulux L BL UVA 18 W/78 lamps) and heated at 60 °C. Biomedical equipment that required sterilization were then placed in an autoclave (Steris Amsco 250LS) for a full sterilization cycle of 45 min, reaching a maximum temperature of 123.6 °C.

Artificial Mucus Model: A total of 0.1, 0.3, 0.5, 1, 1.5, 2, and 4 g of xanthan gum from Xanthomonas campestris, purchased from Sigma-Aldrich, were mixed with 100 ml Milli Q water to reach the final concentrations of 0.1% W/V, 0.3% W/V, 0.5% W/V, 1% W/V, 1.5% W/V, 2% W/V, and 4% W/V xanthan gum/ Milli Q solutions. Solutions were mixed in a 250 mL glass beaker using a magnetic stirrer at 300 RPM at room temperature until the xanthan gum powder was mixed homogenously without any clumping. A glass stirring rod was used to mix the agglutinated xanthan gum on the bottom of glass beaker. Beakers were closed with parafilm to eliminate solution evaporation. All solutions were kept at room temperature for at least 12 h to complete the hydration process. Air bubbles in all solutions were eliminated with a vacuum supplied by a desiccator. Solutions were collected at 50 ml falcon tubes.

Viscosity Measurements: Viscosity of the xanthan gum/Milli Q solutions were measured with a Black Pearl Rotational Rheometer, ATS RheoSystems. Measurements were carried out with a 25 mm concentric cylinder system within a range of 0.1–300 RPM at 25 °C. A 15 mL sample volume was used for each measurement.

Dipping Retention Test: Swabs were dipped in 50 mL falcon tubes containing the artificial mucus. Test swabs were turned three times in the counterclockwise direction inside the falcon tubes. Design IV was specifically tested both clockwise and counterclockwise due to its design. The weight of each test swab was measured before and after being soaked with the artificial mucus using a Sartorius Secura Analytical Balance. The retention rate was measured with five trials for each concentration of the artificial mucus for each design.

Nasal Model Retention Test: The 3D design of the nasal structure was printed using Form 3B SLA printer (Formlabs, Inc.). A clear polyurethane tube (inner diameter = 6.35 mm, outer diameter = 9.52 mm) was used to mimic the nasal canal, through the nasal cavity, to the nasopharynx. Around 10 mL of each artificial mucus solution with different viscosities was poured into a 10 mL Erlenmeyer flask at the end of the tube, to mimic...
the sputum collection area in the nasopharynx. The housing structure for the nasal model was designed by CAD and 3D printed in Castable Wax by SLA in Form 3B (Formlabs, Inc.). The narrow mouth of the Erlenmeyer flask and the tube were sealed using paraffilm to eliminate possible leaks. Test swabs were put into the plastic tube through the 10 mL Erlenmeyer flask and turned three times inside each artificial mucus concentration. The weight of each test swab was measured before and after being dipped in the artificial mucus using a Sartorius Secura Analytical Balance. The retention rate was measured with five trials for each concentration of artificial mucus for each design.

**Flocked Swab Washing:** For the flocked swab (FLOQSwabs 503CS01, Copan Diagnostics) trials, between each consecutive testing, the swab was washed and dried. The flocked swab was cleaned with three wash and dry cycles, followed by three dipping cleaning in 5 mL warm water and the swab head was soaked for 10 min. The wet head was then dried with hot air for fast evaporation at 100 °C. No deformation or melting of the flocked head was observed during the drying phase. This process was repeated as necessary, typically no more than three times, until the cotton swab was clean and weighed its general weight with a precision of ±0.005 g.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

COVID-19, pandemic responses, rapid prototyping, swabs, widespread testings

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