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Original article

3D-printed simulator for nasopharyngeal swab collection for COVID-19

A. Koch [a,*], M. Vermel [a], Y. Hansmann [b], M. Lodi [a,c], C. Mura [b], A. Sananes [a], S. Gallien [d], É. Wurtz [e], A. Bleibtreu [f], M. Martinot [g], J. Exinger [h], X. Lescure [i], S. Kerneis [j], K. Lacombe [k], J.Y. Mootien [l], C. Shawali [m], L. Lecointre [a,n], C. Debry [o,p], N. Lefebvre [b], N. Sananes [a,o]

[a] Obstetrics department, Strasbourg university hospital, Strasbourg, France
[b] Infectious diseases department, Strasbourg university hospital, Strasbourg, France
[c] CNRS UMR 7104, Inserm U964, Institute of genetics and molecular and cellular biology (IGBMC), Illkirch-Graffenstaden, France
[d] Infectious diseases department, Créteil hospital, Créteil, France
[e] Infectious diseases department, Saverne hospital, Saverne, France
[f] Infectious diseases department, Pitié-Salpêtrière hospital, Paris, France
[g] Infectious diseases department, Pasteur hospital, Colmar, France
[h] Medical biology laboratory, Haguenau hospital, Haguenau, France
[i] Infectious diseases department, Bichat hospital, Paris, France
[j] Infectious diseases department, Cochin hospital, Paris, France
[k] Infectious diseases department, Saint-Antoine hospital, Paris, France
[l] Medical Intensive Care Unit, Mulhouse and South Alsace Regional hospital Center, Mulhouse, France
[m] Medical biology laboratory, Sélestat Hospital, Sélestat, France
[n] I-Cube UMR 7357, Engineering, Information Processing and Image Sciences Lab, Strasbourg university, Strasbourg, France
[o] Inserm UMR-S 1121 'Biomaterials and Bioengineering', Strasbourg university, Strasbourg, France
[p] ENT Department, Strasbourg University Hospital, Strasbourg, France

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A B S T R A C T

Objectives: Diagnosis of COVID-19 is essential to prevent the spread of SARS-CoV-2. Nasopharyngeal swabs (NPS) remain the gold standard in screening, although associated with false negative results (up to 30%). We developed a 3D simulator of the nasal and pharyngeal cavities for the learning and improvement of NPS collection.
Patients and methods: Simulator training sessions were carried out in 11 centers in France. A questionnaire assessing the simulator was administered at the end of the sessions. The study population included both healthcare workers (HCW) and volunteers from the general population.
Results: Out of 589 participants, overall satisfaction was scored 9.0 [8.9–9.1] on a scale of 0 to 10 with excellent results in the 16 evaluation items of each category (HCWs and general population, NPS novices and experienced). The simulator was considered very realistic (95%), easy to use (97%), useful to understand the anatomy (89%) and NPS sampling technique (93%). This educational tool was considered essential (93%). Participants felt their future NPS would be more reliable (72%), less painful (70%), easier to perform (88%) and that they would be carried out more serenely (90%). The mean number of NPS conducted on the simulator to feel at ease was two; technical fluency with the simulator can thus be acquired quickly.
Conclusion: Our simulator, whose 3D printing can be reproduced freely using a permanent open access link, is an essential educational tool to standardize the learning and improvement of NPS collection. It should enhance virus detection and thus contribute to better pandemic control.

1. Introduction

Testing is essential for controlling the COVID-19 pandemic since it enables better follow-up of epidemic markers, isolation of positive cases and where applicable contact tracing [1,2]. COVID-19 testing should be performed by obtaining a specimen from the upper respiratory tract [3]. Nasopharyngeal swab (NPS) collection

* Corresponding author. Obstetrics department, Strasbourg university hospital, rue Louis-Pasteur, 67300 Schiltigheim, France.
E-mail address: antoine.koch@chru-strasbourg.fr (A. Koch).

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Fig. 1. Nasopharyngeal swab collection simulator.

is currently the most widely used technique and represents the gold standard in screening, being more sensitive than oropharyngeal swabs and more accessible than bronchoalveolar lavage [4–6]. Saliva tests represent a good alternative, but their sensitivity and specificity remain inferior [7].

The launch of vaccines offers new hope for pandemic control [8]. The scientific community has indeed been working on their development since January 2020 [9–11]. Nevertheless, it is still a matter of debate whether immunization against SARS-CoV-2 will be long-lasting, whether induced by primary infection or by vaccination [12]. The emergence of variant strains with higher transmissibility also calls into question the efficacy of these vaccines [13,14]. Early testing for COVID-19, irrespective of the variant, thus remains essential for controlling the pandemic [15,16].

Nasopharyngeal swabs (NPS), already used on a wide scale, have few contraindications. Nevertheless, if poorly performed, they can be painful and lead to false negative results, of about 30% in current series: the resulting drop in sensitivity has potentially major epidemiological implications [5,17]. The specimen has to be acquired in the part of the nasopharyngeal tract where ACE2 receptor expression is at its highest [18,19]. It is nevertheless not easy for inexperienced personnel to locate and reach the nasopharynx [20]. With an ever-expanding number of screening tests, more and more healthcare professionals, whether or not properly trained in this procedure, are being called on to perform these tests. Therefore, appropriate training is not only essential to improve NPS sensitivity but also to reduce the number of "off-track" specimens, discomfort, turbinate injuries, and even cerebrospinal fluid leak [21–24].

Relevant educational content is available online, such as the video by Marty et al. [21]. Practical training nevertheless remains necessary and simulation teaching is potentially useful because trainees can thus practice in a realistic learning environment. This consideration led us to develop a synthetic simulator of the facial bones (Fig. 1), based on MRI and CT scans of patients: participants could readily train on this simulator, under completely safe conditions, especially from an infectious standpoint, and as often as they wished [25]. The simulator was produced by 3D printing and print files are freely available online.

At the current time, there are no data assessing this type of simulator. The objective of our study was to collate samplers' opinions regarding the realism and utility of this simulator for the learning and improvement of NPS collection.

Table 1
Socio-demographic and professional data of the total study population ($n = 589$).

	Total $n = 589$
Sex	
Male	195 (33.1%)
Female	393 (66.7%)
Mean age (years)	32.4 [31.4–33.4]
Profession	
Medical	244 (41.4%)
Paramedical	266 (45.2%)
Other	79 (13.4%)
Student	
Yes	238 (40.4%)
No	336 (57.0%)
Not specified	15 (2.5%)
Simulation experience	318 (54.0%)
NPS experience	270 (45.8%)
COVID-19 screening	227 (38.5%)
Screening for other infective agents	176 (29.9%)

2. Material and methods

2.1. Study design and population

This was a multicenter prospective survey carried out using a questionnaire in 11 university or general hospital test centers in France between June 2020 and October 2020. Centers were as follows: Bichat, Cochin, Pitié-Salpêtrière, and Saint-Antoine Hospitals (run by the university hospital trust operating in Paris and its surroundings [French acronym AP-HP]), the Paris Center for Training and Skills Development [Picpus]), as well as Strasbourg, Colmar, Haguenau, Mulhouse, Saverne, and Sélestat Hospitals. The first five centers are located in the Île-de-France region and the other six in Alsace; and thereby represent the two French regions most affected by the first wave of the epidemic. All persons in these centers who had to collect NPS were asked whether they wished to take part in the study. They were members of the caregivers (medical and paramedical personnel) as well as members of the general population.

2.2. Simulator

The nasopharyngeal swab collection (NP-SC) simulator was designed to high-level standards by BONE 3D (Paris, France) and is illustrated in Fig. 1 [25]. The simulator was designed to include the main anatomic landmarks: nasal bones (including turbinates), nasopharynx, hard palate, facial skin, and mucosa. Both parts have magnetic contacts, so they can be readily assembled and separated on the midline, illustrating a sagittal section through the nasal cavity. Nasopharyngeal swab collection can be performed via either nostril. Slots on the posterior wall of the nasopharynx allow for fitting a replaceable colored pad. Since it colors the swab tip on correct insertion, real-time feedback is provided to the user. A video presenting the simulator is freely available online via this link: https://landing.bone3d.com/np-swab-simulator, as well as comprehensive 3D files for printing and full instructions for manufacturing models.

2.3. Simulation procedure and data collection

A dedicated trainer in each center gave oral explanations on the use of the simulator at the beginning of each session. A descriptive video on using the simulator was also viewed by participants. Participants were then able to train on the simulator as often as

Table 2
Number of NPS needed to feel at ease and overall satisfaction at each center.

	Number of NPS needed to feel at ease (mean ± SD)	Overall satisfaction out of 10 (mean ± SD)
Alsace (*n* = 324)	2.0 [1.8–2.2]	9.0 [8.9–9.2]
Colmar – RHC (*n* = 34)	2.3 [1.9–2.7]	8.2 [7.7–8.6]
Haguenau – RHC (*n* = 32)	1.4 [1.1–1.6]	9.2 [8.9–9.5]
Mulhouse – RHC (*n* = 21)	1.8 [1.3–2.2]	7.6 [7.0–8.3]
Saverne – RHC (*n* = 68)	1.6 [1.0–2.2]	9.1 [8.8–9.4]
Sélestat – RHC (*n* = 17)	1.8 [1.3–2.3]	9.4 [8.9–9.8]
Strasbourg – UHC (*n* = 152)	2.2 [2.0–2.5]	9.3 [9.1–9.5]
Île-de-France (*n* = 265)	1.6 [1.5–1.7]	9.0 [8.9–9.1]
Bichat – UHC (*n* = 31)	2.3 [1.8–2.7]	8.7 [8.4–9.1]
Cochin – UHC (*n* = 29)	1.8 [1.2–2.3]	8.9 [8.4–9.4]
Picpus – Training Centre (*n* = 143)	1.4 [1.3–1.5]	9.0 [8.9–9.2]
Pitié-Salpêtrière – UHC (*n* = 39)	1.9 [1.6–2.3]	9.6 [9.4–9.8]
Saint-Antoine – UHC (*n* = 23)	1.7 [1.1–2.3]	7.7 [6.6–8.8]
University hospitals (*n* = 274)	2.1 [1.9–2.3]	9.1 [9.0–9.3]
Regional hospitals (*n* = 172)	1.8 [1.5–2.0]	8.8 [8.6–9.0]

RHC: Regional Hospital Centre; UHC: University Hospital Centre.

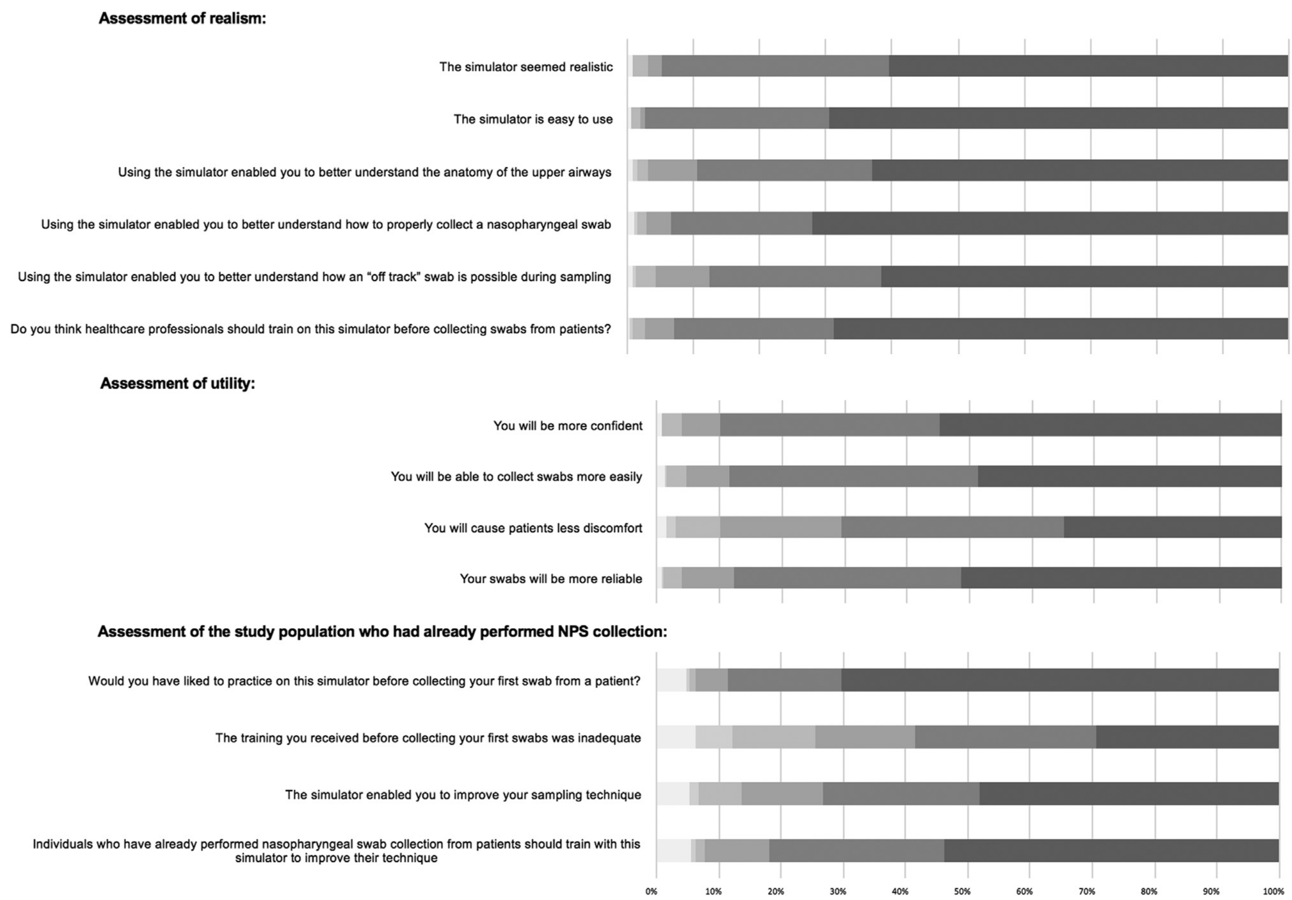

Fig. 2. Assessment of the simulator's realism and utility in the total study population (*n* = 589) and in those who had already performed NPS collection (*n* = 270).

they thought necessary. At the end of the session, all participants were invited to independently complete an original 16-item questionnaire in French assessing the simulator, either by free-field responses or using a 5-point Likert scale. We developed this questionnaire in a multidisciplinary way, which was then tested at the Strasbourg test center for validation. These questions focused on the number of specimens needed before feeling comfortable with the technique, feelings about the quality of future NPS, and overall satisfaction. The questionnaire also requested socio-demographic and professional data (age, profession, student status) and asked about previous experience in simulation and possible prior experience with collecting NPS.

Collated data were processed anonymously, and the questionnaire included a form in which participants had to state that they had no objection to data collection. The study was registered with the French Data Protection Authority (French acronym CNIL, No. 2221408). The study was structured in accordance with the Helsinki Declaration principles.

Infectious Diseases Now 52 (2022) 138–144

Table 3
Assessment of the simulator based on professional categories, professional experience, and NPS collection experience.

	Medical (*n* = 244)	Paramedical (*n* = 266)	*P*-value	Medical and paramedical students (*n* = 225)	Medical and paramedical seniors (*n* = 272)	*P*-value	NPS novices (*n* = 319)	Persons with NPS experience (*n* = 268)	*P*-value
Mean age	28.5 [27.2–29.8]	34.7 [33.2–36.2]	< 0.0001	23.6 [22.9–24.2]	38.5 [37.2–39.9]	< 0.0001	31.8 [30.4–33.3]	33.1 [31.8–34.5]	< 0.001
Student									
Yes	73%	18%	< 0.0001	NA	NA		47%	33%	< 0.01
No	27%	77%		NA	NA		51%	64%	
Simulation experience									
Yes	68%	48%	< 0.001	67%	52%	< 0.001	47%	62%	< 0.001
No	30%	44%		29%	43%		47%	32%	
NPS experience (COVID-19 or other infective agents)									
Yes	48%	56%	0.08	39%	63%	< 0.0001	NA	NA	
No	52%	44%		61%	37%		NA	NA	
The simulator	*n* = 244	*n* = 266		*n* = 225	*n* = 272		*n* = 319	*n* = 268	
Seemed realistic	4.6 [4.5–4.7]	4.5 [4.4–4.6]	0.25	4.6 [4.5–4.7]	4.5 [4.4–4.6]	0.71	4.6 [4.5–4.6]	4.5 [4.4–4.6]	0.39
Was easy to use	4.7 [4.6–4.7]	4.6 [4.6–4.7]	0.90	4.7 [4.6–4.7]	4.7 [4.6–4.7}	0.72	4.7 [4.6–4.7]	4.6 [4.5–4.7]	0.50
Enabled you to better understand the anatomy of the upper airways	4.4 [4.3–4.5]	4.6 [4.5–4.6]	0.005	4.5 [4.4–4.6]	4.4 [4.3–4.5]	0.69	4.6 [4.6–4.7]	4.3 [4.2–4.4]	< 0.0001
Enabled you to better understand how to properly collect NPS	4.6 [4.5–4.7]	4.7 [4.6–4.7]	0.11	4.7 [4.6–4.8]	4.6 [4.5–4.7]	0.18	4.8 [4.7–4.8]	4.5 [4.4–4.6]	< 0.0001
Enabled you to better understand how an “off track” swab is possible during sampling	4.4 [4.3–4.5]	4.5 [4.4–4.6]	0.52	4.5 [4.4–4.6]	4.4 [4.3–4.5]	0.21	4.6 [4.6–4.7]	4.3 [4.2–4.4]	< 0.0001
Do you think it necessary to train with this simulator before collecting NPS in patients?	4.5 [4.4–4.6]	4.6 [4.5–4.7]	0.002	4.6 [4.5–4.7]	4.5 [4.4–4.6]	0.71	4.8 [4.7–4.8]	4.4 [4.3–4.5]	**< 0.0001**
When collecting swabs in the future, do you think that thanks to this simulator	*n* = 244	*n* = 266		*n* = 225	*n* = 272		*n* = 319	*n* = 268	
You will be more confident?	4.4 [4.3–4.5]	4.4 [4.3–4.5]	0.08	4.5 [4.4–4.5]	4.4 [4.3–4.5]	0.75	4.6 [4.5–4.6]	4.3 [4.1–4.4]	< 0.0001
You will be able to collect swabs more easily?	4.3 [4.2–4.4]	4.4 [4.3–4.5]	0.08	4.4 [4.3–4.5]	4.3 [4.2–4.4]	0.78	4.5 [4.4–4.5]	4.2 [4.1–4.3]	< 0.01
You will cause patients less discomfort?	3.9 [3.7–4.0]	4.0 [3.9–4.1]	0.05	4.0 [3.9–4.1]	3.9 [3.7–4.0]	0.12	4.2 [4.1–4.2]	3.8 [3.6–3.9]	< 0.0001
Your swabs will be more reliable?	4.3 [4.2–4.4]	4.4 [4.3–4.5]	0.22	4.4 [4.4–4.5]	4.3 [4.2–4.4]	0.16	4.5 [4.4–4.6]	4.2 [4.1–4.3]	< 0.01
If you have already performed NPS collection	*n* = 118	*n* = 149		*n* = 87	*n* = 172			*n* = 268	
Would you have liked to practice on this simulator before collecting your first NPS from a patient?	4.6 [4.5–4.8]	4.7 [4.6–4.8]	0.39	4.7 [4.5–4.8]	4.6 [4.5–4.7]	0.62	NA	4.6 [4.6–4.7]	NA
The training you received before collecting your first NPS was inadequate	3.4 [3.2–3.6]	3.9 [3.7–4.1]	< 0.001	3.4 [3.1–3.7]	3.8 [3.6–4.0]	0.02	NA	3.7 [3.5–3.8]	NA
The simulator enabled you to improve your sampling technique	4.1 [3.9–4.2]	4.3 [4.1–4.4]	0.11	4.1 [3.9–4.4]	4.2 [4.1–4.4]	0.27	NA	4.2 [4.0–4.3]	NA
Individuals who have already collected NPS from patients should train on this simulator to improve their technique.	4.4 [4.2–4.5]	4.5 [4.3–4.6]	0.52	4.3 [4.1–4.5]	4.4 [4.3–4.6]	0.17	NA	4.4 [4.3–4.5]	NA
How many times did you need to collect a simulated NPS on the manikin before feeling at ease?	2.1 [1.9–2.2]	1.7 [1.5–1.9]	< 0.0001	2.0 [1.8–2.2]	1.8 [1.6–2.0]	0.03	1.9 [1.8–2.1]	1.7 [1.6–1.8]	0.02
Overall satisfaction (mean/10)	9.0 [8.9–9.2]	9.0 [8.8–9.1]	0.87	9.1 [9.0–9.3]	8.9 [8.7–9.1]	0.03	9.2 [9.1–9.3]	8.8 [8.6–9.0]	< 0.01

Two-tailed Mann-Whitney-Wilcoxon test. $\chi 2$ test with Yates correction.

2.4. Statistical analysis

Data were initially analyzed descriptively as a percentage or mean estimation with 95% confidence interval. Statistical analyses were then carried out using the R statistics program version 4.0.3. To compare qualitative variables, we carried out two-tailed χ^2 tests with Yates' correction (or Fisher's exact tests for small size samples). To compare quantitative variables, we applied a two-tailed Mann-Whitney-Wilcoxon test. The difference was considered significant if $P < 0.05$.

3. Results

During the study period, a total of 589 participants tested the simulator and answered the questionnaire. The study population consisted of 244 (41.4%) medical caregivers (physicians and medical students, midwives), 266 (45.2%) paramedical caregivers (nurses, auxiliary nurses, paramedics, medical regulatory assistants, psychologists, physical therapists, firemen, rescuers, laboratory technicians and students in all these different categories), and 79 (13.4%) persons not belonging to these professional categories (Table 1). There were 238 (40.4%) students. Lastly, 318 (54.0%) persons already had some experience in simulation and 270 (45.8%) prior experience with NPS collection.

The mean number of NPS conducted on the simulator for the operator to feel at ease was 1.8 [1.7–1.9]. Overall satisfaction was 9.0 [8.9–9.1] using a 0–10 scale. These results were similar in all study centers (Table 2).

Of the entire study population (Fig. 2), 95% ($n = 558$) agreed or strongly agreed that the simulator was realistic, 97% ($n = 573$) that it was easy to use, 89% ($n = 527$) that it led to a better understanding of the upper airway anatomy, 93% ($n = 550$) to a better understanding of proper NPS collection, 88% ($n = 516$) to a better understanding of the risk of going "off track", and 93% ($n = 547$) that it was necessary to train with this simulator before collecting NPS in patients. Furthermore, 90% ($n = 529$) agreed or strongly agreed that the simulator made them more confident, 88% ($n = 521$) that future NPS would be easier, 70% ($n = 415$) that they would be less painful for patients and 72% ($n = 516$) that they would be more reliable.

Of those participants who had performed NPS in the past ($n = 270$), 89% ($n = 239$) agreed or strongly agreed that they would have benefited from training on this simulator before collecting their first NPS, 59% ($n = 158$) that their initial training had been inadequate, 73% ($n = 198$) that the simulator improved the sampling technique, and 82% ($n = 221$) that training was necessary even for those who had already collected NPS.

Table 3 compares results between medical and paramedical staff, between students and seniors, and between NPS novices and more experienced participants. Satisfaction scores were high in all groups, irrespective of the category.

4. Discussion

Our study shows that the NPS simulator was rated as being very realistic and easy to use by users. Most of the study population thought that the simulator was beneficial as a teaching aid. Satisfaction scores were high in all categories, whether users were members of the medical or paramedical staff, students or senior, NPS novices or more experienced.

Illustrations and videos have been published with the aim of training people to perform NPS collection [20,21]. Use of simulation has also engaged other teams. Chee et al. [26] assessed an NPS simulator manufactured as a 3D reconstruction of the nose. All 23 participants felt more confident after the exercise but reckoned that the simulator did not allow for a good understanding of the nasopharynx position (only 38% of participants reported being satisfied, whereas 89% were satisfied with our simulator). Mark et al. [27] also tested the utility of learning sessions on a Laerdal Airway Management Trainer® manikin with 46 nurses. NPS were collected under the supervision of an ENT specialist who explained to the nurses how to angle the swab and reach the optimal depth. Self-assessment scores on sample quality were boosted by 1.4 points (95% CI, 1.1–1.7), rising from 3.1 to 4.5 ($P < 0.0001$) on a five-item Likert scale. Nevertheless, checking that the swab was anatomically in the right place was not possible. Boscolo Nata et al. [28] had accordingly suggested that it could be beneficial to use a simulator which could be opened on the midline, thus enabling better visualization of the anatomy of the nasopharynx and targeting zone to be reached: this is precisely what our simulator allows [25]. Moreover, coloration of the swab by the blotting paper positioned in the nasopharynx even provides immediate feedback to users on the specimen quality.

Use of a nasal fiberscope for precise collection of nasopharyngeal secretions has also been suggested [29]. Although highly precise, nasal fiberscopy comes with significant constraints in terms of allotted cost, time, and means. Our simulator, for which 3D print files are available free of charge online, was devised in two versions so that it could be readily and freely shared worldwide: a very realistic multi-material model and a mono-material model. The first model, as evaluated above, is more realistic as it is composed of several materials which enable the flexibility of different landmarks and tissues to be mimicked. The second model, currently under evaluation, is less costly as it is made from a single type of plastic and printed at a lower resolution. It can be manufactured on a non-professional 3D printer using FDM technology or even at home [25].

The strength of our study is its large, multicenter study population which also includes various subpopulations of interest. The questionnaire also enables several aspects of the simulator to be assessed both in terms of realism and of teaching utility.

This questionnaire nonetheless remains subjective and does not provide real assessment of the clinical impact of the simulator. Moreover, we did not assess the number of samples properly collected using the color pad. Instead, participants were asked to answer the question about the number of swabs needed to feel at ease with the procedure. A study comparing the sensitivity of NPS collected, along with the incidence of pain and/or inferior turbinate injuries before and after simulator training is desirable. It should also be noted that the simulator reproduces a normal anatomy and is therefore less adapted for individuals with a deviated nasal septum or hypertrophied inferior turbinate.

Three studies also showed the utility of anterior self-collected specimens (tongue, nose, or middle turbinate) in the diagnosis of COVID-19 [30–32]. Our simulator could also be used by patients wishing to learn how to self-collect.

5. Conclusion

To improve the sensitivity of NPS collection performed in the context of COVID-19, we developed a 3D nasopharyngeal simulator which is realistic, educational, and easy to use. It should enhance virus detection and thus contribute to a better pandemic control.

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Disclosure of interest

The authors declare that they have no competing interest.

Availability of data and material (data transparency)

A video presenting the simulator is freely available online via this link: https://landing.bone3d.com/np-swab-simulator, as well as comprehensive 3D files for printing and full instructions for manufacturing models.

Code availability (software application or custom code)

Not applicable.

Contribution of authors

Antoine Koch: conceptualization, methodology, validation, investigation, resources, writing – original draft, supervision, project administration

Muriel Vermel: data curation, writing – original draft.

Yves Hansmann: conceptualization, writing – review & editing.

Massimo Lodi: conceptualization, methodology, formal analysis, writing – review & editing.

Clément Mura: data curation, writing – review & editing.

Axel Sananes: conceptualization, writing – review & editing.

Sébastien Gallien: investigation, writing – review & editing.

Elisabeth Wurtz: investigation, writing – review & editing.

Alexandre Bleibtreu: investigation, writing – review & editing.

Martin Martinot: investigation, writing – review & editing.

Julien Exinger: investigation, writing – review & editing.

Xavier Lescure: investigation, writing – review & editing.

Solen Kerneis: investigation, writing – review & editing.

Karine Lacombe: investigation, writing – review & editing.

Joy Y. Mootien: investigation, writing – review & editing.

Cédric Shawali: investigation, writing – review & editing.

Lise Lecointre: conceptualization, writing – review & editing.

Christian Debry: conceptualization, methodology, validation, writing – review & editing.

Nicolas Lefebvre: conceptualization, methodology, validation, writing – review & editing.

Nicolas Sananes: conceptualization, methodology, validation, resources, funding acquisition writing – review & editing.

Ethics approval

The study was registered with the French Data Protection Authority (CNIL No. 2221408). The study was structured in accordance with the principles of the Helsinki Declaration.

Consent to participate and consent for publication

Collated data were processed anonymously, and the questionnaire included a form in which participants had to state that they had no objection to data collection.

References

[1] Alwan NA, Burgess RA, Ashworth S, et al. Scientific consensus on the COVID-19 pandemic: we need to act now. Lancet Lond Engl 2020;396(10260):e71–2, http://dx.doi.org/10.1016/S0140-6736(20)32153-X.

[2] Fineberg HV. Ten weeks to crush the curve. N Engl J Med 2020;382(17):e37, http://dx.doi.org/10.1056/NEJMe2007263.

[3] Zou L, Ruan F, Huang M, et al. SARS-CoV-2 viral load in upper respiratory specimens of infected patients. N Engl J Med 2020;382(12):1177–9, http://dx.doi.org/10.1056/NEJMc2001737.

[4] Wang X, Tan L, Wang X, et al. Comparison of nasopharyngeal and oropharyngeal swabs for SARS-CoV-2 detection in 353 patients received tests with both specimens simultaneously. Int J Infect Dis 2020;94:107–9, http://dx.doi.org/10.1016/j.ijid.2020.04.023.

[5] Loeffelholz MJ, Tang Y-W. Laboratory diagnosis of emerging human coronavirus infections – the state of the art. Emerg Microbes Infect 2020;9(1):747–56, http://dx.doi.org/10.1080/22221751.2020.1745095.

[6] Bwire GM, Majigo MV, Njiro BJ, Mawazo A. Detection profile of SARS-CoV-2 using RT-PCR in different types of clinical specimens: a systematic review and meta-analysis. J Med Virol 2021;93(2):719–25, http://dx.doi.org/10.1002/jmv.26349.

[7] Ibrahimi N, Delaunay-Moisan A, Hill C, Le Teuff G, Rupprecht J-F, Thuret J-Y, et al. Screening for SARS-CoV-2 by RT-PCR: Saliva or nasopharyngeal swab? Rapid review and meta-analysis. PloS One 2021;16(6):e0253007, http://dx.doi.org/10.1371/journal.pone.0253007.

[8] Lurie N, Saville M, Hatchett R, Halton J. Developing Covid-19 Vaccines at Pandemic Speed. N Engl J Med 2020;382(21):1969–73, http://dx.doi.org/10.1056/NEJMp2005630.

[9] Anderson EJ, Rouphael NG, Widge AT, et al. Safety and immunogenicity of SARS-CoV-2 mRNA-1273 vaccine in older adults. N Engl J Med 2020;383(25):2427–38, http://dx.doi.org/10.1056/NEJMoa2028436.

[10] Polack FP, Thomas SJ, Kitchin N, et al. Safety and efficacy of the BNT162b2 mRNA Covid-19 vaccine. N Engl J Med 2020;383(27):2603–15, http://dx.doi.org/10.1056/NEJMoa2034577.

[11] Richmond P, Hatchuel L, Dong M, et al. Safety and immunogenicity of S-Trimer (SCB-2019), a protein subunit vaccine candidate for COVID-19 in healthy adults: a phase 1, randomised, double-blind, placebo-controlled trial. Lancet 2021;397(10275):682–94, http://dx.doi.org/10.1016/S0140-6736(21)00241-5.

[12] Widge AT, Rouphael NG, Jackson LA, et al. Durability of responses after SARS-CoV-2 mRNA-1273 vaccination. N Engl J Med 2021;384(1):80–2, http://dx.doi.org/10.1056/NEJMc2032195.

[13] Tegally H, Wilkinson E, Giovanetti M, et al. Detection of a SARS-CoV-2 variant of concern in South Africa. Nature 2021;592(7854):438–43, http://dx.doi.org/10.1038/s41586-021-03402-9.

[14] Callaway E. Could new COVID variants undermine vaccines? Labs scramble to find out. Nature 2021;589(7841):177–8, http://dx.doi.org/10.1038/d41586-021-00031-0.

[15] Botti-Lodovico Y, Rosenberg E, Sabeti PC. Testing in a Pandemic — improving access, coordination, and prioritization. N Engl J Med 2021;384(3):197–9, http://dx.doi.org/10.1056/NEJMp2025173.

[16] Priesemann V, Balling R, Brinkmann MM, et al. An action plan for pan-European defence against new SARS-CoV-2 variants. Lancet Lond Engl 2021;397(10273):469–70, http://dx.doi.org/10.1016/S0140-6736(21)00150-1.

[17] Woloshin S, Patel N, Kesselheim AS. False negative tests for SARS-CoV-2 Infection — challenges and implications. N Engl J Med 2020;383(6):e38, http://dx.doi.org/10.1056/NEJMp2015897.

[18] Sungnak W, Huang N, Bécavin C, et al. SARS-CoV-2 entry factors are highly expressed in nasal epithelial cells together with innate immune genes. Nat Med 2020;26(5):681–7, http://dx.doi.org/10.1038/s41591-020-0868-6.

[19] Lu R, Zhao X, Li J, et al. Genomic characterisation and epidemiology of 2019 novel coronavirus: implications for virus origins and receptor binding. Lancet Lond Engl 2020;395(10224):565–74, http://dx.doi.org/10.1016/S0140-6736(20)30251-8.

[20] Higgins TS, Wu AW, Ting JY. SARS-CoV-2 nasopharyngeal swab testing — false-negative results from a pervasive anatomical misconception. JAMA Otolaryngol Neck Surg 2020;146(11):993–4, http://dx.doi.org/10.1001/jamaoto.2020.2946.

[21] Marty FM, Chen K, Verrill KA. How to obtain a nasopharyngeal swab specimen. N Engl J Med 2020;382(22):e76, http://dx.doi.org/10.1056/NEJMvcm2010260.

[22] Föh B, Borsche M, Balck A, et al. Complications of nasal and pharyngeal swabs: a relevant challenge of the COVID-19 pandemic? Eur Respir J 2021;57(4):2004004, http://dx.doi.org/10.1183/13993003.04004-2020.

[23] Alberola-Amores FJ, Valdeolivas-Urbelz E, Torregrosa-Ortiz M, Álvarez-Sauco M, Alom-Poveda J. Meningitis due to cerebrospinal fluid leak after nasal swab testing for COVID-19. Eur J Neurol 2021;28(11):e91–2, http://dx.doi.org/10.1111/ene.14736.

[24] Sullivan CB, Schwalje AT, Jensen M, et al. Cerebrospinal fluid leak after nasal swab testing for coronavirus disease 2019. JAMA Otolaryngol Head Neck Surg 2020;146(12):1179–81, http://dx.doi.org/10.1001/jamaoto.2020.3579.

[25] Sananès N, Lodi M, Koch A, et al. 3D-printed simulator for nasopharyngeal swab collection for COVID-19. Eur Arch Otorhinolaryngol 2020;278(7):2649–51, http://dx.doi.org/10.1007/s00405-020-06454-1.

[26] Chee J, Lin X, Lim WS, Loh WS, Thong M, Ng L. Using 3D-printed nose models in nasopharyngeal swab training. Oral Oncol 2020;113:105033, http://dx.doi.org/10.1016/j.oraloncology.2020.105033.

[27] Mark ME, LoSavio P, Husain I, Papagiannopoulos P, Batra PS, Tajudeen BA. Effect of implementing simulation education on health care worker comfort with nasopharyngeal swabbing for COVID-19. Otolaryngol Neck Surg 2020;163(2):271–4, http://dx.doi.org/10.1177/0194599820933168.

[28] Boscolo Nata F, Pedruzzi B, Ferri E, et al. Could a mannequin simplify rhinopharyngeal swab collection in COVID 19 patients? Eur Arch Otorhinolaryngol 2020;277(10):2947–8, http://dx.doi.org/10.1007/s00405-020-06113-5.

[29] Tagliabue M, Pietrobon G, Ugolini S, Chu F, Ansarin M. Nasopharyngeal swabs during SARS-CoV-2 pandemic: a role for the otolaryngologist. Eur Arch Otorhinolaryngol 2020;277(7):2155–7, http://dx.doi.org/10.1007/s00405-020-06027-2.
[30] Tu Y-P, Jennings R, Hart B, et al. Swabs collected by patients or health care workers for SARS-CoV-2 testing. N Engl J Med 2020;383(5):494–6, http://dx.doi.org/10.1056/NEJMc2016321.
[31] Therchilsen JH, von Buchwald C, Koch A, et al. Self-collected versus healthcare worker-collected swabs in the diagnosis of severe acute respiratory syndrome Coronavirus 2. Diagnostics 2020;10(9):678, http://dx.doi.org/10.3390/diagnostics10090678.
[32] Kojima N, Turner F, Slepnev V, et al. Self-collected oral fluid and nasal swabs demonstrate comparable sensitivity to clinician collected nasopharyngeal swabs for Coronarovirus disease 19 detection. Clin Infect Dis 2021;73(9):e3106–9, http://dx.doi.org/10.1093/cid/ciaa1589.