Original Article

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Conflict of interest
None.

3D printing and silicone models of primary skin lesions for dermatological education as remote learning tool

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Summary

Background and objectives: The corona pandemic affects many aspects of life – with challenges in medical treatment undoubtedly of paramount importance. However, continuing medical education needs to be consistently provided. During a semester with lockdown-phases and limited student-to-patient-contact availability, we supplied silicone models of primary skin lesions to every student and asked them to evaluate this teaching tool.
Methods: In two anonymous online surveys, we asked students enrolled in dermatology (n = 222) at the Medical Facility of the Ludwig Maximilian University of Munich in the winter semester 2020/2021 – subsequent to online teaching – about their understanding and self-assessment of primary skin lesions before and after receiving silicone models for practice. The models were produced by layering different types of silicone into negative 3D printed molds made from polylactide to attain different degrees of hardness and colors.
Results: Data from 211 (95.0 %) and 213 (95.9 %) of the 222 students were analyzed before and after receiving the silicone models, respectively. In all questions the students stated a highly significant improvement in their skills ($P < 0.001$). The majority of students evaluated the silicone models positively and reported a better understanding and learning of primary skin lesions.
Conclusions: This study demonstrates the benefit of haptic experience in dermatology teaching not only in the time of COVID-19, but also thereafter.

Introduction

During the year 2020, the novel corona virus Sars-CoV-2 changed the world as we knew it. Not only did urgent medical decisions need to be made, for example how to treat respiratory symptoms of COVID-19, how to deal with associated health problems [1–3] and how to prevent further spreading [4], but also in the medium to long term how to rapidly develop vaccines and maintain high quality education for medical students [5]. The latter is especially challenging in the field of dermatology, where the physician often depends on visual and tactile impressions to diagnose and treat patients with skin diseases. Lockdown measures involving primarily online teaching has forced educators to develop new methods to teach these sensory skills.

In the 19th century and flourishing all over Europe in the 20th century, in the absence of photography European artists increasingly developed wax models to illustrate medical (mostly anatomical and dermatological) abnormalities and diseases [6] – the so-called "moulages" (French mouler: to mold/to cast). To create these models, a plaster cast was applied to the abnormal or diseased body part of patients and after solidification it was removed and lined with dyed wax to resemble the skin color of the patient. Often, colored wax was added to the wax model by painting the negative plaster cast mold with dyed wax, but in particular the finer details were painted on afterwards, after separating the wax model from the plaster cast mold. Nowadays, a few central European dermatological university clinics or pathology institutes still have their own highly treasured collections of medical moulages. With the advent of photography, especially color photography in the middle of the twentieth century [7], the number of moulage artists decreased steadily, despite the inability of the newer method to reproduce the 3D aspect of the models.

In order to combine all the advantages of the abovementioned models and to address the problems arising with the COVID-19 pandemic, we created a new tool for the education of undergraduate medical students using silicone models cast in negative 3D printed molds. The models cannot only be colored differently and represent three-dimensional structures, but also – most importantly – they can provide tactile information such as soft and hard structures (for instance to differentiate ulcus molle from ulcus durum). We designed a silicone model of primary skin lesions and evaluated this model in the winter semester 2020/21 at the medical faculty of the Ludwig-Maximilians-Universität (LMU) in Munich/Germany.

Methods

Surveys

From October to December 2020, we conducted a prospective longitudinal study using online surveys in German language rendered completely and irreversibly anonymous (translated versions: Online Supplementary File 1). The recruitment took place during the winter semester 2020/2021 in the context of dermatological education for 5th year medical students of the LMU in Munich/Germany. Education in this semester was comprised of online lectures, online seminars in groups of approximately 20 students and only one day of bedside teaching due to lockdown restrictions and contact avoidance measures. The first online lecture of the semester introduced the concept of primary skin lesions to the students.

The objective of the present study was to determine the student's understanding of primary skin lesions and their self-assessment. Firstly, they were asked demographic questions, their interest in dermatology, self-assessment of their anamnestic and physical examination skills, as well as their opinion on the relevance of describing dermatological lesions. After receipt of the silicone models, the students were asked the same questions with the addition of questions about the quality of the models, their personal experience with this teaching tool and whether they would recommend it for future student teaching.

Silicone models

To manufacture the silicone models (Figure 1a, b), 30 negative molds made from polylactide (PLA) via 3D printing (fused deposition modeling technique) were produced on an Anycubic i3 Mega S printer (ShenZhen ANYCUBIC Technology Co., Ltd, Shenzhen, Guangdong, China) using Maertz PLA Matt Filament (IGO3D GmbH, Hannover, Germany). As 3D printers capable of printing silicone cannot print multiple materials (for example, in different colors and/or different strengths) in parallel and lack sufficient resolution to produce accurate models, this production route was chosen. Settings used were as follows: 0.1 mm layer height, no support structures, no attachment layer, 60°C platform temperature and 200°C extrusion temperature. Post-print smoothing was performed by repeated mechanical scrubbing of the surface of the 3D model with a cotton swab soaked in tetrahydrofuran (Sigma Aldrich, Steinheim, Germany). The 3D file (Figure 1c) was designed with TinkerCAD online software (Autodesk, Inc, San Rafael, California, USA) (Online Supplementary File 2). The slicing software used was Ultimaker Cura (version 4.8, Ultimaker BV, Utrecht, Netherlands).

Briefly, the primary skin lesion equivalents (type, materials and colors: see below) were first poured into their designated areas and allowed to polymerize overnight at room temperature. The skin-colored back layer was cast on the second day. After overnight polymerization, the model could be stripped off the mold and mounted onto quarter-page-sized overhead transparencies labelled with the primary skin lesions (Figure 1a, b). Finally, to closely imitate the haptic sensation of human skin, the model was sparingly powdered with household starch (purchased locally) to achieve a matte surface.

For the single primary skin lesions the combinations of silicone type and color as shown in Figure 1d were used. All materials (KauPo Plankenhorn e.K., Spaichingen, Germany) were used according to the manufacturer's instructions: briefly, equal amounts of part A and part B were mixed, color was added *quantum satis* and mixed in, the silicone was degassed for one minute in a glass desiccator with vacuum applied by a vacuum pump (diaphragm vacuum pump, Vacuubrand GmbH + CO KG, Wertheim, Germany) and then carefully poured into the molds. The colors chosen (approximately Fitzpatrick type 2 skin, red/pink macule, brownish red plaque) (Figure 1d) were exemplary, as the primary focus for the students should be their haptic/tactile impression. This 5.2 cm × 7.4 cm silicone model was attached to a 10.5 cm × 14.8 cm transparent polymer foil (postcard size) and sent to every student as a model by mail.

Statistics

Metric variables were reported as mean values ± standard deviation (SD). Reported percentages refer to the applicable cases. Group comparisons were made using chi-square tests for categorical variables and t-tests for metric variables. The study compared the answers given before and after receipt

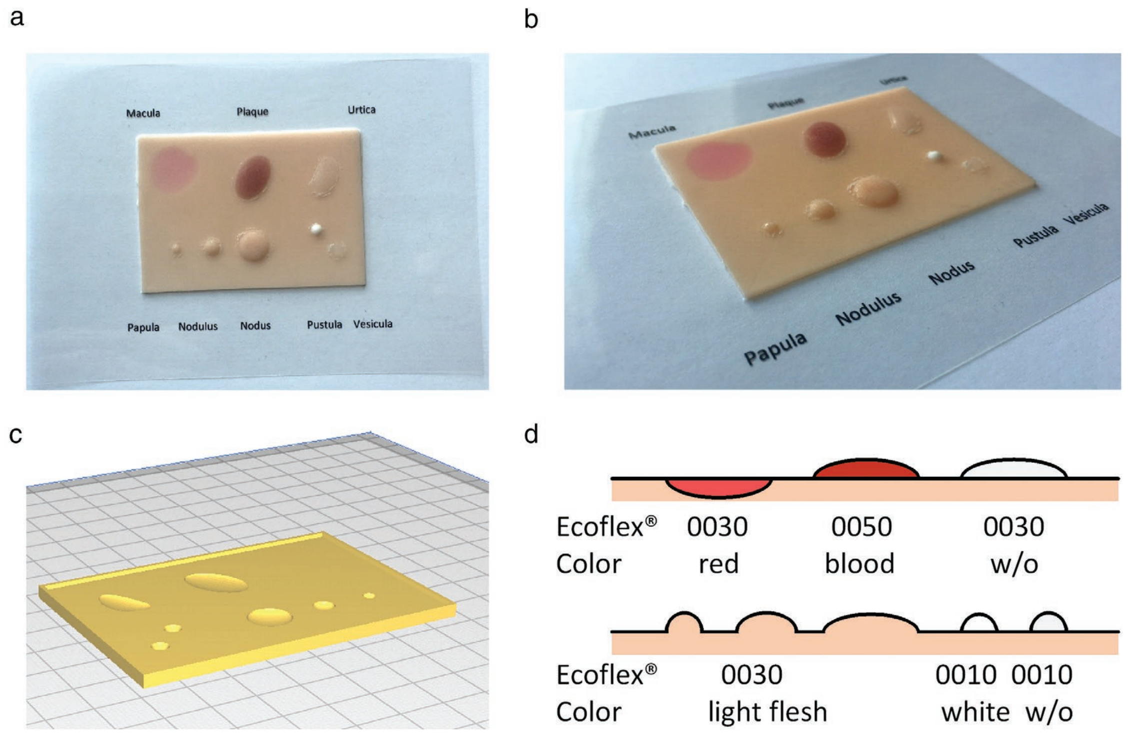

Figure 1 Silicone model from above: Upper row depicting patch (Macula), plaque (Plaque) and wheal (Urtica), lower row depicting papule (Papula), nodulus (Nodulus), nodule (Nodus), pustule (Pustula) and vesicle (Vesicula) (left to right, respectively; Latinized German terms in brackets) (a). Same silicone model from a sideways perspective (identical labels as in Figure 1a) (b). 3D model file of the negative mold used to make the silicone models (visualized with Ultimaker Cura software) (c). Schematic representation of the colors and materials (Ecoflex® silicone) used for the silicone models ("cut-through" through both lines of skin lesions).

of the silicone models. The software used for statistic calculations was SPSS statistics 26.0 (IBM Corp., released 2019, Armonk, NY/USA) and GraphPad Prism version 5.01 (GraphPad Software Inc., La Jolla, CA/USA).

The level of knowledge resulting from haptic models for dermatological education was the primary subject of our interest. The value $P < 0.05$ (*) was defined as the significance level for all analyses, P values < 0.01 (**) and P values < 0.001 (***) were defined as highly significant. The data were evaluated descriptively.

The study was approved by the local ethics committee of the LMU (project KB 20/001).

Results

Production of the models

We 3D-printed 30 molds in batches of six over night (approximate time: 16.5 hours per batch). Subsequently, we produced 30 silicone models per batch: On the first day, the single non-skin-colored primary lesions were cast (mixing, coloration, degassing of silicone, pouring of 30 models; approx. 1.5 hours) and set aside over night for polymerization. On the next day, the skin-colored portions and the silicone sheet were cast (approximately 0.5 hours). After polymerization was complete, the silicone models were attached to plastic cards (approximately 5 min). In summary, the production time for 30 models was about two hours in total.

Study population

Overall, 211 (95.0 %, before receipt of model) and 213 (95.9 %, after receipt of model) surveys were collected from 222 officially enrolled students, respectively. Detailed information on the study population can be found in Table 1.

General survey

When asked about their interest in this course, 23.0 % (97/421) were "very interested", 37.8 % (159/421) were "interested", 27.3 % (115/421) were "moderately interested", 8.1 % (34/421) were "mildly interested" and 3.8 % (16/421) were "not interested". To test the students' clinical skills, they were asked in the first survey whether they would

Table 1 Detailed characteristics of the study population.

Study population (n = 211 [first survey] + 213 [second survey] = 424 survey participants)				
Gender (n = 421)	293 × ♀	(69.6 %)	128 × ♂	(30.4 %)
Age	25.93 ± 4.39 years	(average ± SD)	24 years	(median)
Semester	9th	(median)	6th to 12th	(min. to max.)
Previous dermatology internship? (n = 419)	32 × yes	(7.6 %)	387 × no	(92.4 %)

feel confident to obtain a structured medical history from a patient using a verbal rating scale (VRS). Almost half of the students (49.5 %, 104/210) answered "strongly agree", 37.6 % (79/210) answered "agree", and the rest (12.9 %, 27/210) answered "neutral, disagree or strongly disagree". They were also asked whether they felt capable of performing a general physical examination. Over one third of the students (35.2 %, 74/210) answered "strongly agree", 49.5 % (104/210) answered "agree", and the rest (15.2 %, 32/210) answered "neutral, disagree or strongly disagree". Furthermore, the students were asked whether they considered diagnostic and therapeutic skills in dermatology relevant for their future medical career. Over one third of the students (38.1 %, 80/210) answered "strongly agree", 36.2 % (76/210) answered "agree", and the rest (25.7 %, 54/210) answered "neutral, disagree or strongly disagree". Most of the students denied having worked with moulages before (98.1 %, 207/211), while 1.4 % (3/211) said they did and 0.5 % (1/211) did not know. Strikingly, 88.1 % (185/210) agreed that moulages would be of advantage when learning about primary skin lesions, while 1.0 % (2/210) denied and 11.0 % (23/210) did not know. Detailed results can be found in Table 2.

Comparison of the pre and post results

The students were asked the following questions with the possibility to answer with a VRS from "strongly agree" (1) to "strongly disagree" (5), in parenthesis the median (1–5) of answers before (pre) and after (post) receipt of the silicone models and the resulting P value is given (Figure 2).

"I feel well-prepared to obtain a structured dermatological anamnesis" (pre: 3, post: 3, $P < 0.001$). "I feel well-prepared to describe the skin findings in a structured manner" (pre: 4, post: 3, $P < 0.001$). "I feel well-prepared to describe the skin findings with the appropriate dermatological terminology" (pre: 4, post: 2, $P < 0.001$). "I know the difference between primary and secondary skin lesions" (pre: 3, post: 2, $P < 0.001$). "I can explain every primary skin lesion" (pre: 4, post: 2, $P < 0.001$). "I can explain the difference

Table 2 Detailed results of the general survey.

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	n
Interested in this course?	23.0 % (97)	37.8 % (159)	27.3 % (115)	8.1 % (34)	3.8 % (16)	421
Obtaining a structured medical history	49.5 % (104)	37.6 % (79)	9.0 % (19)	3.3 % (7)	0.5 % (1)	210
Performing a general physical examination	35.2 % (74)	49.5 % (104)	11.9 % (25)	2.4 % (5)	1.0 % (2)	210
Skills in Dermatology are relevant in my future medical career	38.1 % (80)	36.2 % (76)	15.7 % (33)	8.6 % (18)	1.4 % (3)	210
	Yes	No	I don't know			
Did you work with moulages before?	1.4 % (3)	98.1 % (207)	0.5 % (1)			211
Do you think moulages are of advantage for learning?	88.1 % (185)	1.0 % (2)	11.0 % (23)			210

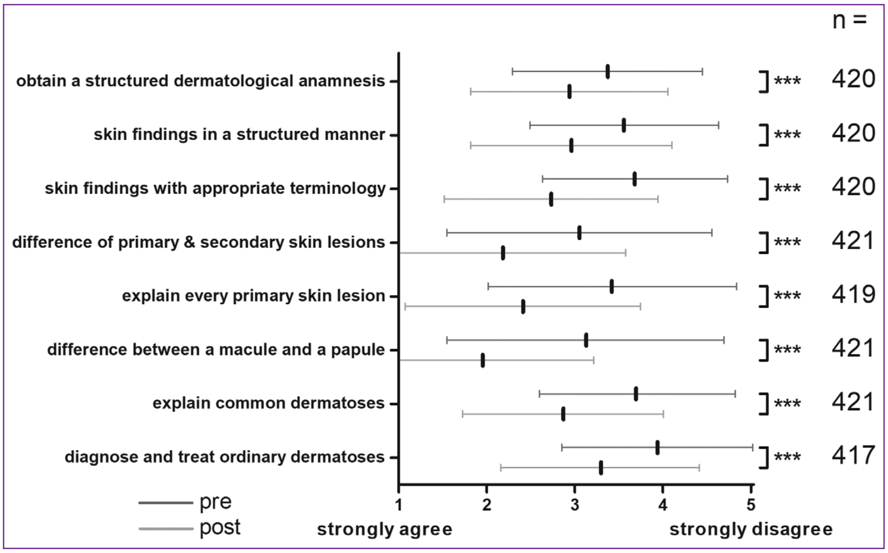

Figure 2 Plot of answers given in the survey before and after receipt of the silicone models, highlighting a highly significant improvement in every pair of questions (pre and post).

between a macule and a papule and *vice versa*" (pre: 4, post: 1, $P < 0.001$). "I feel well-prepared to explain common dermatoses with the corresponding primary skin lesions" (pre: 4, post: 3, $P < 0.001$). "I feel well-prepared to diagnose and treat ordinary dermatoses" (pre: 4, post: 3, $P < 0.001$).

Evaluation

Over one third of the students (36.4 %, 67/184) answered "strongly agree" when asked if the overall quality of the teaching course is high. Almost half of the students (47.8 %, 88/184) answered "agree", and the rest (15.8 %, 29/184) answered "neutral, disagree or strongly disagree". Likewise, more than half of the students (51.8 %, 103/199) strongly agreed that the silicone models helped to improve the understanding of the primary skin lesions. Over one quarter (26.1 %, 52/199) agreed and the rest (22.1 %, 44/199) answered "neutral, disagree or strongly disagree". Also, more than half of the students (54.1 %, 105/194) strongly agreed that the silicone models helped in learning the primary skin lesions. Over one quarter (26.3 %, 51/194) agreed and the rest (19.6 %, 38/194) answered "neutral, disagree or strongly disagree". Almost half of the students (45.5 %, 90/198) strongly agreed that the silicone models increased their motivation to deal with the topic. Over one quarter (27.8 %, 55/198) agreed and the rest (26.8 %, 53/198) answered "neutral, disagree or strongly disagree". Almost two thirds of the students (62.1 %, 126/203) strongly agreed that they would recommend teaching with silicone models. Almost one fifth (18.7 %, 38/203) agreed and the rest (19.2 %, 39/203) answered "neutral, disagree or strongly disagree". Finally, the students were asked to rate the teaching course on a scale from "very good" (1) to "very bad" (5), where 39.2 % (74/189) of them stated "very good", 47.6 % (90/189) stated "good", 9.5 % (18/189) stated "moderate", 3.7 % (7/189) stated "bad" and "very bad". Detailed results can be found in Table 3.

At the end of the survey, we included free text fields where the students could write what they liked and disliked and make comments. Most positive comments mentioned the additional dimension with which silicone models manage to convey haptic/sensory impressions. The students also praised the realistic feeling of the models and many appreciated the opportunity to learn by "hands-on" experience. They also expressed their desire and motivation to work with silicone models, presumably a fascination that not even the best book can offer. Other comments urged for continued teaching with the models in the future and described the joyful anticipation of receiving further models. Additionally, our teaching staff was applauded for their engagement in designing and supplying the models.

Most critical and negative comments described problems with postal delivery and the time of delivery. Also, many students expressed the wish to have more skin lesions (for example also secondary skin lesions and different sizes and colors) on their models, as well as models of common dermatoses like basal cell carcinoma and malignant melanoma. Many students had very good ideas for additional silicone model projects.

Discussion

Few medical fields are better suited than dermatology for integrating multisensory learning in medical student education. It is known to greatly enhance learning compared to uni-sensory and bi-sensory formats such as podcasts, lectures

Table 3 Detailed results of the evaluation.

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	n
Good quality of the course	36.4 % (67)	47.8 % (88)	13.0 % (24)	1.6 % (3)	1.1 % (2)	184
Silicone models helped to improve the understanding	51.8 % (103)	26.1 % (52)	13.1 % (26)	5.5 % (11)	3.5 % (7)	199
Silicone models helped to learn primary skin lesions	54.1 % (105)	26.3 % (51)	10.8 % (21)	5.2 % (10)	3.6 % (7)	194
Silicone models increased my motivation for the topic	45.5 % (90)	27.8 % (55)	15.2 % (30)	6.6 % (13)	5.1 % (10)	198
I would recommend teaching with silicone models	62.1 % (126)	18.7 % (38)	12.8 % (26)	3.0 % (6)	3.4 % (7)	203
	Very good	Good	Moderate	Bad	Very bad	
Rating of the teaching course	39.2 % (74)	47.6 % (90)	9.5 % (18)	1.6 % (3)	2.1 % (4)	189

and seminars [8]. Practical dermatology uses the concept of primary and secondary skin lesions to classify and structure dermatological thoughts and facilitate differential diagnosis of skin diseases due to its guiding and framing character [9]. Furthermore, dermatological terminology is also important for other medical specialties. With regard to the general practitioner, studies have shown that between 6 % and up to 24 % of the patients seeking advice in their practice present with dermatological problems [10–13].

Due to the circumstance that our university has the largest medical faculty in Germany, we were able to perform our survey on a large cohort of students. A large majority of our students were previously unaware of moulages, but agreed that they would be beneficial for learning dermatology, as other studies had shown before [7, 14] – probably especially in times like these, where universities are forced to quickly establish new teaching formats [15], but also where continued medical education relies heavily on online resources [16]. A study published in 2010 evaluated the effectiveness of teaching with 2D compared to 3D prosthetic mimics in dermatology and demonstrated significantly higher overall performance, skin lesion management and recognition skills of students in the 3D group [17].

These results are consist with our findings, as the students showed in every asked question a significant improvement after having the educative support of the silicone models. For example, they felt better-prepared to describe skin findings in a structured manner and with the right terminology, and subsequently to describe common skin conditions with their associated skin lesions. Furthermore, the students confirmed that the models are well suited to teach dermatology and to improve understanding, and additionally, that they increased their motivation to deal with the subject. Also, most of the students would recommend this form of teaching, showing that 3D silicone models are a good teaching method to improve the dermatological skills of medical students. Besides dermatology, such 3D models are also commonly used to teach anatomical or surgical methods, for instance in cardiology [18, 19]. Moreover, new teaching concepts, for example on the topic of wound management [20], may strongly benefit from realistic models for hands-on teaching in small groups.

The list of potential uses of simple silicone models is virtually endless and only limited by one's imagination: The correct application of topical therapies could be trained or demonstrated, especially when treatment often fails due to application errors [21]; easy dermatosurgical procedures like rotation flaps could easily be trained with the corresponding models [22], as well as more complicated ones like bilobed flaps in the facial area for large defects [23].

The students' responses in the free text fields were mainly positive, with negative ones mostly underlining the wish to have more models of different skin conditions (secondary skin lesions or common dermatoses). As these problems can easily be solved in the future, they do not portray a limitation for a broad implementation of 3D models in dermatologic teaching. Also, the cost of a 3D printer nowadays isn't exceptionally high – the printer we used for our models costed around 300 € (acquisition cost) plus 30 € (cost for the filament, 1,000 g PLA, enough for approximately 200 molds).

However, a main limitation of this study is the subjective mode of evaluation of the learning effect. The outcome was not measured objectively nor was there a control group. An interesting next step would be to perform a case control study to objectify the learning effect between students with and without the model to directly compare the effect between groups. Additionally, there were no control measures to ensure that students complied with the planned chronological order (theoretical teaching, first questionnaire, receipt of the model, second questionnaire).

Furthermore, future challenges will include the manufacturing of non-planar structures/models (most likely realized by the production of negative molds and casting with silicone). Moreover, certain surface qualities will be difficult to realize.

In summary, we hypothesize that silicone models as presented here have great potential in bringing additional dimensions into medical teaching. The survey results were mostly positive and showed an increased motivation to learn. Thus, such models may offer a huge benefit not only in times of COVID-19, but also for regular medical education.

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