The Journal of
Laryngology
& Otology

cambridge.org/jlo

Three-dimensional printing as a tool in otolaryngology training: a systematic review

G Chen[1], M Jiang[1], J Coles-Black[1,2], K Mansour[3], J Chuen[1,2] and D Amott[4]

[1]3dMedLab, Austin Health, University of Melbourne, Australia [2]Department of Vascular Surgery, Austin Health, Heidelberg, Australia [3]Department of Surgery, Royal Melbourne Hospital, Australia and [4]Ear, Nose and Throat Surgery Unit, Northern Hospital, Australia

Review Article

Dr J Coles-Black takes responsibility for the integrity of the content of the paper

Cite this article: Chen G, Jiang M, Coles-Black J, Mansour K, Chuen J, Amott D. Three-dimensional printing as a tool in otolaryngology training: a systematic review. *J Laryngol Otol* 2020;**134**:14–19. https://doi.org/10.1017/S0022215119002585

Accepted: 29 October 2019
First published online: 23 December 2019

Key words:
3-Dimensional Printing; Otolaryngology; Surgery; Simulation Training; Education

Author for correspondence:
Dr Jasamine Coles-Black,
Department of Vascular Surgery,
Austin Health,
145 Studley Road, Heidelberg 3084,
Victoria, Australia
E-mail: jasminecb@gmail.com

Abstract

Objective. Three-dimensional printing is a revolutionary technology that is disrupting the status quo in surgery. It has been rapidly adopted by otolaryngology as a tool in surgical simulation for high-risk, low-frequency procedures. This systematic review comprehensively evaluates the contemporary usage of three-dimensional printed otolaryngology simulators.
Method. A systematic review of the literature was performed with narrative synthesis.
Results. Twenty-two articles were identified for inclusion, describing models that span a range of surgical tasks (temporal bone dissection, airway procedures, functional endoscopic sinus surgery and endoscopic ear surgery). Thirty-six per cent of articles assessed construct validity (objective measures); the other 64 per cent only assessed face and content validity (subjective measures). Most studies demonstrated positive feedback and high confidence in the models' value as additions to the curriculum.
Conclusion. Whilst further studies supported with objective metrics are merited, the role of three-dimensional printed otolaryngology simulators is poised to expand in surgical training given the enthusiastic reception from trainees and experts alike.

Introduction

Three-dimensional (3D) printing, also known as rapid prototyping or additive manufacturing, is the new frontier of personalised medicine and surgery. The manufacturing process involves the construction of models layer-by-layer, allowing for the production of intricate structures that would otherwise be too complex by traditional means. Within the last decade, the ability of 3D printing to easily produce patient-specific 3D models has empowered surgeons in a vast field of applications, from treating life-threatening tracheobronchomalacia with a bio-resorbable airway splint[1] to pre-operative plate bending in acute midface trauma.[2] Whilst maxillofacial and orthopaedic surgery lead the field in implant and pre-operative applications,[3] within otolaryngology the principal utilisation of 3D printed models to date has been in the production of surgical simulators.

The traditional Halstedian apprenticeship model of 'see one, do one, teach one' faces significant challenges in ensuring trainees gain adequate experience in a specialty's full case mix through purely opportunistic encounters.[4] Thus, increasingly, surgical educators have turned to a complement of other training modalities to achieve cost-effective means of training confident surgeons without compromising patient safety.[5] Live animal and cadaveric models offer the highest level of fidelity in simulation, but are restrictive in cost and accessibility in light of ethical, legal and biohazardous storage issues.[5] Hence, the use of procedural simulators has become a crucial part of modern surgical education. The adoption of this modality of teaching allows for the efficient development and assessment of trainee skills in a diverse range of clinical scenarios.[5]

Otolaryngologists have recognised that 3D printing technology is uniquely positioned for the production of surgical simulators, offering the potential to create models with any anatomical or pathological variation of adult or paediatric size, for any surgical task. Furthermore, the manufacturing of these models on a consumer scale is increasingly affordable, because production costs continue to decrease as the technology matures.[6]

This article provides an overview of the current state of play and the future of such models' applications, as otolaryngology develops tools to enhance the surgical skills of its trainees.

Materials and methods

A literature search of the Medline and Embase databases was performed using the terms '3D printing', 'otolaryngology' and 'simulation'. Articles available in English language, published within the past 10 years, which met the inclusion criterion of describing 3D printed models utilised for surgical education, were appraised. Articles that did not report the results of the usage of such models as simulators were excluded, as were 3D printed models used for other purposes such as pre-operative planning. Our last search was conducted on 16 July 2019.

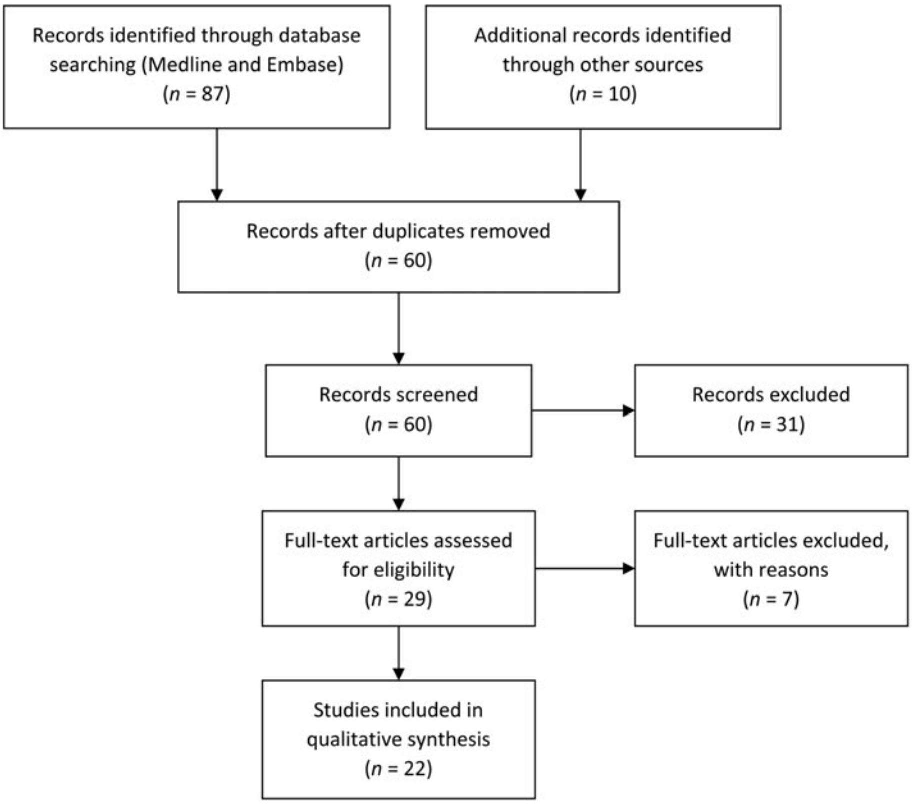

Fig. 1. Flowchart of the literature search.

Results

Twenty-two papers were identified for inclusion in the study (Figure 1).[7–28] Of these articles, eight (36 per cent) were prospective cohort studies.[11,12,14,16,17,21,23,28] The cohort studies objectively measured surgical skill (utilising a septoplasty model, a functional endoscopic sinus surgery model, a transcanal endoscopic ear surgery model, an otosclerosis prosthesis model, a needle cricothyroidotomy model and a costal cartilage airway grafting model), and demonstrated varying levels of construct validity. The other 14 articles (64 per cent) were cross-sectional studies.[7–10,13,15,18–20,22,24–27] These reported subjective measures demonstrating largely positive outcomes in terms of anatomical fidelity, haptic feedback, and value in the translation of surgical skill to the operating theatre. Several studies reported unanimous interest for integration into the curriculum.[12,18,24]

Discussion

Printing workflow

In order to generate an end-product of a 3D printed simulator, medical imaging datasets, such as from computed tomography or magnetic resonance imaging, are processed using medical image processing software. This process utilises both automated and manual methods to outline the anatomical structures of interest that form the basis of the 3D model. Computer-aided design software can be used to further refine the model, after which it can be physically printed.

Printing materials and cost

Three-dimensional printing encompasses several different technologies and materials, with dramatically different implications for mechanical properties and cost.

Stereolithography was the first 3D printing process developed. It boasts favourable cost and resolution; however, the resin models produced are not widely used in otolaryngological simulators because of their undesirable haptic feedback profile when drilled.

Conversely, fused deposition modelling uses thermoplastics such as acrylonitrile butadiene styrene and polylactic acid to produce extremely low cost models. These include the acrylonitrile butadiene styrene temporal bone for USD$1.92, created by Mowry *et al.*,[9] at the expense of resolution.

Inkjet and Polyjet printing technologies are favoured amongst the reviewed studies. These offer high-resolution models made from photopolymers, such as the Rose *et al.*[10] temporal bone model (USD$400), which feature good haptic feedback and a multi-coloured model at the price of high-end initial printer and material costs.

Silicone moulding is a technique commonly combined with 3D printed negative moulds to create realistic soft tissue structures at extremely low costs. These include the costal cartilage models created by Ha *et al.*[28] for USD$0.60 each, and the endoscopic nasal surgery simulator created by Chang *et al.*[18] for USD$21.

Simulator types

Over the past decade, the application of 3D printing in otolaryngology has produced a significant variety of simulators, as detailed in Table 1.[7–28]

Temporal bone models

One of the earliest models in otolaryngology was a temporal bone simulator produced by Suzuki *et al.*[29] in 2004, which has since become the most widely reported simulator.[7–11,30,31]

As 3D printing technology advanced and educators became more creative in their simulator designs, models have

Table 1. Existing 3D printed simulators in otolaryngology

Source	Study design	Simulator type	Material & cost*
Da Cruz & Francis (2015)[7]	Cross-sectional, $n = 9$	Temporal bone surgery	Cast powder & bonding agent (binder jetting)
Hochman *et al.* (2015)[8]	Cross-sectional, $n = 10$	Temporal bone surgery	Cyanoacrylate with hydroquinone (Inkjet), ReoFlex 40 urethane for dural membrane
Mowry *et al.* (2015)[9]	Cross-sectional, $n = 7$	Temporal bone surgery	ABS (FDM)
Rose *et al.* (2015)[10]	Cross-sectional, $n = 8$	Temporal bone surgery	Unspecified polymers (Polyjet) for USD$400
Nguyen *et al.* (2017)[11]	Prospective cohort, $n = 13$	Otosclerosis prosthesis with force sensors	Commercial Phacon temporal bone model modified with additional stereolithography-printed ossicles & force sensors
Barber *et al.* (2016)[12]	Prospective cohort, $n = 6$	Paediatric endoscopic ear trainer (peg transfer)	Calcium sulphate hemihydrate powder (Inkjet) for USD$10
Monfared *et al.* (2012)[13]	Cross-sectional, $n = 18$	Middle-ear stapedotomy	Unspecified polymer (Polyjet)
Ding *et al.* (2019)[14]	Prospective cohort, $n = 20$	Endoscopic endonasal sellar base surgery	Unspecified polymer (Polyjet) with an egg at sellar base
Hsieh *et al.* (2018)[15]	Cross-sectional, $n = 9$	FESS & skull base surgery	VeroWhite polymer (Polyjet) for USD$800
Yoshiyasu *et al.* (2019)[16]	Prospective cohort, $n = 32$	FESS	Silicone using ABS (FDM) negative mould for USD$110 (same model created by Chang *et al.* (2017)[10])
Alrasheed *et al.* (2017)[17]	Prospective cohort, $n = 20$	FESS	VeroWhite polymer (Polyjet) for bony structure & TangoPlus polymer for mucosa for CAD$230
Chang *et al.* (2017)[18]	Cross-sectional, $n = 7$	FESS	Silicone using ABS (FDM) negative mould for USD$110
Narayanan *et al.* (2015)[19]	Cross-sectional, $n = 15$	Endoscopic clival surgery	Unspecified polymer (Polyjet)
Cote *et al.* (2018)[20]	Cross-sectional, $n = 12$	Incomplete cleft palate surgery	Silicone soft palate using PLA 3D printed negative mould & PLA printed hard palate for USD$7.31
AlReefi *et al.* (2017)[21]	Prospective cohort, $n = 20$	Septoplasty	VeroWhite polymer (Polyjet) for bony structure & TangoPlus polymer for mucosa, for CAD$186
Al-Ramahi *et al.* (2016)[22]	Cross-sectional, $n = 10$	Rigid bronchoscopy & foreign body removal	Unspecified polymer (Polyjet)
Gauger *et al.* (2018)[23]	Prospective cohort, $n = 12$	Needle cricothyroidotomy	Silicone using unspecified 3D printed negative mould
Barber *et al.* (2018)[24]	Cross-sectional, $n = 10$	Tracheoesophageal puncture & prosthesis placement	PLA (FDM) for oesophageal lumen & superficial stoma, for USD$15, with squid for tracheoesophageal common wall
Kavanagh *et al.* (2017)[25]	Cross-sectional, $n = 4$	Paediatric laryngeal simulator (bronchoscopy, laryngoscopy, microlaryngoscopy)	Silicone using unspecified 3D printed negative mould for USD$6.89
Ainsworth *et al.* (2014)[26]	Cross-sectional, $n = 25$	Transcervical laryngeal injection with real-time electrical feedback	Silicone using ABS (FDM) negative moulds with wired thyroarytenoids infiltrated with metallic filaments
Chari & Chan (2018)[27]	Cross-sectional, $n = 10$	Congenital aural atresia surgery	Unspecified
Ha *et al.* (2017)[28]	Prospective cohort, $n = 18$	Airway graft carving of costal cartilage	Silicone: cornstarch using ABS (FDM) negative mould for USD$0.60

*Cost included if described in article. 3D = three-dimensional; ABS = acrylonitrile butadiene styrene; FDM = fused deposition modelling; FESS = functional endoscopic sinus surgery; PLA = polylactic acid

demonstrated gains in anatomical fidelity and function. Rose *et al.*[10] created a multi-material and multi-coloured temporal bone model that revealed facial nerve and carotid arteries clearly if improperly dissected, displaying the potential for trainer model realism to be further refined. Nguyen *et al.*[11] modified commercial 3D printed temporal bones with force sensors attached to 3D printed ossicular bones for augmented stapes fixation training, showing the capacity of simulators to teach highly specialised skills through the creative modifications of existing models. Kozin *et al.*[31] coupled a 3D printed temporal bone with a commercial virtual reality skull base navigation system, demonstrating the role of physical simulators in the developing field of virtual reality in surgical teaching.

Whilst the aforementioned simulators have all featured temporal bones, the diversity of their applications exemplifies the versatility of being able to create a model to suit any teaching need of the surgical educator.

Other simulators

Other simulators that have been created and assessed for their utility in surgical teaching include: skull base models,[15,19,32] endoscopic nasal surgery simulators,[15,18,21] cleft palate surgery models,[20] endoscopic ear surgery simulators,[12,13] airway

Table 2. Construct validity of 3D printed simulators in otolaryngology

Source	Study design	Study objective	Validity
Ding *et al.* (2019)[14]	Prospective cohort, $n = 20$	Endoscopic endonasal sellar base surgery	Significant decreases in time taken & error rates whilst drilling, curetting & biting, & aspirating, across participants. On initial trial, residents outperformed graduate students on time taken & error rates, but by final trial there was no significant difference in any metric
Gauger *et al.* (2018)[23]	Prospective cohort, $n = 12$	Needle cricothyroidotomy	Significant improvement in performance scoring (Cricothyroidotomy Skills Maintenance Program checklist & Global Rating Scale). Decrease in procedural time taken, but not statistically significant
Yoshiyasu *et al.* (2019)[16]	Prospective cohort, $n = 32$	FESS	Significant difference in observation-based performance (task-specific checklist) for senior (attendings & PGY 3–5) *vs* junior (PGY 1–2) groups; largest differences in inferior turbinate & uncinate incisions. No significant difference between attendings & PGY 3–5
Alrasheed *et al.* (2017)[17]	Prospective cohort, $n = 20$	FESS	Significantly shorter completion times when comparing experts *vs* senior *vs* junior trainees in injecting middle turbinate, pledget insertion & frontal sinus dissection
AlReefi *et al.* (2017)[21]	Prospective cohort, $n = 20$	Septoplasty	Significant differences ($p < 0.05$) between expert, intermediate & novice groups in time taken & nares cuts
Barber *et al.* (2016)[12]	Prospective cohort, $n = 6$	Paediatric endoscopic ear trainer (peg transfer)	Between 1st & 3rd trial: significant decreases in time taken for overall time ($p < 0.05$) & dominant hand trials ($p < 0.05$). Significant difference in time taken when comparing senior & junior groups
Nguyen *et al.* (2017)[11]	Prospective cohort, $n = 13$	Otosclerosis prosthesis with force sensors	Senior surgeons' force application significantly lower on stapes during prosthesis placement ($p = 0.008$) & during prosthesis crimping ($p = 0.02$). No significant differences in time taken ($p = 0.18$) or force applied to incus ($p = 0.11$)
Ha *et al.* (2017)[28]	Prospective cohort, $n = 18$	Airway graft carving of costal cartilage	No significant differentiation could be made between participants of different PGY levels in terms of time taken or quality of carving ($p > 0.05$)

3D = three-dimensional; FESS = functional endoscopic sinus surgery; PGY = post-graduate year

simulators with difficult anatomy for bronchoscopy,[22] models for laryngoscopy and microlaryngoscopic procedures,[25] tracheoesophageal puncture with prosthesis placement models,[24] needle cricothyroidotomy models,[23] and costal cartilage models for airway graft carving.[28]

Model validation

Given the scarcity of time allotted for training, it is imperative that new teaching methods are proven to be effective. If simulators are to be used to complement surgical education, their validity should be demonstrated. The validity of a simulator can be expressed in terms of face validity, content validity, construct validity and predictive validity.[33] These forms of validity help to confirm whether a simulator truly does train or assess the skills it claims to.

Face validity is 'validity that is assessed by having experts review the contents of a test to see if it seems appropriate'.[33] It is a highly subjective measure, assessed with surveys that simply express whether the evaluators think the simulator is an accurate facsimile. The surveys focus on anatomical fidelity and haptic feedback in comparison to current 'gold standards' of teaching or to procedures in the operating theatre. It was the most common validity type measured in the articles reviewed (64 per cent) because of its ease of assessment. Whilst simulators received mostly positive feedback regarding anatomical fidelity, finer structures like trabecular bone in the mastoid[8] have been found to be lacking. Deficiencies in anatomical accuracy may represent a limitation of the imaging datasets from which models were derived, the segmentation process or the type of 3D printer used.

Content validity is 'an estimate of the validity of a testing instrument based on a detailed examination of the contents of the test items'.[33] This remains a subjective measure, often determined using post-simulation survey data that describe whether participants felt the model improved task-specific surgical skills and increased confidence. Content validity was assessed simultaneously with face validity in post-simulation Likert surveys in the articles reviewed (64 per cent), with highly positive results for all simulators. Studies by Barber *et al.*[12,24] and Chang *et al.*[18] even report unanimous support for the inclusion of simulators into the existing curriculum. However, trainees were reluctant to endorse the replacement of existing teaching methods such as cadaveric temporal bones with 3D printed models.[8]

Construct validity is 'a set of procedures for evaluating a testing instrument based on the degree to which the test items identify the quality, ability, or trait it was designed to measure'.[33] This is an objective measure that only a few of the reviewed studies attempted to assess (36 per cent), but it provides a stronger indication of the utility of 3D printed simulators than subjective measures. Articles that assessed construct validity are detailed in Table 2.[11,12,14,16,17,21,23,28] Primarily, construct validity has been shown by observing a difference in task completion, through comparing time taken and/or error rates, between different groups with varying experience (trainees *vs* consultants). Seven out of eight studies that attempted to show construct validity succeeded. However, Ha *et al.*[28] were unable to show a significant difference between experts and trainees, citing heterogeneity of the participant groups (amongst other confounding factors) as a potential reason.

Predictive validity is 'the extent to which the scores on a test are predictive of actual performance'.[33] This form of validity is objective; it provides the most conclusive support that a simulator will result in improved clinical outcomes for trainees' patients and is therefore considered the gold standard method of evaluating a training method before implementation into training programmes. However, it is also the most difficult type of validity to assess, requiring significant follow-up time. Given the relative infancy of 3D printed simulators, to date no publication in the field has attempted to assess predictive validity.

It seems intuitive that physical surgical simulators will be beneficial to clinical outcomes, giving trainees more opportunities to practise procedural tasks before attempting them on a patient. However, there remains a clear need for objective evidence, which is currently lacking in the otolaryngological literature, to support the adoption of these training tools.

Limitations

Barriers to adoption

Three-dimensional printed simulators face several practical barriers before they become more widely adopted in surgical training. The segmentation of the 3D models from medical imaging data and subsequent refinement requires specific skills in 3D modelling software that may be inaccessible without detailed instruction. Also, there may be large initial costs to 3D printing technology; printer prices currently range from a few hundred dollars to tens of thousands of dollars. These issues may be eased by the co-operation of multiple hospitals in a shared 3D printing facility operated by specialists.

Research methodology

The over-reliance on face and content validity types as subjective measures of the utility of 3D printed simulators in otolaryngology training is an issue faced by the field of surgical education as a whole.[34] Whilst considerations must be made as to whether certain study designs are feasible, objective evaluations of skill acquisition will supersede subjective evaluations. The gold standard of randomised, controlled trials will be difficult to accomplish for multiple reasons, including heterogeneity in the experience levels of the participants and the inability to blind participants when comparing against the simulators currently used in the curriculum.[34]

Therefore, single-subject designs that expose each subject to interventions and make comparisons amongst subjects are most preferred, with participants acting as their own control.[34] Participant performance can be objectively assessed using quantitative measurements such time taken, error rate, number of corrective manoeuvres, and scores on task-specific checklists or global rating scales, amongst other validated assessment tools.[34] Nevertheless, there remain merits in utilising subjective measurements; confidence-based marking and self-marking are strongly correlated with test performance,[34] which may be confirmed using correlation analyses.

Conclusion

The early-phase adoption of 3D printed simulators in otolaryngology has seen the production of a wide variety of simulators, with enthusiastic reception from trainees and experts alike. As models become more refined and the barriers to 3D printing lowered, their use in surgical simulation will continue to expand and become commonplace in surgical skills acquisition.

Acknowledgements. The authors would like to thank the staff at Austin Health Services Library, Melbourne. This research was made possible by grant funding received from the Harold and Cora Brennen Benevolent Trust.

Competing interests. None declared

References

1 Zopf DA, Hollister SJ, Nelson ME, Ohye RG, Green GE. Bioresorbable airway splint created with a three-dimensional printer. *N Engl J Med* 2013;**368**:2043–5
2 Dorrity JA, Odland R. 3D printing and preoperative planning in acute midface trauma. *Otolaryngol Head Neck Surg* 2017;**157**(1 suppl):P181–2
3 Martelli NPP, Serrano CP, van den Brink HPP, Pineau JP, Prognon PPP, Borget IPP *et al.* Advantages and disadvantages of 3-dimensional printing in surgery: a systematic review. *Surgery* 2016;**159**:1485–500
4 Shaharan S, Neary P. Evaluation of surgical training in the era of simulation. *World J Gastrointest Endosc* 2014;**6**:436–47
5 Forgione A, Guraya SY. The cutting-edge training modalities and educational platforms for accredited surgical training: a systematic review. *J Res Med Sci* 2017;**22**:51
6 Coles-Black J, Chao I, Chuen J. Three-dimensional printing in medicine. *Med J Aust* 2017;**207**:102–3
7 Da Cruz MJ, Francis HW. Face and content validation of a novel three-dimensional printed temporal bone for surgical skills development. *J Laryngol Otol* 2015;**129**(suppl 3):S23–9
8 Hochman JB, Rhodes C, Wong D, Kraut J, Pisa J, Unger B. Comparison of cadaveric and isomorphic three-dimensional printed models in temporal bone education. *Laryngoscope* 2015;**125**:2353–7
9 Mowry SE, Jammal H, Myer C, Solares CA, Weinberger P. A novel temporal bone simulation model using 3D printing techniques. *Otol Neurotol* 2015;**36**:1562–5
10 Rose AS, Kimbell JS, Webster CE, Harrysson OL, Formeister EJ, Buchman CA. Multi-material 3D models for temporal bone surgical simulation. *Ann Otol Rhinol Laryngol* 2015;**124**:528–36
11 Nguyen Y, Mamelle E, De Seta D, Sterkers O, Bernardeschi D, Torres R. Modifications to a 3D-printed temporal bone model for augmented stapes fixation surgery teaching. *Eur Arch Otorhinolaryngol* 2017;**274**:2733–9
12 Barber SR, Kozin ED, Dedmon M, Lin BM, Lee K, Sinha S *et al.* 3D-printed pediatric endoscopic ear surgery simulator for surgical training. *Int J Pediatr Otorhinolaryngol* 2016;**90**:113–18
13 Monfared A, Mitteramskogler G, Gruber S, Salisbury JK Jr, Stampfl J, Blevins NH. High-fidelity, inexpensive surgical middle ear simulator. *Otol Neurotol* 2012;**33**:1573–7
14 Ding CY, Yi XH, Jiang CZ, Xu H, Yan XR, Zhang YL *et al.* Development and validation of a multi-color model using 3-dimensional printing technology for endoscopic endonasal surgical training. *Am J Transl Res* 2019;**11**:1040–8
15 Hsieh TY, Cervenka B, Dedhia R, Strong EB, Steele T. Assessment of a patient-specific, 3-dimensionally printed endoscopic sinus and skull base surgical model. *JAMA Otolaryngol Head Neck Surg* 2018;**144**:574–9
16 Yoshiyasu Y, Chang DR, Bunegin L, Lin RP, Aden JK, Prihoda TJ *et al.* Construct validity of a low-cost medium-fidelity endoscopic sinus surgery simulation model. *Laryngoscope* 2019;**129**:1505–9
17 Alrasheed AS, Nguyen LHP, Mongeau L, Funnell WRJ, Tewfik MA. Development and validation of a 3D-printed model of the ostiomeatal complex and frontal sinus for endoscopic sinus surgery training. *Int Forum Allergy Rhinol* 2017;**7**:837–41
18 Chang DR, Lin RP, Bowe S, Bunegin L, Weitzel EK, McMains KC *et al.* Fabrication and validation of a low-cost, medium-fidelity silicone injection molded endoscopic sinus surgery simulation model. *Laryngoscope* 2017;**127**:781–6
19 Narayanan V, Narayanan P, Rajagopalan R, Karuppiah R, Rahman ZA, Wormald PJ *et al.* Endoscopic skull base training using 3D printed models with pre-existing pathology. *Eur Arch Otorhinolaryngol* 2015;**272**:753–7
20 Cote V, Schwartz M, Arbouin Vargas JF, Canfarotta M, Kavanagh KR, Hamdan U *et al.* 3-Dimensional printed haptic simulation model to teach incomplete cleft palate surgery in an international setting. *Int J Pediatr Otorhinolaryngol* 2018;**113**:292–7
21 AlReefi MA, Nguyen LH, Mongeau LG, Haq BU, Boyanapalli S, Hafeez N *et al.* Development and validation of a septoplasty training model using 3-dimensional printing technology. *Int Forum Allergy Rhinol* 2017;**7**:399–404
22 Al-Ramahi J, Luo H, Fang R, Chou A, Jiang J, Kille T. Development of an innovative 3D printed rigid bronchoscopy training model. *Ann Otol Rhinol Laryngol* 2016;**125**:965–9
23 Gauger VT, Rooney D, Kovatch KJ, Richey L, Powell A, Berhe H *et al.* A multidisciplinary international collaborative implementing low cost, high fidelity 3D printed airway models to enhance Ethiopian anesthesia resident emergency cricothyroidotomy skills. *Int J Pediatr Otorhinolaryngol* 2018;**114**:124–8

24 Barber SR, Kozin ED, Naunheim MR, Sethi R, Remenschneider AK, Deschler DG. 3D-printed tracheoesophageal puncture and prosthesis placement simulator. *Am J Otolaryngol* 2018;**39**:37–40

25 Kavanagh KR, Cote V, Tsui Y, Kudernatsch S, Peterson DR, Valdez TA. Pediatric laryngeal simulator using 3D printed models: a novel technique. *Laryngoscope* 2017;**127**:E132–7

26 Ainsworth TA, Kobler JB, Loan GJ, Burns JA. Simulation model for transcervical laryngeal injection providing real-time feedback. *Ann Otol Rhinol Laryngol* 2014;**123**:881–6

27 Chari DA, Chan DK. Novel inexpensive method to improve surgical training in congenital aural atresiaplasty using 3D simulation software. *Otolaryngol Head Neck Surg* 2018;**159**(1 suppl):P307–8

28 Ha JF, Morrison RJ, Green GE, Zopf DA. Computer-aided design and 3-dimensional printing for costal cartilage simulation of airway graft carving. *Otolaryngol Head Neck Surg* 2017;**156**:1044–7

29 Suzuki M, Ogawa Y, Kawano A, Hagiwara A, Yamaguchi H, Ono H. Rapid prototyping of temporal bone for surgical training and medical education. *Acta Otolaryngol* 2004;**124**:400–2

30 Kasbekar A, Narasimhan G, Lesser T. The development of a new 3D printed temporal bone model and its comparison to other training models. *J Laryngol Otol* 2016;**130**(suppl 3):S187

31 Kozin ED, Barber SR, Wong K, Kiringoda R, Kempfle J, Remenschneider A *et al.* 3D printed temporal bone coupled with surgical navigation. *Otolaryngol Head Neck Surg* 2017;**157**(1 suppl):P233

32 Chan HH, Siewerdsen JH, Vescan A, Daly MJ, Prisman E, Irish JC. 3D rapid prototyping for otolaryngology-head and neck surgery: applications in image-guidance, surgical simulation and patient-specific modeling. *PLoS One* 2015;**10**:e0136370

33 Gallagher AG, Ritter EM, Satava RM. Fundamental principles of validation, and reliability: rigorous science for the assessment of surgical education and training. *Surg Endosc* 2003;**17**:1525–9

34 Kostusiak M, Hart M, Barone DG, Hofmann R, Kirollos R, Santarius T *et al.* Methodological shortcomings in the literature evaluating the role and applications of 3D training for surgical trainees. *Med Teach* 2017;**39**:1168–73