Comparison of 3- vs 2-Dimensional Endoscopy Using Eye Tracking and Assessment of Cognitive Load Among Surgeons Performing Endoscopic Ear Surgery

Lukas Anschuetz[1], MD; Laura Niederhauser[2], MSc; Wilhelm Wimmer[3], PhD; Abraam Yacoub[1], MD; David Weibel[4], PhD; Fred W. Mast[4], PhD; Marco Caversaccio[2], MD

[1] Department of Otorhinolaryngology, Head & Neck Surgery, Inselspital, University Hospital and University of Bern, Switzerland

[2] Department of Psychology, Swiss University of Distance Education, Switzerland

[3] ARTORG Center for Biomedical Engineering, University of Bern, Switzerland

[4] Department of Psychology, University of Bern, Switzerland

Financial Disclosures

No funding is reported for the present study.

Conflict of Interest

The authors declare no conflict of interest.

Corresponding Author

Lukas Anschuetz, MD

Department of Otorhinolaryngology, Head & Neck Surgery, Inselspital, University Hospital and University of Bern, 3010 Bern, Switzerland

Email: anschuetz.lukas@gmail.com

Tel: +41-31-6322654; Fax: +41-31-6324872

Key words

Endoscopic ear surgery; 3D endoscopy; 2D endoscopy; tympanoplasty; stapedotomy; cognitive load; eye tracking

Manuscript word count: 3000

Date of revision: 05.06.2019

Keypoints

Question: What differences between three-dimensional (3D) and two-dimensional (2D) endoscopy are important in endoscopic ear surgery (EES)?

Findings: The surgical assessment revealed similar operating times for both techniques with a slight advantage for the 3D technique when used by inexperienced surgeons. Surgeons indicated a preference for the 3D technique, even though a higher incidence of eye strain was observed. Recordings of eye movements suggest the need for dedicated training in 3D endoscopy, even for experienced surgeons.

Meaning: Three-dimensional endoscopy is suitable for EES, especially for young surgeons whose mental model of the intervention has still to be consolidated. The application of 3D endoscopy in clinical routines and for educational purposes appears feasible and beneficial.

Abstract

Importance: Endoscopic ear surgery (EES) is an emerging technique to treat middle ear pathologies; however, the interventions are performed in two-dimensional (2D) endoscopic views, which do not provide depth perception. Recent technical developments now allow the application of three-dimensional (3D) endoscopy in EES.

Objective: We aimed to investigate the usability, advantages and disadvantages of 3D vs. 2D endoscopy in EES under standardized conditions.

Design: Randomized Crossover Study

Setting: Tertiary academic medical center

Participants: Residents and consultants of the Department of Otorhinolaryngology, Head & Neck Surgery, Inselspital Bern, Switzerland.

Interventions: Each participant performed selected steps of a type I tympanoplasty and stapedotomy in 2D as well as in 3D view in a cadaveric model.

Main Outcomes and Measures: Time taken, number of attempts and accidental damage during the dissections were compared between 3D and 2D endoscopy. Eye-tracking was performed throughout the interventions. Cognitive load and subjective feedback was measured by standardized questionnaires.

Results: Assessment of surgical time revealed similar operating times for both techniques. Most surgeons preferred the 3D technique, even though a higher incidence of eye strain was observed. Eye movement assessment revealed a higher duration of fixation for consultants and residents in 2D compared to 3D endoscopy, indicating a less efficient application of previously acquired experiences using the new technique. Cognitive load was similar for both techniques.

Conclusions and Relevance: Three-dimensional endoscopy is suitable for EES, especially for young surgeons whose mental model of the intervention has yet to be consolidated. The application of 3D endoscopy in clinical routines and for educational purposes appears feasible and beneficial.

Introduction

Endoscopic ear surgery (EES) is gaining popularity among ear surgeons since it permits minimally invasive and functional surgery. Advantages of the endoscopic technique include: (i) panoramic views of middle ear anatomy,[1] especially of the retro- and hypotympanum;[2-4] (ii) enhanced magnification of very small anatomical structures, e.g. a malformed stapes;[5] (iii) the possibility to use angled endoscopes;[6] (iv) preservation of healthy mastoid and middle ear mucosa;[7] and (v) possible shorter operating times.[8] However, the endoscopic technique has its inherent challenges: (i) as it is a one-handed technique, the learning curve is deemed to be slower and management of bleeding may be challenging;[9] (ii) the narrow space available in the external auditory canal (EAC) limits the movements of surgical instruments; (iii) pathologies inside the mastoid may not be addressed; and (iv) until recently, high definition camera systems were exclusively two-dimensional (2D).

However, recent technical developments now permit three-dimensional (3D) endoscopy based on two-lens camera systems and passive polarizing glasses worn by the surgeon, providing stereoscopic depth perception, which may improve visibility and spatial acuity in the operating field. The applicability of 3D endoscopy in EES has recently been reported in a case series.[10]

To the best of our knowledge, no comparative studies have been performed in EES to investigate surgical performance in 3D vs. 2D endoscopy. Using a randomized, crossover study design, we aimed to assess the usability, advantages and disadvantages of 3D vs. 2D endoscopy in EES. In addition, we looked into the effect of the additional information provided by 3D endoscopy on eye movement patterns. It has been shown that eye movement analysis (duration and number of fixations, blink rates) is able to distinguish between different tasks, different levels of expertise, and different contexts.[11,12] Therefore, we aimed to determine differences in gaze behavior to offer additional and objective insights into the usability and benefits of 3D vs. 2D endoscopy.

Materials and Methods

Ethical Issues

The institutional review board (Kantonale Ethikkomission Bern) granted approval to perform this study (REQ-2018-00310). All participants signed an informed consent form.

Study Set-up and Participants

All senior surgeons and residents of the Otorhinolaryngology, Head and Neck Surgery (ORL-HNS) Department at Inselspital, University Hospital Bern, Switzerland were invited to participate in this study. The only restriction was normal visual acuity or vision corrected by contact lenses. Glasses were not permitted because of simultaneous eye tracking. Demographic characteristics were assessed, including the participants' prior endoscopic experience.

A within-subjects design was used: the participants were consecutively taught to perform predefined surgical steps of a relatively easy task (type I tympanoplasty) and an advanced task (stapedotomy) in 2D and in 3D view in each intervention. We used a Latin square[13] to counterbalance the order of interventions (tympanoplasty, stapedotomy) and techniques (2D, 3D endoscopy) resulting in four different experimental sequences, each administered to a quarter of the participants (eTable 1).

Specimen Preparation

First, the specimen (right ear of a Thiel-fixed, whole head preparation) was positioned and a tympanomeatal flap, including detachment of the eardrum from the handle of the malleus, was prepared according to a previously published dissection manual.[14] A slight enlargement of the EAC and curettage of the scutum were performed consecutively to allow unhindered access to the stapes. The chorda tympani was resected to guarantee standardized conditions for all participants (in case of accidental transection). The incudostapedial joint was disarticulated and the stapes suprastructure removed using a diode laser (FOX laser, A.R.C. Laser, Nuremberg, Germany), followed by a laser platinotomy.

Dissection Tasks

Participants performed the surgical steps on the same cadaveric specimen using 4 mm diameter, 18 cm length 2D and 3D endoscopes (Karl Storz, Tuttlingen, Germany). Standard otology tools were used. Before the measurements were taken, the participants were instructed on the handling of the endoscopes and had time to explore the middle ear.

For the tympanoplasty task, the participants were asked to place the tympanomeatal flap on the anterior wall of the EAC and to place an artificial membrane (Biodesign, Cook Medical, USA) using the underlay technique. The task was considered successfully completed if the membrane was positioned on the handle of the malleus and completely covered the superior quadrants of the eardrum. Thereafter, the tympanomeatal flap was brought back on the membrane and into its final position.

The stapedotomy task consisted of the positioning of a piston prosthesis (0.5 x 4.5 mm, Kurz, Germany) on the long process of the incus and inside the platinotomy. No crimping was performed to facilitate removal of the prosthesis.

Perioperative Measurements

For both tasks, the time taken for completion and the number of attempts required were measured. During the tympanoplasty task, two graders, blinded to the study hypothesis, assessed the number of involuntary contacts with the ossicular chain. In addition, we measured the participants' cognitive workload after each trial using the NASA Task Load Index.[15] The questionnaire consists of six subscales (mental demand, physical demand, temporal demand, performance, effort, and frustration), each scale ranging from 0 to 100.[16-19]

While performing the tasks, the surgeons' eye movements during the task were recorded with a head-mounted eye-tracking device (SensoMotoric Instruments (SMI), Berlin, Germany) (Figure 1). The applied eye-tracker has a gaze position accuracy of 0.5° and a frame rate of 60 Hz, and was calibrated before each task with a three-point calibration method. For computation of fixation durations (average duration of fixations per task) and blink rates (blinks per minute), we used SMI BeGaze Analysis software version 3.7.

Postoperative Assessment

Immediately upon completion of all four dissection trials, participants completed computer-based questionnaires (presented with www.qualtrics.com). They were asked to rate the 3D endoscope and the 2D endoscope separately based on a seven- or five-point Likert scale with regard to the usability,[20] naturalness,[20] perceived discomfort,[20] depth perception,[21] and image quality[21] of the techniques (eTable 2). Participants also made a direct comparison of the two endoscopes with regard to nine aspects (Table 1).

Statistical Analysis

We used an analysis of variance (general linear model for repeated measures) to examine differences in the dependent variables assessed during surgery (time required, cognitive workload, fixation duration, blink rate). Endoscopic technique (3D and 2D) and task (tympanoplasty and stapedotomy) were used as within-subject variables and medical experience (residents vs. consultants) as a between-subject variable. A square-root transformation of the indices was considered where appropriate. The values for the involuntary contacts with the ossicular chain and the number of attempts were highly right-skewed (skewness > 1.10), indicating that distributions were not normal.[22] Because transformation did not strongly decrease skewness (>0.95), we used nonparametric Wilcoxon signed-rank tests for paired samples to compare these values between the two techniques. Student's *t* tests for paired data were used to analyze the ratings of the two endoscopic techniques, and binomial tests to examine the direct comparisons. Variables are described in terms of mean values and standard deviations unless otherwise noted. Effect size metric, including Cohen's d, were used to describe the magnitude of the difference between compared groups and, where appropriate 95% CI were used to describe the precision of the effect size metric. Cohen suggested that d=0.2 be considered a 'small' effect size, 0.5 represents a 'medium' effect size and 0.8 a 'large' effect size.[23] A p-level below 0.05 was deemed statistically significant. All computations were executed in R (version 3.5).[24]

Results

Participants

A total of 64 surgical interventions in 2D and 3D views were analyzed performed by 16 participants. The mean age of participants was 36 years (range 25–57) with 50%

female. All participants were assigned as either residents (n=11) or consultants (n=5) according to their clinical function. Regarding prior experience in endoscopic surgery including functional endoscopic sinus surgery (FESS), there was a large difference between the groups with a median experience of 0 procedures (range 0-40) in the residents group and 300 procedures (range 200-5000) in the consultants group.

Personal Preference

The subjective feedback provided by participants at the end of all surgical tasks revealed a significant difference in two ratings (eTable 1): (i) visual discomfort was perceived to be higher for 3D endoscopy compared to 2D endoscopy (mean difference = 0.74, 95% CI: 0.29 to 1.20, r = 0.67) and (ii) depth perception was rated higher when using the 3D compared to the 2D technique (mean difference = 1.62, 95% CI: 0.49 to 2.76, r = 0.62). Direct comparison revealed a preference of the participants for the 3D endoscope (Table 1).

Surgical Assessment

The order of trials had no significant effect on the time required for the tasks, indicating a successful application of the Latin square design. Results showed that the time required for the trials differed between the two surgical tasks, as well as between the two experience levels. The tympanoplasty took longer to complete than the stapedotomy task, independent of the function or the endoscopic technique (mean difference: 85.31 ± 23.98 s, 95% CI: 37.96 to 132.67 s, r = 0.59). Moreover, residents needed more time to complete the tasks than the consultants which is illustrated in Table 2. These observations were independent of the task or the technique used (total mean difference = 83.35 ± 31.83 s, 95% CI: 17.25 to 149.44 s, r = 0.59), which was confirmed by Kendall's *Tau* = 0.245. We observed a tendency towards faster execution of the surgical tasks using 3D endoscopy in the residents group; in contrast, consultants took longer to perform the same interventions in 3D compared to 2D (mean difference: –52.64 ± 63.46 s, 95% CI: –183.32 to 78.05 s, r = 0.22) as shown in Table 2.

Analysis of the number of attempts required to fulfill the assignments and the number of involuntary contacts with the ossicular chain revealed no meaningful differences between the two techniques (median difference for number of involuntary contacts: -0.50, 95% CI:-1.50 to 0.99).

Surgical speed in the standard 2D technique is another indicator of expertise. By calculating a 3D/2D ratio, it would be possible to draw conclusions on the utility of the 3D technique, especially in surgeons not previously trained in it. Therefore, we investigated the effect of the endoscopic technique on the time required to fulfill the tasks by dividing the participants by median split into two groups according to the average time required for both tasks in the 2D technique: group A < 150 s and group B ≥ 150 s. Subsequently, to analyze the effect of prior experience in 2D (faster surgical time), we compared the 3D/2D time ratio of these groups using a Welch t-test. The ratio of 3D/2D completion time was significantly higher in group A (mean = 1.52) compared to group B (mean = 0.79), $t(12.31) = 3.07$, 95% CI = 0.21 to 1.24, r = 0.659 (Figure 2).

Cognitive Load

Assessment of cognitive load after each task revealed a lower cognitive load with increasing experience. Residents (mean = 49.02, SD = 16.40) had a higher workload than consultants (mean = 27.21, SD = 12.20), independent of the technique used or the task (mean change = 21.81, 95% CI: 7.52 to 36.10).

Intraoperative Analysis of Eye Movements

Mean duration of fixation differed between residents and consultants (Figure 3). Residents had longer fixation duration in the stapedotomy task than in the tympanoplasty task (eTable 3), independent of the endoscopic technique used (mean change: -0.24 s, 95% CI: -0.36 to -0.12 s). Consultants also had higher mean fixation duration for the stapes task than the tympanoplasty task; however, this difference increased when using the 2D endoscope (eTable 3;
mean change: 0.34 s, 95% CI: 0.09 to 0.70s). While the fixation duration between the tasks differed marginally between residents and consultants in 3D endoscopy (0.07 s), it increased when consultants used the 2D endoscope (0.47 s) (Figure 3). Furthermore, blink rate was higher in 3D endoscopy (mean = 9.10, SD = 8.45) than in 2D endoscopy (mean = 6.68, SD = 5.40), independent of the task completed or participants' medical experience (mean change: 2.42 ± 1.02, 95% CI: 0.26 to 4.57, r = 0.49).

Discussion

Surgical Considerations

This study investigates, in a randomized crossover design, the effect of 3D vs. 2D endoscopy in EES. Under standardized and controlled laboratory conditions, the study participants performed a type I tympanoplasty, an easy or beginners' operation, and the placement of a stapes prosthesis during stapedotomy, an advanced surgical task. Moreover, the tympanoplasty task requires less depth perception as the surgical steps are performed in almost the same plane, whereas the placement of the stapes prosthesis requires good depth perception. The main surgical outcome in terms of operating time revealed shorter surgical times with growing experience confirming a realistic experimental set-up.

Comparing results from FESS, a recently published study observed a significantly shorter time in 3D compared to 2D endoscopy on a surgical simulator. Moreover, beginners reported a preference for 3D compared to experts.[25] Another study identified the 3D system to be useful in clinical practice.[26] Similar results have also been reported for laparoscopic surgery.[27,28] We observed a tendency towards faster execution of the surgical tasks using 3D endoscopy in the residents group; in contrast, consultants took longer to perform the same interventions in 3D endoscopy. Whether these differences would represent a clinically significant impact during real procedures is difficult to assess since this study was conducted under standardized conditions in a model. Interestingly, the 3D/2D ratios between the fast and slow group in 2D (Figure 2) showed differences with regard to surgical speed. A possible explanation for this finding might be because surgical speed in the standard 2D technique is another measure of expertise, therefore the decreased 3D/2D ratio for the slower surgeons in 2D may indicate an increased utility of 3D endoscopy for inexperienced surgeons. This can be related to the strategies developed by the experienced surgeons to overcome the limited depth perception in the 2D technique and therefore the measurable benefit from the additionally provided information in 3D would be lower. In contrast, inexperienced surgeons do not rely on previously acquired skills and may easily benefit from the additionally offered information in 3D view.

Cognitive Load

The subjective assessment of mental workload was comparable between 2D and 3D endoscopy, indicating no disadvantage for either technique in this setting. Previous research using the same subjective measurement for cognitive load but applied to laparoscopic tasks showed variable outcomes. Gómez-Gómez et al. (2015)[29] and

Smith et al. (2014)[30] found a decrease in cognitive load for the 3D technique, suggesting a benefit for surgeons' cognitive capacity using 3D technology. However, Wilhelm et al. (2014)[19] observed no difference between 2D and 3D set-ups. Taken together, there is no reason to assume that 3D endoscopy affects the surgeon's cognitive capacity in any negative way.

Eye Movements

Fixation duration answers the question of how long the eyes and therefore the attention of the surgeon stay still and focused on a specific area of the surgical field.[31] In our study, this focus differed between residents and consultants, which is in line with previous research reporting longer fixation durations for experienced surgeons.[32-35] These observations are interpreted under the information reduction hypothesis, which assumes that experts limit the processing of information which is not task-relevant. Therefore, expert surgeons have longer fixation periods on the relevant area of interest as learned with growing experience.[36] Also, the overall fixation duration was longer during the stapedotomy task, which is presumably due to the different kind of surgical task, which is consistent with previous results.[32] Interestingly, in the present study, the 3D technique significantly influenced the consultants' eye movements, leading to shorter fixation duration, whereas it only marginally affected the residents' gaze. These results indicate a hindered efficiency of the target-focused strategy in well-known tasks for the 3D technique. One likely explanation for this phenomenon could be the increase in information provided in 3D view. Perceiving more depth detail in 3D view, consultants might be distracted and less able to count on their mental model of the task. This could suggest that, even though the consultants' surgical performance did not suffer in 3D endoscopy, it requires the development of a new gaze strategy. In our opinion, this is an important observation as it indicates the necessity for a dedicated learning curve, even for well-trained surgeons, when adopting a new surgical technique.

Blink rate has often been associated with mental workload, indicating lower blink rates for higher workloads.[37] However, when compared with the subjective assessment in the present study, the patterns diverge. Thus, it seems more plausible that the difference in blink rate was caused by the medium's effect on the eyes. In several cases, blink rate has been linked to eyestrain and visual discomfort, especially for 3D displays.[38,39] This outcome also agrees with the participants' personal rating which states that more visual discomfort was perceived in 3D than in 2D endoscopy. In our experience, this represents the only limitation to the application of 3D endoscopy in EES.

Personal Preference of Surgeons

In total, 10 out of 16 participants in the present study preferred the 3D over the 2D technique. Thirteen participants would even adopt the 3D technique in their future practice if they could choose. We observed that residents favored the 3D technique overall (8:3 in favor of 3D). These subjective perceptions indicate that 3D endoscopy will play an important part in the development of future surgical techniques.

Limitations

This study was performed on a cadaveric model and therefore the results may not be directly applicable to real surgery. Although we used 4 mm diameter, 18 cm length endoscopes for both techniques, the shape of the endoscopes is not completely similar for 2D and 3D endoscopy (Figure 1).

Conclusions

The surgical assessment revealed similar operating times for both 2D and 3D techniques. Most surgeons expressed a preference for the 3D technique, even though a higher incidence of eye strain was observed. Eye movement assessment revealed a decreased fixation duration for 3D endoscopy in experienced surgeons indicating a less efficient application of previous experiences. Therefore, 3D endoscopy is suitable for EES, especially for young surgeons whose mental model of the intervention has yet to be consolidated. The application of 3D endoscopy in clinical routines and for educational purposes appears feasible and beneficial.

Acknowledgments

No funding is reported.

Lukas Anschuetz and Laura Niederhauser had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

References

1. Anschuetz L, Huwendiek S, Stricker D, Yacoub A, Wimmer W, Caversaccio M. Assessment of middle ear anatomy teaching methodologies using microscopy versus endoscopy: a randomized comparative study. Anat Sci Educ. 2018 Nov 14. doi: 10.1002/ase.1837. [Epub ahead of print]
2. Bonali M, Anschuetz L, Fermi M, et al. The variants of the retro- and hypotympanum: an endoscopic anatomical study. Eur Arch Otorhinolaryngol. 2017 May;274(5):2141-2148.
3. Anschuetz L, Alicandri-Ciufelli M, Bonali M, et al. Novel surgical and radiologic classification of the subtympanic sinus: Implications for endoscopic ear surgery. Otolaryngol Head Neck Surg. 2018 Jul 1:194599818787180. [Epub ahead of print]
4. Alicandri-Ciufelli M, Fermi M, Bonali M, et al. Facial sinus endoscopic evaluation, radiologic assessment, and classification. Laryngoscope. 2018 Mar 7. doi: 10.1002/lary.27135. [Epub ahead of print]
5. Marchioni D, Soloperto D, Villari D, et al. Stapes malformations: The contribute of the endoscopy for diagnosis and surgery. Eur Arch Otorhinolaryngol. 2016 Jul;273(7):1723-1729.
6. Bennett ML, Zhang D, Labadie RF, Noble JH. Comparison of middle ear visualization with endoscopy and microscopy. Otol Neurotol. 2016 Apr;37(4):362-366.
7. Presutti L, Anschuetz L, Rubini A, et al. The impact of the transcanal endoscopic approach and mastoid preservation on recurrence of primary acquired attic cholesteatoma. Otol Neurotol. 2018 Apr;39(4):445-450.

8. Kaya I, Sezgin B, Sergin D, et al. Endoscopic versus microscopic type 1 tympanoplasty in the same patients: a prospective randomized controlled trial. Eur Arch Otorhinolaryngol. 2017 Sep;274(9):3343-3349.

9. Anschuetz L, Bonali M, Guarino P, et al. Management of bleeding in exclusive endoscopic ear surgery: pilot clinical experience. Otolaryngol Head Neck Surg. 2017 Oct;157(4):700-706.

10. Bernardeschi D, Lahlou G, De Seta D, Russo FY, Mosnier I, Sterkers O. 3D endoscopic ear surgery: a clinical pilot study. Eur Arch Otorhinolaryngol. 2018 Feb;275(2):379-384.

11. Ashraf H, Sodergren MH, Merali N, Mylonas G, Singh H, Darzi A. Eye-tracking technology in medical education: A systematic review. Med Teach. 2018;40(1):62-69.

12. Hermens F, Flin R, Ahmed I. Eye movements in surgery: A literature review. J Eye Mov Res. 2013;6(4):1-11.

13. Bradley, J. Complete counterbalancing of immediate sequential effects in a Latin square design. J Am Stat Assoc. 1958;53(282):525-528.

14. Anschuetz L, Presutti L, Marchioni D, et al. Discovering middle ear anatomy by transcanal endoscopic ear surgery: A dissection manual. J Vis Exp. 2018 Jan 11;(131).

15. Hart SG, Staveland LE. Development of NASA-TLX (Task Load Index). Adv Psychol. 1988;52:139-183.

16. Dias RD, Ngo-Howard MC, Boskovski MT, Zenati MA, Yule SJ. Systematic review of measurement tools to assess surgeons' intraoperative cognitive workload. Br J Surg. 2018;105(5):491-501.

17. Yurko YY, Scerbo MW, Prabhu AS, Acker CE, Stefanidis D. Higher mental workload is associated with poorer laparoscopic performance as measured by the NASA-TLX tool. Simul Healthc. 2010;5(5):267-271.

18. Zheng B, Cassera MA, Martinec D V., Spaun GO, Swanström LL. Measuring mental workload during the performance of advanced laparoscopic tasks. Surg Endosc Other Interv Tech. 2010;24(1):45-50.

19. Wilhelm D, Reiser S, Kohn N, et al. Comparative evaluation of HD 2D/3D laparoscopic monitors and benchmarking to a theoretically ideal 3D pseudodisplay: Even well-experienced laparoscopists perform better with 3D. Surg Endosc Other Interv Tech. 2014;28(8):2387-2397.

20. International Telecommunication Union (ITU) Radio Communication Sector: 'Methodology for the subjective assessment of the quality of television pictures', ITU-R BT.500-11, January 2002.

21. Loertscher ML, Weibel D, Spiegel S, et al. As film goes byte: The change from analog to digital film perception. Psychol Aesthet Creat Arts. 2016;10(4):458-471.

22. Lienert GA, Raatz U. Testaufbau und Testanalyse [Test construction and test analysis]. 6th ed. 1998; Weinheim, Germany: Psychologie Verlags Union.

23. Cohen J. Statistical Power Analysis for the Behavioral Sciences. Second ed. London, England: Routledge; 1988

24. R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.

25. Rampinelli V, Doglietto F, Mattavelli D, et al. Two-dimensional high definition versus three-dimensional endoscopy in endonasal skull base

surgery: A comparative preclinical study. World Neurosurg. 2017 Sep; 105:223-231.

26. Albrecht T, Baumann I, Plinkert PK, Simon C, Sertel S. Three-dimensional endoscopic visualization in functional endoscopic sinus surgery. Eur Arch Otorhinolaryngol. 2016 Nov;273(11):3753-3758.

27. laraimi B, El Bakbak W, Sarker S, et al. A randomized prospective study comparing acquisition of laparoscopic skills in three-dimensional (3D) vs. two-dimensional (2D) laparoscopy. World J Surg. 2014 Nov;38(11):2746-2752.

28. Matsunaga R, Nishizawa Y, Saito N, Kobayashi A, Ohdaira T, Ito M. Quantitative evaluation of 3D imaging in laparoscopic surgery. Surg Today. 2017 Apr;47(4):440-444.

29. Gómez-Gómez E, Carrasco-Valiente J, Valero-Rosa J, et al. Impact of 3D vision on mental workload and laparoscopic performance in inexperienced subjects. Actas Urol Esp. 2015;39(4):229-235.

30. Smith R, Schwab K, Day A, et al. Effect of passive polarizing three-dimensional displays on surgical performance for experienced laparoscopic surgeons. Br J Surg. 2014;101(11):1453-1459.

31. Holmqvist K, Nyström M, Andersson R, et al. Eye tracking: A comprehensive guide to methods and measures. New York, NY: Oxford University Press; 2011.

32. Eivazi S, Hafez A, Fuhl W, et al. Optimal eye movement strategies: A comparison of neurosurgeons gaze patterns when using a surgical microscope. Acta Neurochir (Wien). 2017;159(6):959-966.

33. Wilson MR, McGrath JS, Vine SJ, Brewer J, Defriend D, Masters RSW. Perceptual impairment and psychomotor control in virtual laparoscopic surgery. Surg Endosc Other Interv Tech. 2011;25:2268-2274.

34. Khan RSA, Tien G, Atkins MS, Zheng B, Panton ONM, Meneghetti AT. Analysis of eye gaze: Do novice surgeons look at the same location as expert surgeons during a laparoscopic operation? Surg Endosc Other Interv Tech. 2012;26(12):3536-3540.

35. Richstone L, Schwartz MJ, Seideman C, Cadeddu J, Marshall S, Kavoussi LR. Eye metrics as an objective assessment of surgical skill. Ann Surg. 2010;252(1):177-182.

36. Haider H, Frensch PA. Eye movement during skill acquisition: more evidence for the information-reduction hypothesis. J Exp Psychol Learn Mem Cogn 1999;25(1):172–190.

37. Brookings J, Wilson G, Swain C. Psychophysiological responses to changes in workload during simulated air traffic control. Biol Psychol. 1996;42(3):361-377.

38. Cho S-H, Kang H-B. An assessment of visual discomfort caused by motion-in-depth in stereoscopic 3D video. Proc Br Mach Vis Conf. 2011:1-10.

39. Lee EC, Heo H, Park KR. The comparative measurements of eyestrain caused by 2D and 3D displays. IEEE Trans Consum Electron. 2010;56(3):1677-1683.

Figure Titles and Legends

Figure 1: Experimental set-up

Illustration of the eye tracking glasses and endoscopic set-up: panels A and B for three-dimensional endoscopy, panels C and D for two-dimensional endoscopy.

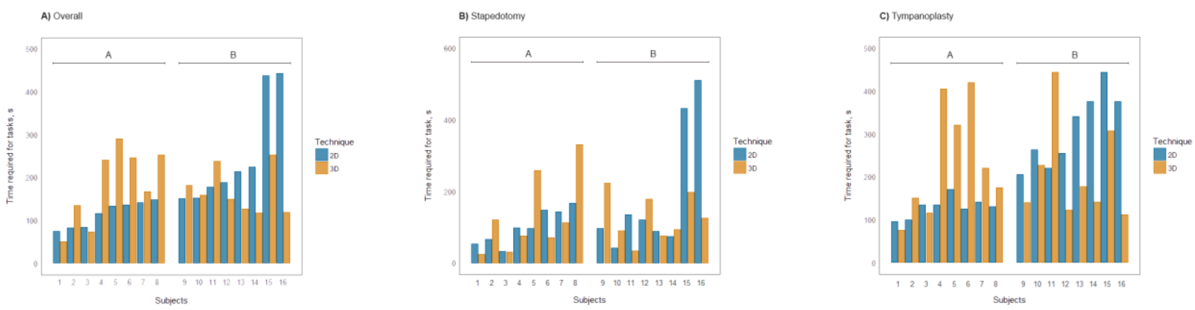

Figure 2: Surgical completion times for all surgeons

Panel A shows the average time for both tasks, panel B for stapedotomy and panel C for type I tympanoplasty.

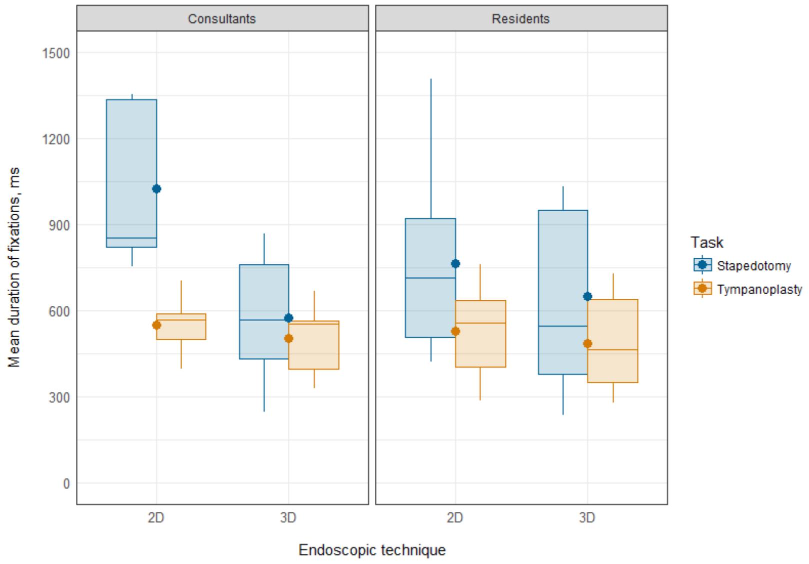

Figure 3: Eye movement analysis

Duration of eye fixation specified per position, task and endoscope used. The box represents 50% of procedures, the line indicates the median value, and the point the mean value.

Tables

Table 1: Participant's assessment of the two endoscopic techniques (n=16).

Questions	**Participants in favor of 3D**	**Participants in favor of 2D**
If you had the choice, with which endoscopic technique would you perform future interventions?	13	3
Which technique offers the better depth perception?	13	3
Which technique offers the better views of middle ear anatomy?	13	3
Overall, with which technique were the tasks easier?	11	5
Which endoscope was easier to handle?	5	11
Overall, which technique did you prefer?	10	6
Which technique offered the better image quality?	9	7
Overall, in which technique were the tasks more comfortable?	9	7

Table 2: Time required to complete procedure as a function of task and experience

Time Required to Complete Procedure as a Function of Task and Experience								
	2D				3D			
	Resident (n=22)	Consultant (n=10)	Difference	95% CI	Resident (n=22)	Consultant (n=10)	Difference	95% CI
Tympanoplasty (n=32)	264 sec (+/- 106)	120 sec (+/- 21)	144	46.3 to 242.3	256 sec (+/- 128)	147 sec (+/- 55)	109	-12.7 to 229.7
Stapedotomy (n=32)	167 sec (+/- 154)	92 sec (+/- 59)	75	-69.8 to 219.9	129 sec (+/- 73)	123 sec (+/-124)	6	-92.6 to 103.7
Total (n=64)	216 sec (+/- 138)	106 sec (+/- 44)	110	1.6 to 217.7	192 sec (+/- 121)	135 sec (+/- 91)	57	-23.4 to 137.4