Digital Image Enhancement Improves Sensitivity of Cholesteatoma Detection During Endoscopic Ear Surgery

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Abstract

Objective: This study evaluates the benefits and limitations of selected modalities of digital image enhancement in detection of cholesteatoma remnants during endoscopic ear surgery (EES) and compares their usefulness in recognizing residual disease. Study Design: Cross-sectional study Setting: Tertiary referral hospital Methods: A total of 10 questionnaires of 18 intraoperative pictures with equal numbers of cholesteatoma and non-cholesteatoma images, each presented in three different image enhancing modalities (clara, spectra A, spectra B), were generated. Fifty-one experienced ear surgeons participated in the survey and were randomly assigned to a questionnaire and completed it at two time points. The experts were asked to rate for each picture whether cholesteatoma was present or not. Results Clara showed the highest accuracy in cholesteatoma detection, followed by spectra A and lastly spectra B. In contrast, spectra B showed the highest sensitivity and clara the highest specificity, while spectra A was placed in the middle for both values. Using the spectra B modality, most responses agreed across the two time points,. Ear surgeons assessed the usefulness, as well as preference among image modalities in the following order: clara, spectra B, spectra A. Conclusion The suitability of image enhancement techniques for application in EES could be shown. Clara can be considered the state-of-art technique throughout the procedure and has subjectively been evaluated best by surgeons. Due to its high sensitivity, spectra B is recommended regarding the final check after resection to prevent cholesteatoma residuals.

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Keywords: Endoscopic ear surgery; cholesteatoma; outcome; image enhancement; SPIES; Clara, Spectra A, Spectra B

Key points

- Detection and radical removal of even microscopic residuals is required to prevent re-growth and complications of middle ear cholesteatoma.
- Despite technical advancements regarding the visual control of the middle ear as offered by the endoscopic approach, the complete eradication of the squamous cell matrix from the middle ear is still a surgical challenge.
- Digital enhancement technologies are applicable to EES and appear to improve the overall accuracy in detecting of cholesteatoma remnants compared to white light endoscopy.
- White light (and the corresponding Clara enhancement) showed the greatest specificity and can be used during all surgical steps.
- The Spectra B modality showed the highest sensitivity for cholesteatoma remnants detection and can be recommended for the final overview.

Funding disclosures

No funding is reported for the present study

Conflict of interest

The authors declare no conflict of interest.

Data Availability

Data available on request from the authors

Introduction

Endoscopic ear surgery (EES) has become an internationally recognized surgical method to treat all kind of middle ear disease. Due to its wide-angled view and the possibility to use angled lenses to access hidden anatomical areas of the middle ear, it is a suitable technique, especially in the treatment of cholesteatoma[1-3]. Recent studies confirm the efficacy and suitability of these technical refinements offering a minimal-invasive surgical method to remove cholesteatoma, minimize the amount of residual tissue and prevent recurrences[3-6]. Due to the locally invasive and destructive behavior of middle ear cholesteatoma, detection and radical removal of even microscopic residuals is required to prevent re-growth and complications[7].

Despite technical advancements regarding the visual control of the middle ear as offered by the endoscopic approach, the complete eradication of the squamous cell matrix from the middle ear is still a surgical challenge. Especially in diffusely infiltrating cholesteatoma it may be difficult removing the cholesteatoma-sac “en-bloc”. Moreover, the quest for possible cholesteatoma remnants is often time consuming and impacts on surgical time.

To improve the detection of disease, digital technologies to enhance the signal visible on the screen have been developed[8]. As an example, narrow band imaging (NBI) technology by Olympus uses a filter, enabling narrow band light to penetrate tissues at different depths, whereby the superficial subepithelial microvascular pattern can be recognized[8,9]. Several studies have shown a significant added value in detection of neoplasms in the larynx, oro-hypopharynx[10,11].

Similarly, the Storz Professional Image Enhancement System (SPIES), allows the surgeon to use four modalities of digital image modifications in addition to traditional white light during endoscopic surgeries. For increased tissue contrast, spectra A and spectra B use shade shift and swap, clara enables homogeneous illumination and chroma causes a contrast enhancement as well as an improvement of the image sharpness. In the context of cholesteatoma surgery, the use of this digital image enhancement (DIE) technology was also applied to EES. So far, in a small case series on forty-five patients reported by Lucidi et al. (2020), an added value in cholesteatoma detection was supposed[8]. Therefore, we aim to investigate possible benefits and limitations of the SPIES in EES. We hypothesize an increased sensitivity regarding cholesteatoma detection by using DIE technologies.

Materials and Methods

Patients and images

A total of 12 patients undergoing endoscopic resection of middle ear cholesteatoma were prospectively enrolled in the present study. All patients provided informed consent and the study was approved by the local ethical committee (Kantonale Ethikkommission Bern KEK2019-00555). At the end of the cholesteatoma resection a final endoscopic check for residual disease is routinely performed. During this complete check of the middle ear, zones with residual tissue (cholesteatoma, granulation tissue, but not macroscopically normal mucosa) were photographed using the three DIE modalities clara (normal image), spectra A and spectra B as illustrated in Figure 1. Light intensity standardized to 70% for every imaging modality (PowerLED300, Karl Storz, Tuttlingen, Germany).

Thereafter the photographed tissue was removed and sent for separate histopathological evaluation. From the histopathological analysis 10 sites of residual cholesteatomatous tissue and 10 sites of non-cholesteatomatous tissue (e.g. granulation tissue, mucosa) were selected. Accordingly, 20 different surgical sites provided the final set of 60 images (each site registered with 3 different image modalities) representing residual cholesteatoma or residual granulation tissue for further analysis.

Questionnaires and participants

We generated 10 online questionnaires on Qualtrics (www.qualtrics.com), each containing 18 images out of the image set of 60 images, balanced regarding the three different imaging techniques and presence of cholesteatoma or not (Table 1). We chose 18 images per questionnaire in order to complete the questionnaire in an acceptable time and therefore receive more responses overall, while still allowing a solid statistical analysis. All 60 images were used and every image was present in three different questionnaires.

Thereafter, we reached out to ear surgeons with expertise in cholesteatoma surgery to rate the images regarding the presence of cholesteatoma or not. No additional detailed instructions were sent to the participants. The image enhancement technique was indicated on every image. Moreover, general information (age, gender), details regarding the surgical experience (microscopic and endoscopic ear surgery) as well as subjective preferences regarding the three different imaging modalities were assessed (usefulness on a scale from 1-5 and single choice for one of the three imaging techniques). The study participants were randomly assigned to a questionnaire. After a few weeks, we asked participants to complete the same questionnaire for a second time.

Statistical analysis

Variables are described in terms of mean or median and standard deviation (SD).

Chi-square tests were applied to analyze the differences between the three imaging techniques in terms of distribution of correct and incorrect responses (accuracy) and in terms of distribution of agreement between time point one and two. We calculated sensitivity and specificity values [with 95% confidence intervals (CIs)] for all three imaging techniques. Sensitivity refers to the ability of an evaluator to correctly classify an image as 'diseased', while specificity as the ability to correctly classifiy as 'disease-free'[12].

Results

Participants at time point one

Fifty-one participants (7 female [13.73%]) with an average age of 44.80 years (SD 9.94 years; range 27-66) from 9 different countries filled out the questionnaires at time point one. They all had experience in cholesteatoma surgery and microscopic ear surgery in particular, with 72.55% (n=37) of them having performed more than 200 microscopic ear surgeries. Around 41% (n=21) had performed more than 200 endoscopic ear surgeries.

Questionnaires and images at time point one

Each questionnaire was answered by a minimum of four and a maximum of eight participants. This resulted in an unbalanced response distribution for the 20 images. Table 1 shows the number of responses for each image and the questionnaire in which they were presented, distributed over the three different imaging techniques. All three imaging techniques received the same number of responses overall.

Responses at time point one

Out of 918 responses overall, 653 (71.13%) were correct. Accuracy was highest with the clara technique (221; 72.22%; 95%CI 67-77%) followed by the spectra A technique (218; 71.24%; 95% CI: 66-76%), and the spectra B technique (214; 69.93%; 95%CI: 64-75%). This difference was not statistically significant (p=0.7112). Table2 shows all responses across the three DIE techniques.

To compare the different DIE techniques, we calculated sensitivity and specificity values for each technique. Sensitivity was highest for spectra B (82.35%; 95%CI: 75-88%), followed by spectra A (81.05%; 95%CI: 74-87%) and clara (75.81%; 95%CI: 68-82%). Specificity was highest for clara (68.63%; 95%CI: 61-76%), followed by spectra A (61.44%; 95%CI: 53-69%), and spectra B (57.52%; 95%CI: 49-65%). Specificity, sensitivity and accuracy are depicted in Figure 2.

If we combine values that are responsible for the high specificity of clara (105 TN) and the high sensitivity of spectra B (126 TP), we obtain a theoretical accuracy of 231 correct responses (75.49% of 306). This means, 10 more images would be answered correctly if the two techniques were combined instead of using clara alone.

Additionally, we calculated the positive and negative predictive values for each technique, which are also included in table 2. Highest positive predictive value was reached by clara (70.73%), followed by spectra A (67.76%), and spectra B (65.97%). Highest negative predictive value was reached by spectra B (76.52%), followed by spectra A (76.42%), and clara (73.94%).

Additionally, we inspected accuracy for all images separately. Figure 3 shows that certain images were very difficult to interpret, or information were interpreted wrongly with accuracy below 40% (image 4 and image 8). To illustrate this challenge, the most difficult images are presented in Figure 4.

Sample at time point two and intra-rater reliability

Forty-three (84.31%) participants filled out the questionnaire a second time. Time between the two responses was a median of 45 days (mean 55.8 days, SD 27.8). The sample consisted of 38 male participants (88.37%) and had an average age of 44.7 years (SD 9.87). Out of 792 responses at time point two, 609 (78.68%) were consistent with responses from time point one. On average, 14 images were evaluated the same by the participants at both time points. The agreement was higher for images evaluated with the spectra B technique (215, 83.34%) than with the clara and spectra A technique (both 197, 76.36%). The difference was however, not statistically significant (p = 0.082).

Subjective evaluation

Responses for subjective evaluation were collected from time point one, or if missing, from time point two. One participant failed to fill out the subjective evaluation questions; one participant had partial missing data. This resulted in 50 responses for the single choice and 49 to 50 responses for the usefulness rating. Participants' evaluation in terms of usefulness was highest for the clara technique (mean 3.32, SD 0.98), followed by spectra B (mean 3.00, SD 1.08), and spectra A (mean 2.90, SD 1.10). The overall technique choice was also in favour of the clara technique, with 29 votes for clara, 11 votes for spectra B, and 10 votes for spectra A.

Discussion

Residual cholesteatoma is the first cause of failure in cholesteatoma surgery, leading sometimes the surgeon to adopt expensive and invasive strategies such as the "second look" tympanoplasty. Among strategies to reduce the risk of residual cholesteatoma, EES has shown an improvement in the visualization of hidden areas of the middle ear and has consequently been accepted as a useful tool in cholesteatoma surgery. DIE endoscopic visualization may be a further advance in the intraoperative detection of residual cholesteatoma.

DIE systems such as SPIES have been developed to better identify and distinguish pathological from healthy tissue and thereby remove the disease while respecting normal mucosa. In contrast to the commonly used white light, DIE makes avascular structures (e.g. cholesteatoma) appear whiter than vascularized tissues: This allows the surgeon to define its extension precisely and to remove the disease completely.

In other surgical specialties such as ureteroscopy, endoscopic thyroidectomy and laparoscopy, SPIES was already used for early tumour detection by means of highlighting hyper-vascular structures[13,14]. Improved visualisation of differently vascularized tissue and thus clearer distinction between pathologies and normal anatomy are generally cited as the main advantages[8,9].

To the best of authors' knowledge, the retrospective case series by Lucidi et al. (2020) was the first paper to investigate the usefulness of the SPIES image enhancing system in ear surgery[8]. The challenge in cholesteatoma surgery is to completely remove the squamous epithelial, while sparing normal middle ear and mastoid mucosa. According to the previously mentioned study, spectra A and B filters in EES are deemed suitable to recognize cholesteatoma remnants[8].

In our study, the comparison of the three DIE techniques (clara, spectra A, spectra B) makes clear that each of those modalities brings along its own advantages. When considering the surgeons' point of view on the suitability of the three image-improving modalities, a general attitude in favour of the use of clara followed by spectra B and lastly spectra A was found. This is expected, as Clara is the "state-of-the-art" technique used to perform EES. The spectra A and B techniques have recently been introduced to depict residual cholesteatoma after complete removal of the disease.

We investigated and quantified separately the added value of clara, spectra A and spectra B for the first time. In all three imaging techniques, diseased images are detected more successfully than disease-free images. This difference becomes very apparent with Spectra B. With the highest sensitivity but the lowest specificity, a lot of tissue is misinterpreted as cholesteatoma but only few cholesteatomas are missed. In our opinion, this increase in sensitivity justifies its use at the end of every cholesteatoma surgery. Using the spectra B technique most cholesteatoma-remnants are detected and results regarding residual cholesteatoma may be improved. Moreover, a high intra-rater reliability was observed and was highest for spectra B. In our opinion, this further indicates an additional value regarding the performance of spectra B. Clara in contrast has the highest accuracy overall and its general image properties with high illumination makes it most suitable to perform the surgery itself. By having the smallest number of false positives, Clara is considered the most conservative restrained method. Spectra A lies between Clara and Spectra B in terms of sensitivity-specificity-difference, as well as in terms of detection, missing, identification and misidentification of cholesteatoma. Therefore, we don't see any indication in the use of the Spectra A technique in cholesteatoma surgery.

Interestingly, some special situations require special considerations while using digital image enhancement in EES (figure 4). For example, the tendon of the tensor tympani muscle appears bright at its insertion in the malleus and may be mistaken for squamous epithelium. Similarly, upon thorough review of the image set represented in Figure 4 D-F and related histopathology, it appears that bone fragments produced during drilling may also be mistaken for cholesteatoma. In summary, Clara may be considered the most appropriate image modality for use during surgery. However, as the removal of small amounts of inflamed mucosa has few consequences for the patient, whereas cholesteatoma remnants can result in serious complications and require a second operation, we recommend the use of Spectra B as a final overview at the end of cholesteatoma surgery, in order to avoid missing any pathological finding. Indeed, the combined use of Clara and Spectra B, as proposed, permits to increase the overall accuracy of the endoscopic visualization up to 75.4% in our study.

The present study includes responses from ear surgeons with different surgical background (microscopic and endoscopic), different experience and from different countries. This is a strength of the study, as it explores the accuracy of the DIE technique in ear surgeons with variable experience in dealing with endoscopic images of the middle ear, eventually providing data which can be considered closer to real-life. In addition, this can also explain the difference of the observed sensitivity and specificity compared with previous studies[8] and permits to hypothesize a learning curve-related outcome.

Since not all surgeons who were invited to fill out the questionnaires responded, we eventually obtained an uneven distribution of responses across the questionnaires. As a result, not all images were presented with each technique the same number of times overall. This is certainly a limitation of the current study, as some responses therefore influenced the overall result heavier than others. Nonetheless, due to the high number of responses received, the limited availability of ear surgeons overall and also limited time resources specifically, we decided to stop data collection with a slightly unbalanced distribution. Additionally, the images in the questionnaire were always presented in the same order, which could have influenced the intra-rater reliability measure. However, as the focus of the current study was on the results of the first time point, this limitation can be neglected.

Finally, another limitation can be the static nature of pictures, which is different from the dynamic visualization, which occurs during EES along with the manipulation of the suspicious tissue. Indeed, accuracy in the detection of cholesteatoma could be affected by the dynamic movements of the endoscope, changes in the point of view, light reflexion, direct suction and information about previous surgical steps.

Conclusions

Digital enhancement technologies are applicable to EES. Clara can be considered the state-of-the-art technique and is valued by most surgeons. Spectra B has the highest sensitivity of cholesteatoma detection and can be recommended using as a final overview at the end of cholesteatoma surgery, in order to avoid missing any pathological findings.

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Table 1

Number of responses for each image divided by imaging technique. Due to differences in surgeon response to the invitation to participate in the present study, not every image was equally rated.

	Clara	Spectra A	Spectra B	Total
Image number	No. of responses	No. of responses	No. of responses	
1	12	16	18	46
2	21	18	8	47
3	18	8	20	46
4	8	20	18	46
5	15	18	14	47
6	18	14	14	46
7	14	14	15	43
8	14	15	18	47
9	15	18	12	45
10	18	12	16	46
11	12	16	18	46
12	21	18	8	47
13	18	8	20	46
14	8	20	18	46
15	15	18	14	47
16	18	14	14	46
17	14	14	15	43
18	14	15	18	47
19	15	18	12	45
20	18	12	16	46
Total	306	306	306	918

Table 2

	clara	**clara**		**spectra A**	**spectra A**		**spectra B**	**spectra B**	
	cholesteatoma yes	cholesteatoma no		cholesteatoma yes	cholesteatoma no		cholesteatoma yes	cholesteatoma no	
yes	116 (70.7%) *TP*	48 (29.3%) *FP*	164	124 (67.8%) *TP*	59 (32.2%) *FP*	183	126 (65.9%) *TP*	65 (34.0%) *FP*	19
no	37 (26.1%) FN	105 (73.9%) *TN*	142	29 (23.6%) *FN*	94 (76.4%) *TN*	123	27 (23.5%) *FN*	88 (76.5%) *TN*	11
	153	153	306	153	152	306	153	153	30

All responses for the three imaging techniques.

TP (True positives); TN (True negatives); FP (False positives); FN (False negatives)

Figure Legends

Figure 1

Illustration of residual cholesteatoma in the top row (A-C) and granulation tissue in the bottom row (D-F) in the three different image modalities: A/D=spectra B, B/E=spectra A, C/F=clara.

Figure 2

Accuracy, sensitivity and specificity (with the respective 95% CI) for the three imaging techniques.

Figure 3

Accuracy for image number 1-10 (without cholesteatoma) and 11-20 (with cholesteatoma). Δ: Cholesteatoma, O: no cholesteatoma. Green: accuracy> 60%,

Purple: accuracy 40 to 60%, Orange: accuracy: <40%

Figure 4

Examples of two special non-cholesteatoma situations leading to frequent false positive responses. Top row (A-C): tendon of the tensor tympany muscle mistaken for cholesteatoma. Bottom row (D-F): histologically proven granulation tissue and bonemeal from drilling, mimicking residual cholesteatoma. A/D=clara, B/E=spectra A, C/F=spectra B

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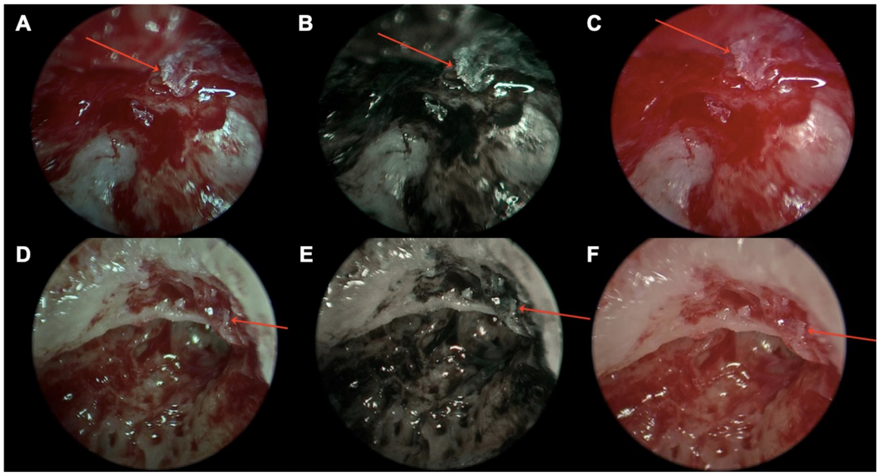
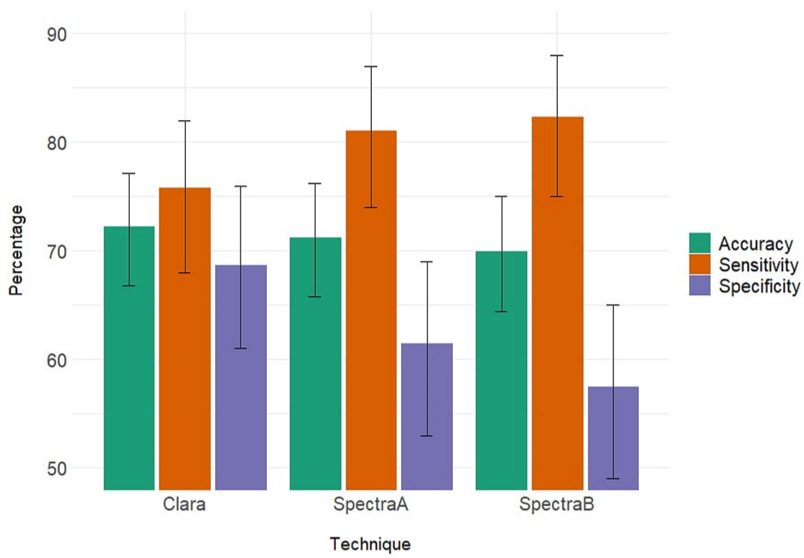

A
B
C
D
E
F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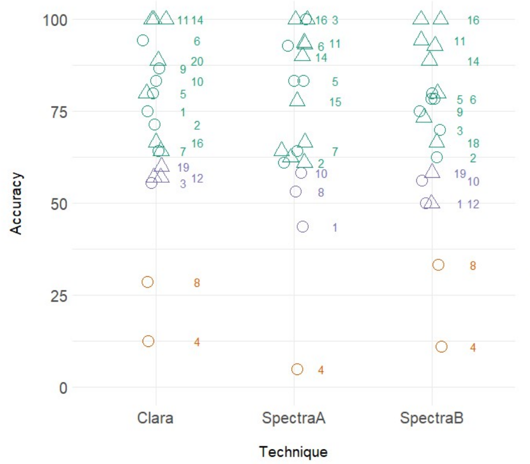
Percentage
Clara
SpectraA
SpectraB
Technique
Accuracy
Sensitivity
Specificity



Accuracy
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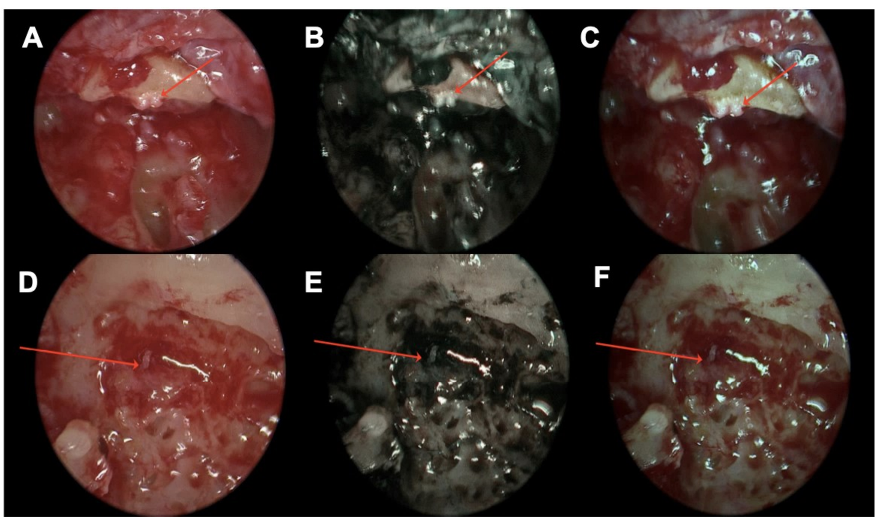
Clara
SpectraA
SpectraB
Technique



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B
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