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Anti-confocal versus confocal assessment of the middle ear simulated by Monte Carlo methods

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Abstract: The ability to monitor the inflammatory state of the middle ear mucosa would provide clinical utility. To enable spectral measurements on the mucosa whilst rejecting background signal from the eardrum an anti-confocal system is investigated. In contrast to the central pinhole in a confocal system the anti-confocal system uses a central stop to reject light from the in-focus plane, the eardrum, with all other light detected. Monte Carlo simulations of this system show an increase in detected signal and improved signal-to-background ratio compared to a conventional confocal set-up used to image the middle ear mucosa. System parameters are varied in the simulation and their influence on the level of background rejection are presented.

OCIS codes: (170.1790) Confocal microscopy; (170.3880) Medical and biological imaging; (170.4940) Otolaryngology; (110.0113) Imaging through turbid media.

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1. Introduction

Otitis media with effusion (OME) is a chronic inflammatory condition of the middle ear mucosa resulting in a liquid filling the middle ear cavity which impairs the movement of the eardrum and middle ear ossicles resulting in hearing loss. The only effective treatment is to remove the fluid surgically and ventilate the middle ear cavity by placing a tympanostomy tube in the eardrum. This is a common condition and the surgery is among the commonest performed in the developed world [1]. However, 25 % of treated children have a recurrence requiring further surgery [2]. Our hypothesis is that these cases are remaining in an inflammatory state. Currently, there is no clinical means of detecting middle ear inflammation and predicting the recurrence.

To explore this hypothesis, we aim to develop a device able to assess the inflammatory state of the middle ear mucosa after tympanostomy tube placement, using spectroscopy to assess the blood content in the mucosa as for example used previously for periodontal inflammation [3]. If successful, it could be used during diagnosis to predict the likelihood of a recurrence of OME. Whilst Sundberg et al. [4] suggest that the reflectance spectrum of the eardrum is a promising measure to assess OME, being able to separate background signal from the eardrum and so assess the middle ear mucosa alone is likely to improve the predictive capability. We propose application of an anti-confocal system to filter out background signal [5].

This paper theoretically investigates the anti-confocal system, and shows possible applications and limitations. The system is described and simulated, with the optical system and tissue parameters varied. Experimentally work to validate these results will be published in future.

2. Anti-confocal system

A conventional confocal system as illustrated in Fig. 1 (top) uses a pinhole to select light from a single spot in the sample and reject all other light. With the illumination focused on the same spot within the sample, this results in confined sampled area and good depth discrimination. In this application, the system would be focused on the mucosa to reject light from the eardrum.

However, due to the small pinhole, most of the signal is lost, only a small volume of mucosa is sampled, and scanning is necessary to acquire representative tissue properties averaged over a larger area. Further, the position of the mucosa is not known and so focusing of the system is challenging. As in this sample the background signal originates from a single layer (the eardrum) that is separated from the target (the mucosa) and the requirement is to obtain a single measurement averaged over the sample volume rather than an image, use of an anti-confocal system is appropriate [5].

Here, the idea of confocal imaging is inverted by replacing the pinhole with a central stop to reject all light within its radius. Consequently, light from the focal spot is rejected but all other

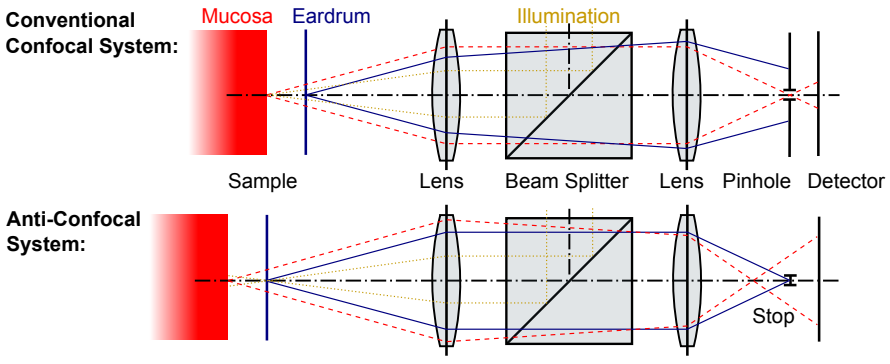

Fig. 1. Principles of the conventional confocal and anti-confocal system.

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light is detected as shown in Fig. 1 (bottom). Illumination and imaging optics are focused on the eardrum that is readily observable, to reject light backscattered from it. Most light that passes through the translucent eardrum and is backscattered from the mucosa passes outside the stop and is detected providing a signal that has 'sampled' an extended volume of the mucosa.

3. Monte Carlo simulation

Monte Carlo simulations [6] were used to investigate light propagation inside the middle ear while photons exiting the medium were propagated through the optical system using geometrical optics [7]. All code was implemented in MATLAB with confocal and anti-confocal systems simulated and compared. The performance of the system was analysed with respect to the signal power (proportion of detected photons backscattered from the mucosa) and signal-to-background ratio (SBR; signal power divided by background power, i.e. detected photons backscattered from the eardrum). The position of every photon at the detector was recorded and signal and SBR calculated in a separate step. All simulations were conducted with 10^8 photons.

The NA of the optical system is 0.08, determined by the otoscope speculum used inside the narrow ear canal, and the sample is modelled as the eardrum (scattering coefficient $\mu_s = 11\,\mathrm{mm}^{-1}$, scattering anisotropy $g = 0.99$, absorption coefficient $\mu_a = 1.8\,\mathrm{mm}^{-1}$, refractive index $n = 1.43$, and thickness $t = 0.1\,\mathrm{mm}$), air filled middle ear cavity of 3 mm depth, and mucosa ($\mu_s = 6.25\,\mathrm{mm}^{-1}$, $g = 0.897$, $\mu_a = 0.035\,\mathrm{mm}^{-1}$, $n = 1.4$, $t = \infty$) as illustrated in Fig. 1. The optical properties were drawn from literature (at 800 nm) and experiments [5]. Unless otherwise stated, these values are used in the simulations presented below.

4. Simulation results

The simulated signal power and SBR of the anti-confocal and conventional confocal system are shown in Figs. 2 to 4. The influence of the radius of pinhole or stop, the distance between eardrum and mucosa, and finally the scattering properties of the eardrum are presented.

4.1. Radius of the filtering element

Figure 2 shows the effect of aperture/stop radius for the confocal/anti-confocal set-ups. As expected, in the confocal case the signal level increases with increasing radius with the SBR decreasing. Almost no background is detected at a radius bigger than 0.5 mm, hence the SBR increases slightly due to further increasing signal. The anti-confocal system behaves inversely, the signal level decreases with increasing radius whilst the SBR increases as a higher portion of the background is rejected. The detected signal is dependent on the scattering characteristics of the eardrum, as shown in Section 4.3, the sampled volume (given by collection aperture and stop radius), and light distribution inside the tissue (given by optical parameters of the mucosa).

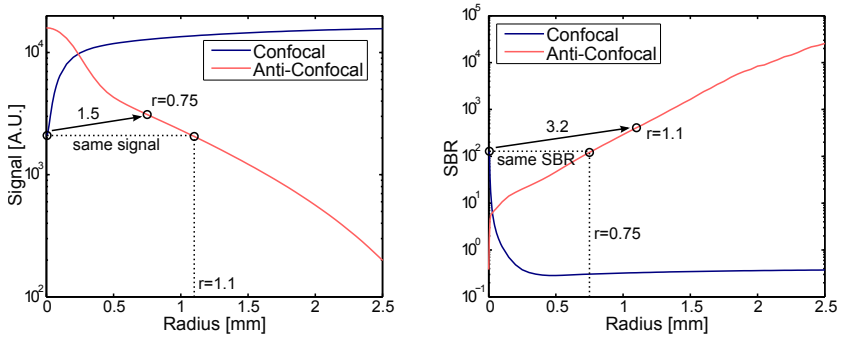

Fig. 2. Effects of radius of pinhole/stop on signal (left) and SBR (right).

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A confocal microscope achieves best performance with respect to SBR and signal level at a pinhole radius of just below 4 optical units $OU = \frac{\lambda}{2\pi NA}$ [8]. Here, this value is $4 \cdot OU = 0.0064$ mm and a pinhole radius of 0.005 mm is used for further analysis of the confocal setup. The anti-confocal reaches the same SBR as the confocal system at a stop radius of 0.75 mm, but the signal level is improved by factor 1.5. At a stop radius of 1.1 mm, the signal level is the same and the SBR is improved by a factor of 3.2 and this configuration is used for further analysis.

4.2. *Distance between eardrum and mucosa*

The distance between eardrum and mucosa can vary, thus the dependence of this parameter on signal and SBR was investigated with results shown in Fig. 3. A wide range of distances is investigated to further enhance the understanding of the system. In the confocal case, the signal is highest for smallest separation distance and with increasing distance, the signal level decreases and approaches a fixed value whilst the SBR increases. In the anti-confocal case, the signal gradually decreases with increasing distance and since the noise is unaffected by the distance, the SBR also decreases with increasing distance, showing some fluctuations.

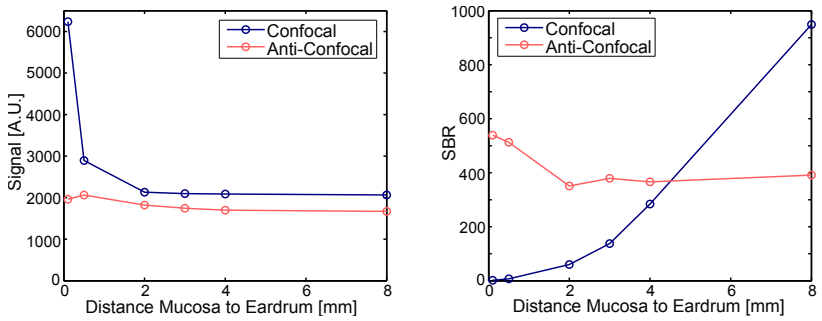

Fig. 3. Effects of distance between eardrum and mucosa on signal and SBR.

4.3. *Scattering of the eardrum*

The properties of the eardrum change from person to person, especially during OME since it can become thicker and a biofilm may become attached to it. A wide range of scattering parameters is simulated in order to cover the whole possible range including values estimated in literature of $\mu_S < 22\,\mathrm{mm}^{-1}$ at 1310 nm [9]. Figure 4 shows the signal and SBR for increased scattering coefficient and changed scattering anisotropy of the eardrum.

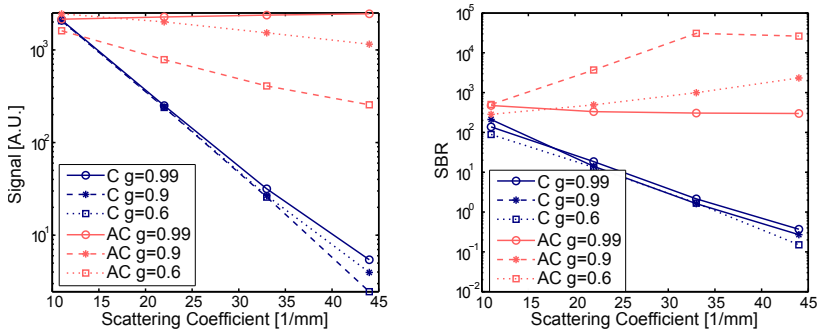

Fig. 4. Effects of eardrum scattering on signal and SBR. C – confocal, AC – anti-confocal

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In the confocal system, the detected signal decreases with increasing scattering coefficient and is almost independent of the scattering anisotropy with the SBR also decreasing. The anti-confocal system shows an interesting behaviour, since for highly forward scattering ($g = 0.99$), the detected signal increases with increasing scattering coefficient. For less forward scattering (g of 0.9 and 0.6), the signal decreases with increased scattering coefficient. The SBR increases for less forward scattering, but decreases for a highly forward scattering medium.

5. Discussion

The results show that an up to 200 times higher SBR is achieved for an anti-confocal set-up with stop radius of 2.5 mm compared to the confocal system, although the signal is reduced to 10 %. As compromise, signal level and SBR are compared for radii where the other measure is equal. Both cases show improvement, demonstrating superiority of the anti-confocal system. Eardrum and mucosa were simulated as flat parallel surfaces, but can be rough and tilted in reality. Hence, light will be reflected away from the detection aperture. This is expected to have a high influence on the background as mostly caused by direct reflections, a low influence on the signal as mostly caused by scattering, and rather improve the system performance.

For a small distance between mucosa and eardrum, the confocal system detects most signal as photons with a small scattering angle can still illuminate the sampled volume and can be detected. With increasing distance, these photons are spread further and less scattered photons are detected, thus decreasing the signal. The fixed value is reached when only unscattered photons reach the focus spot and a further increase in the distance has no effect. In the anti-confocal system, the signal decreases slightly as two opposite effects are present. First, as the stop is placed further away from the focus of the mucosa surface, more photons pass the stop, and second, the effective NA decreases with the optics focused on the eardrum moving away from the mucosa, decreasing the number of detected photons. The SBR is expected to behave the same way as the noise is unaffected by the distance and this is shown in Fig. 3 although the SBR shows fluctuations due to a low number of detected noise photons. Nonetheless, the decrease in performance is small, indicating suitability of the anti-confocal system even for an altered distance.

A confocal system mostly detects photons unscattered by the eardrum. Increasing its scattering coefficient will decrease the number of unscattered photons and the signal level. The scattering anisotropy does not have a significant influence as it does not affect the number of scattering events, only the scattering angle. The noise is relatively unaffected by the scattering parameters as it mostly results from reflections from the eardrum surface. In the anti-confocal system, the signal power can increase with increasing scattering coefficient because scattered light is detected. The signal increases in the cases where more light is scattered away from the optical axis, blocked by the stop, into the detection area. But more noise is scattered into the detection aperture at the same time, reducing the SBR for the very forward scattering eardrum. Less noise is detected for less forward scattering ($g = 0.6$ and 0.9), increasing the SBR. This emphasises good performance of the anti-confocal system, even for a high scattering eardrum.

In additional simulations not presented above, the NA of the system was varied from 0.027 to 0.27 in order to investigate its influence for other applications where the NA is not restricted as it is the case here. For both the confocal and anti-confocal systems, signal and SBR improve with increasing NA, with a higher increase in the anti-confocal case. In the confocal case, a higher portion of the backscattered signal is detected and the depth discrimination ability increases. In the anti-confocal case, multiple scattered photons with higher exit angle can be detected and the sampled area increases. Measurements with high NA are favourable as more signal can be detected. At small NA the anti-confocal system is limited as it is dependent on scattered photons that are easily rejected by small apertures.

As mentioned above, an advantage of the anti-confocal system is that it is focused on the eardrum with known position. The importance of the accuracy of the focus was investigated

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by moving the focus of the optical system towards the mucosa. Differences are only visible for small stop radii where the size of the defocus spot on the eardrum approaches the stop radius. But at the NA of 0.08, distance of 3 mm, and stop radii bigger than the defocus spot, no significant changes are observed even far beyond the depth of focus. This shows that no exact focus of the anti-confocal system is necessary to achieve good performance, resulting in simple deployment. The illuminated spot size on the eardrum increases with distance of the focus point from the eardrum and the NA. This means accurate focusing is more important at higher NA. So far, the illumination NA was equal to the detection NA. Reducing the illumination NA reduces the defocus spot size and illuminated area on the mucosa. Using standard parameters above, the effect of light distribution on mucosa is minimal as the signal is affected more by scattering inside the mucosa than by the beam size itself. In case of a defocussed beam, the SBR is less degraded compared to a high illumination NA as the illuminated area on the eardrum is smaller.

The penetration depth (defined as depth where power is reduced to $\frac{1}{e}$) in the simulated mucosa is about 1 mm. This is more than the thickness of the mucosa in the middle ear and hence the underlying tissue is sampled as well. But as the intensity falls off exponentially this has a minimal contribution to the overall measurement. The illumination beam in the anti-confocal system has a radius of $r \approx NA \cdot d = 0.24\,\text{mm}$ at the surface of the mucosa, assuming no scattering in the eardrum, and increases with increasing NA and separation. When scattering is included, this value increases according to the scattering characteristics of the eardrum and further, light propagates inside the mucosa sampling an even bigger volume. Hence, for a homogeneous mucosa, scanning of the sample might not be necessary to obtain an average measure of inflammation.

6. Conclusion

This paper first introduces the problem of spectroscopically assessing the middle ear mucosa in order to assess its inflammatory state. An anti-confocal system that is able to minimise background signal caused by the eardrum in the light path is proposed. Monte Carlo simulations are used to investigate the anti-confocal system and compare it to a conventional confocal system.

Simulations showed that the anti-confocal system is able to separate background from signal and can reach higher signal levels and SBR than the confocal system. This superiority stems from the special geometry in the middle ear, where the target is separated from the scattering layer and large volume sampling of a largely homogeneous sample rather than high resolution imaging is required. The eardrum is readily observable and exact focusing of the anti-confocal system is not necessary, both increasing the ease of use. An increase in the distance between eardrum and mucosa only slightly decreases the performance of the anti-confocal system. Whilst increasing scattering in the eardrum always decreases the performance in the confocal system, this is not the case in the anti-confocal system where signal and SBR can even increase in certain cases. This shows that high performance of the anti-confocal system is given for a wide range of optical parameters including those expected in the inflamed middle ear.

Next, the anti-confocal system will be assessed in experiments using optical tissue phantoms modelling the mucosa and the eardrum. This is the first step in this project, showing that the required photons returning from the mucosa can be detected while minimising background signal. The next step is to consider multiple wavelengths and how to extract information about the inflammatory state from this signal. Maximum exposure limits of the tissue, noise of the system determining the minimum required signal level, and variations in eardrum and mucosa must be considered to evaluate the overall performance.

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