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Project summary: The acoustic diagnosis of middle ear problems (glue ears)

Author: Jessye Tu

What is glue ear?

Have you ever known someone who had an *ear infection* when they were a child? Or perhaps someone who had *grommets*? Chances are, that means you've known someone who has had the childhood condition known as *glue ear*.

In a nutshell, a child has glue ear when there is an abnormal accumulation of fluid behind the ear drum. The accumulation of fluid is known as an effusion. 80% of children will have the disease at least once before the age of 10[1] and it is the leading cause of childhood surgery in the UK[2]. It is most prevalent in children between 1 and 5 years old, although it can sometimes occur in adults[3].

Symptoms of glue ear include earache and a feeling of fullness within the ear. The most common symptom is hearing loss[4]. Glue ear causes discomfort and confusion for children, as well as worry for parents when they cannot be certain of the cause of hearing loss. Often, general practitioners find it difficult to diagnose glue ear, so a child will require an appointment with an ear, nose, and throat (ENT) specialist. Waiting times for these appointments can be long, and although most cases will resolve naturally, 40% of cases will persist for over 3 months[5]. Prolonged deafness in young children is a serious issue because it can impact their speech and language development, which can also impact their educational and social development[6]. If left untreated, glue ear can lead to more serious complications such as facial paralysis or brain abscess[7], further motivating the need for the early and accurate diagnosis of the condition.

What's wrong with the current diagnosis?

Clinicians face a challenge in determining appropriate treatment plans for patients with glue ear due to the limitations of current diagnostic methods. These methods fail to provide sufficient insight into the impact of glue ear on hearing, which is a crucial factor in determining what degree of medical intervention is necessary.

One such diagnostic method is acoustic reflectometry. In this method, a multi-frequency sound wave is played into the ear (typically varied between 1800 and 5000 Hz in typical

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[1] Little Ears (2021). *Glue Ear: How Common is Glue Ear?* University of Southampton. url: https://www.littleears.soton.ac.uk/about-glue-ear/how-common-glue-ear (visited on 24/07/2023).
[2] Cullen, K. et al. (2006). National Health Statistics Reports Number 11 January 28.
[3] Bupa (2022). Glue Ear. Bupa. url: https://www.bupa.co.uk/health-information/ ears-nose-throat/glue-ear (visited on 24/07/2023).
[4] Patient.info (2022). Glue Ear. Patient. url: https://patient.info/ears-nosethroat-mouth/hearing-problems/glue-ear (visited on 24/07/2023).
[5] Parker, D.M. et al. (2016). "Variation in Utilization and Need for Tympanostomy Tubes across England and New England". In: Journal of Pediatrics 179.
[6] Paradise, J.L. et al. (1976). "Tympanometric Detection of Middle Ear Effusion in Infants and Young Children". In: Pediatrics 58.
[7] Glasscock, M.E. et al. (1990). Surgery of the Ear. Fourth. Philadelphia, PA.

commercial devices) and a microphone is used to measure the pressure field in the ear canal. An acoustic reflectometer produces a plot of 'reflectivity' (a normalised measure of the measured pressure field) as a function of frequency.

Typical curves comparing a healthy and an effused ear are illustrated in Figure 1.

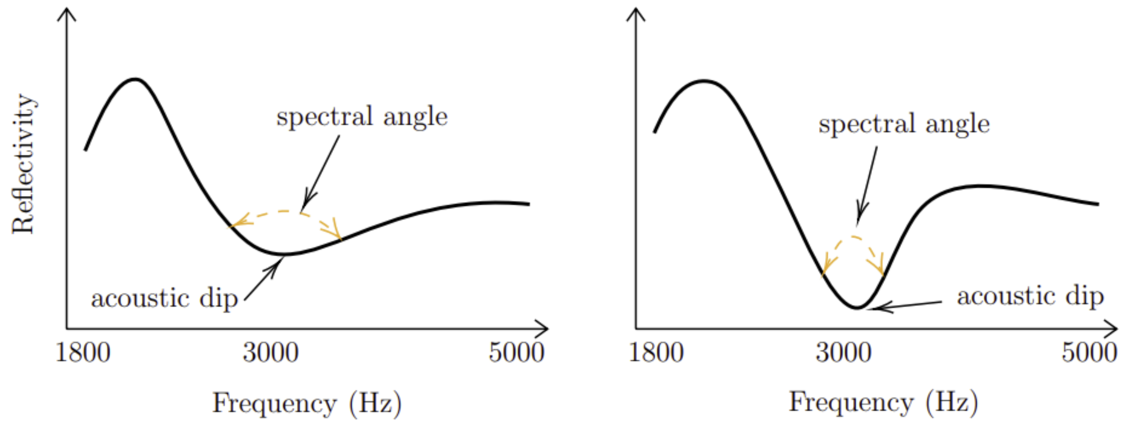

Figure 1: Plots of the output from acoustic reflectometry of a healthy ear (left) and an effused ear (right). The spectral angle is labelled and is narrower for the effused ear.

The pressure field measured by the microphone (and therefore the 'reflectivity') depends on the sound reflected by the eardrum, as the reflected wave interferes with the incident wave. Commercial devices make a diagnosis based on the sharpness of the acoustic dip (the minimum point on the plot) through a measure called the 'spectral angle', as shown on Figure 1. The current heuristic is that the smaller the spectral angle, the more likely an effusion is present. Typical explanations for this heuristic are over-simplistic - they often just claim that an effused ear has a 'narrow echo' when compared to a healthy ear with no further detail.

Despite these limitations, acoustic reflectometry has been shown to be as effective as other more established diagnostic methods (e.g., tympanometry), and can even be used be parents, thus reducing the need to wait for an appointment with an ENT doctor. If the method and the understanding of its underlying mechanisms were refined, there could be potential to extract more information from the diagnostic output. The understanding of acoustic reflectometry is still evolving, and more research is needed to accurately judge its utility in clinical applications.

My project:

The aim of the project is to improve the physical understanding of acoustic reflectometry so that clinicians may better infer how glue ear affects hearing. The focus on hearing is important because hearing loss is both a common and concerning symptom for young patients with glue ear – a patient who experiences hearing loss warrants more medical intervention than a patient who experiences an earache. The project will allow clinicians to better monitor the progression and impact of glue ear, thus improving patient care.

My main results:

How does glue ear impact hearing?

Glue ear results in both an accumulation of fluid (known as an effusion) and an underpressure in the middle ear cavity positioned behind the eardrum. Existing literature suggests that the presence of effusion can have a greater impact on hearing than the underpressure, and that there is a 'critical' level of effusion (around 50 % effusion) necessary for hearing to become severely affected. We propose a hypothesis for why this 'critical' level occurs by assuming effused parts of the ear are made effectively rigid. In particular, once the ossicular chain (the three bones in the middle ear which transfer sound) is fixed at both ends, further increases in the level of effusion no longer affect hearing loss.

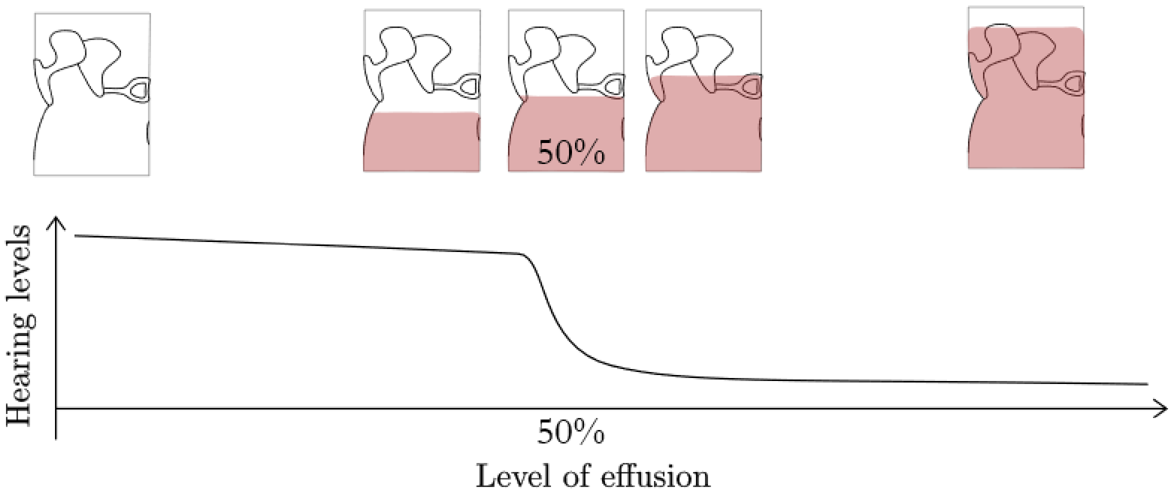

Figure 2: Illustrative diagram of how hearing levels are affected by the amount of effusion behind the eardrum – a 50% effused ear has the same decrease of hearing loss as a 100% effused ear.

How does acoustic reflectometry work?

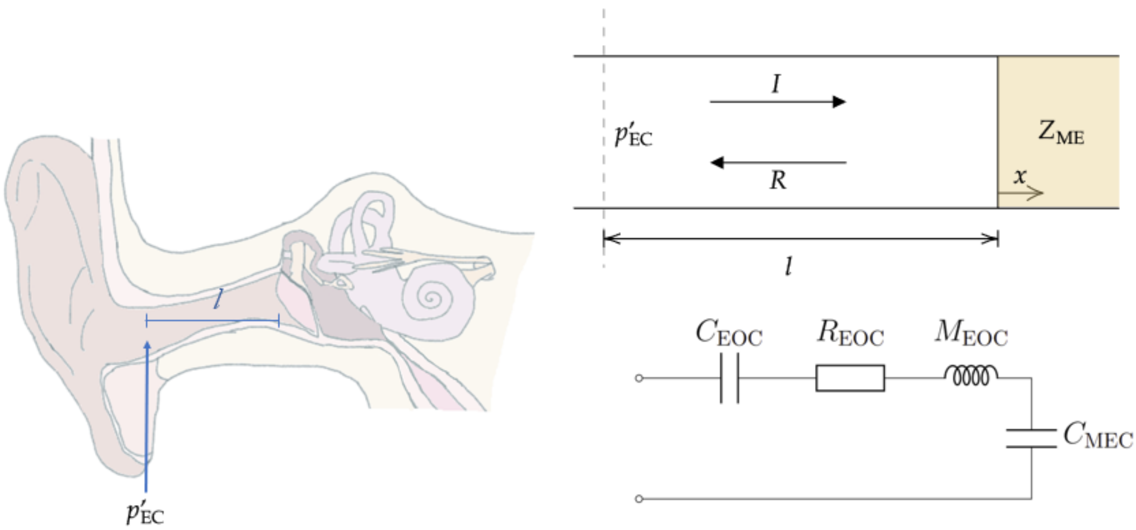

Figure 3: Our new model for acoustic reflectometry.

In order to explain how acoustic reflectometry, we employ an existing lumped-element model of the middle ear and d'Alembert's solution to the 1D wave equation to develop a new mathematical model for acoustic reflectometry. Our model enables us to investigate how changes in the level of effusion affect the acoustic reflectometry response.

Using our model, we find that once effusion reaches 50 %, the spectral angle remains relatively constant. In this respect, the behaviour of the spectral angle is similar to the behaviour of the ossicular chain displacement. Therefore, acoustic reflectometry can be used to detect when hearing levels are affected by glue ear.

Design of a new diagnostic method

Our research opens up pathways for the design and manufacture of a new generation of acoustic reflectometers. Instead of 'reflectivity', we propose measuring the acoustic impedance in the ear canal. This is feasible using a single microphone if we assume a stiff speaker (which is already being assumed for earbuds that have a built-in microphone next to the speaker for active noise reduction). Therefore, it would be possible to design a wearable acoustic reflectometer using commercially available earbuds with a noise cancellation feature. This would lower manufacturing costs and further increase the accessibility of the diagnosis of glue ear.

Our results could also be used to design a 'auto-tuning' hearing aid for glue ear patients. Since most hearing aids are in the form of an earbud, it is viable to design a hearing aid that has the functionality of being able to conduct acoustic reflectometry. Our hearing aid would be able to then automatically adjust its settings based on the levels of effusion detected when functioning as an acoustic reflectometer. This could potentially reduce the frequency of trips to an ENT doctor for hearing aid adjustments. This is particularly useful in the context of glue ear because patients face long waiting times. A hearing aid capable of functioning as an acoustic reflectometer would therefore mitigate the negative effects of hearing loss in young patients by correcting their hearing while they wait for further treatment.