Ear infection detecting smartphone-based devices.

BY

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A PROJECT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF BACHELOR OF ENGINEERING IN BIOMEDICAL ENGINEERING KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG
ACADEMIC YEAR 2022

SCHOOL OF ENGINEERING

KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG

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ABSTRACT

Middle ear infections are a common health condition that affects people of all ages. Appropriate treatment and prevention of complications require immediate and accurate detection of such infections. In this study, we present an innovative approach for detecting middle ear infections using a smartphone-based machine learning system. Our system integrates an otoscope and an acoustic analysis module based on acoustic reflectometry theory into a custom smartphone application. The otoscope enables users to observe the ear's condition, allowing the detection of earwax and other abnormalities. By connecting the otoscope to the smartphone application, users can acquire high-quality images and videos of the ear canal, thereby facilitating the identification of potential infection indicators. Additionally, we developed an earphone device that is composed of speaker and microphone at the same inlet that can emit and receive chirping noises into the ear and is connected to the smartphone application. The embedded microphone within the earphone captures the reflected sound waves, which are then analyzed using a machine learning algorithm. The results are then divided into three categories: "no water," "monitor," and "water." The recognition and identification of middle ear fluid, which can serve as an essential indicator of middle ear infection, is an important aspect of our research. The buildup of fluid in the middle ear, or otitis media with effusion (OME), is a frequent precursor to middle ear infections. By precisely detecting the presence of fluid, our smartphone-based system can provide early warning signs and facilitate early intervention, potentially preventing the onset of an infection. To verify the effectiveness of our system, we conducted extensive testing on a large number of subjects with a variety of ear's audible conditions. We determined the accuracy of our method by comparing the system's diagnostic results to Earcheck™ device, acoustic reflectometry commercial device. The outcomes revealed a high degree of concordance between our smartphone-based system and Earcheck™. This research represents a significant advancement in the field of middle ear infection detection, as it provides a non-invasive, accessible, and cost-effective solution that can be used at home or in clinical settings. Our smartphone-based system has the potential to reduce the risk of complications associated with middle ear infections by allowing users to monitor their own ear health.

Keywords — Ear infection, Middle Ear Effusion, Acoustic reflectometry, Tympanometry, Machine learning learning, Otitis media.

ACKNOWLEDGEMENTS

We would like to thank everyone who helped us complete this thesis. First and foremost, we would like to thank our advisor, Assoc. Prof. Dr. Wibool Piyawattanametha, for his continuous support, advice, and crucial comments throughout the research process. His knowledge and mentoring have been beneficial in shaping this dissertation. We would also want to thank our co-advisor, Dr. Natthaphong Angasudhasavit. for his tremendous guidance, mentorship, and involvement during the course of this project. We are very appreciative for their consistent support and aid in making this research a success.

We would also like to thank our colleagues and research team for their collaborative efforts and assistance in data collection and analysis. Their dedication and hard work have substantially aided the accomplishment of our study.

We would like to acknowledge the support of King Mongkut's institute of technology Ladkrabang for providing the necessary resources and facilities for conducting this research.

Furthermore, we extend our appreciation to our family and friends for their constant encouragement, understanding, and motivation during this journey.

Once again, thank you to all those who have supported and encouraged me throughout this thesis. Your contributions are deeply appreciated.

Samaphoo Assametankul & J-Tapol Sirprayoon

TABLE OF CONTENTS

Page

CHAPTER 1 INTRODUCTION

CHAPTER 2 REVIEW OF THEORY RELATED

LIST OF SYMBOLS/ABBREVIATIONS

Symbols/Abbreviations	**Terms**
AR	Acoustic Reflectometry
CIE	Computer Innovation Engineering
MEE	Middle ear effusion
OME	Otitis media with effusion
SIIE	School of International Interdisciplinary Engineering Programs

LIST OF TABLES

Tables Page

LIST OF FIGURES

Figures Page

CHAPTER 1
INTRODUCTION

Ear infections, also known as "otitis media," account for $10 billion in healthcare costs, while AOM (Acute Otitis Media) accounts for 30 million office visits in the United States alone [1]. The infection is frequently experienced because of other illnesses such as a cold, flu, allergy, or any other illness that may cause nasal congestion and swelling, potentially introducing a bacterium or virus into the middle ear, causing fluids to become trapped in an air-filled space behind the eardrum, containing tiny vibrations bones of the ear, causing hearing problems and other serious hearing complications. While in many cases, infections can clear up on their own with antibiotics.

A pneumatic otoscope is a specialized tool used by doctors to diagnose ear infections. This instrument allows doctors to see into the ear canal and determine whether or not there is fluid behind the eardrum. The doctor uses an otoscope to gently puff air against the eardrum. The observed eardrum will have little to no movement if the middle ear is filled with fluid due to an abnormality. A Tympanometry device, which uses sound tones and pressure, is also widely used by doctors. It is a small, soft plug device with a tiny microphone, speaker, and a device that varies air pressure into the ear, observing eardrum flexibility at different pressures.

The Otoscopic approach is now used in the majority of middle ear fluid examinations. These procedures necessitate additional specialized knowledge, can be difficult to perform successfully in squirming or screaming children and rely heavily on human judgment to interpret a sample image or measurement of the eardrum. Otoscopic accuracy has been found to be as low as 50% in primary care settings [2]. Statistics show that half of all children do not receive an accurate diagnosis. As a result, payer costs are increasing, and patients are receiving excessive antibiotics. Acoustic reflectometry (AR) is a more accurate diagnostic technique. According to studies, AR improves accuracy by 68.18% [3]. However, using AR techniques is expensive. The diagnosis process incurs indirect and direct costs due to time consumption and diagnosis, respectively. The inability of children to communicate verbally makes diagnosing AOM difficult. When a child has AOM, parents are often unaware, necessitating more frequent doctor visits. As a result, there is an urgent need to develop low-cost technology that can detect ear infections with high accuracy while requiring little expertise and can be used in households.

As our goal was "Everyone deserves great quality healthcare," we were inspired to create an ear infection diagnosing app on an IOS platform that is affordable, versatile, convenient, and precise. By allows the user to see inside one's ear using an otoscope camera, and the application is able to release, receive, and generate sounds, as well as analyze data obtained from the earphones using integrated deep learning technology. The data obtained by the device will be classified based on the reflecting sound waves projected within the ear canal. Hopefully, the user will be given an accurate ear health status at no cost. This project will then be a disruptive healthcare technology that can be accessed by anyone.

CHAPTER 2
REVIEW OF THEORY RELATED

2.1 Anatomy of an ear and hearing

Ears are an organ placed on each side of the head, with the purpose to not only receive sounds but also play a role in our sense of balance. Any dysfunction of an ear can negatively affect your daily life, and if it occurs in young children it can delay their overall development. The ear is made up of three main parts: the external ear, the middle ear, and the inner ear, where each part is made up of the following:

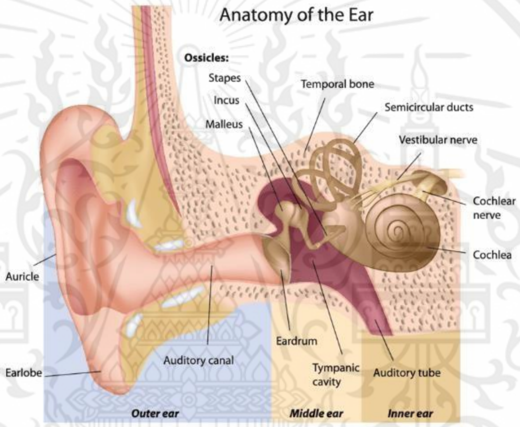


Fig. 1: Ear anatomy, including, outer ear, middle ear, and inner ear [4].

External ear [5]

1. The outermost part of the ear can be called either an Auricle, Concha, or Pinna. Made up of cartilage and skin, its function is a collector, where the sound waves collected are led into the ear canal.
2. Passing through the Pinna, ear canals are lined with ear hairs and sebaceous glands preventing it from drying out and keeping out bugs, dust, and infections. The buildup is secreted as ear wax. The ear canal is around 2.5-3 centimeters long which is about a quarter length of the soundwave with frequencies of 3,000 Hz. Once the sound wave passes through the ear canal it gets louder 10 decibels making it easier for the human ear to comprehend the sound within 2,000-3,000 Hz which is the normal range of a normal human's voice.
3. An oval shaped thin film separating the middle ear from the external ear is the eardrum. It vibrates when sound waves are received and will vibrate accordingly

to the frequency it receives. The vibration helps expand the sound before it is sent further into the ear.

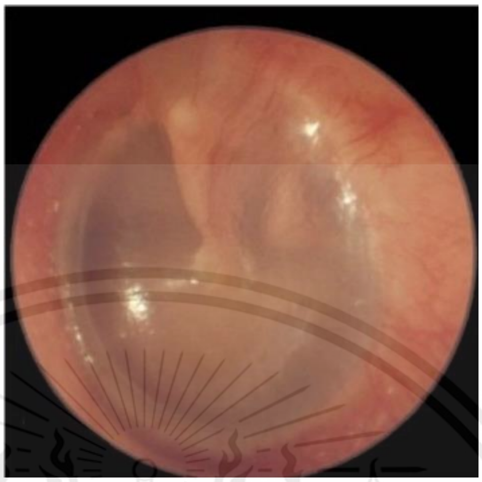


Fig.2: Normal tympanic membrane [6].

Middle ear

It is a hollow cavity placed next to the nasal cavity which is connected to the pharynx via a tube called eustachian tube. The tube is kept shut most of the time, but in order to adjust the pressure on both eardrums the tube will open once one start chewing, swallowing, and/or yawning, since the imbalance of pressure between the outside and inside of an ear can cause the eardrum to not work its full capability. And in the case where the eustachian tube is blocked it will cause tinnitus with ear pain. The body will adjust the pressure in the middle ear canal by passing some air pressure through the Eustachian tube If there is an infection of the upper respiratory tract, it may result in the infection entering the middle ear through this tube leading to otitis media [5].

There are three main bones in the middle ear: Malleus, Incus, and Stapes mentioned respectively to their size. All three bones work together in a lever system to emphasize the level of vibration of the soundwaves before sending it further into the inner ear through an oval window next to the stapedial footplate of the stapes. The bones can help absorb and reduce the volume of the sound entering the inner ear. Along with the help of the muscles call stapedius and tensor tympani separating the bones, the middle ear will receive soundwaves best at its frequency of 1,000 Hz while the transfer function of the external ear and middle ear makes human ear the most sensitive the sounds in the frequency of 1-3 KHz [7]

Inner ear

In charge of changing the soundwaves into electrical waves and being aware of the movement of one's head in order to promote body balance. Within the inner ear is where cochlea, a hollow, spiral-shaped bone is found. The spiral are differentiate into three parts, the Scala tympani and the Scala vestibuli on each end of the spiral is filled with fluid called perilymph and the Scala media which is in the middle is filled with fluid called endolymph, it also contain stria vascularis and organ of corti that contain an important component which is hair cells which is receives the sound vibrations and changes the vibration of the fluid in the tube into electrical waves and sends it to the brain in order to comprehend what the sound is.[8]

Fig.3: Inner ear components [9].

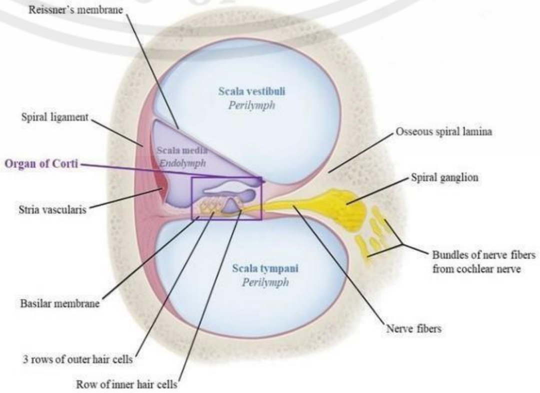


Fig.4: Inner construction of cochlear [10].

Sound conducting mechanism.

Sound is an energy produced by the vibrations of compressed air expanding alternately, causing changes in atmospheric pressure higher and lower according to the compression and expansion of the molecules in the air. A normal human voice frequency is between 20-20000 Hz. and the sound used in talking is between 500-2000 Hz. There are 2 mechanisms in conducting sound: through the air and through the bone. Conducting sound through the air is the conduction of sound that passes from the outer ear to the middle ear forward to the inner ear, in which each part is responsible for conducting and amplifying the sound. As for the sound conduction through the bone, it will conduct from the sound that is sent directly to the skull, mostly in the position of the bone cavity behind the ear (mastoid), which sends signals directly to the inner ear. However, it has been proven that sound conducted through bone is less audible than air as it is not amplified by each part of the ear.

2.2 Middle ear infection or otitis media

Middle ear infection (Otitis media or Middle ear infection) is a common disease in people of all ages. But it is more common in infants and young children. (Less than 3 months to 3 years old) due to the ear's anatomy, physiology, and the child's immune system. Especially if there are environmental factors involved the risk of developing otitis media increases.[11]

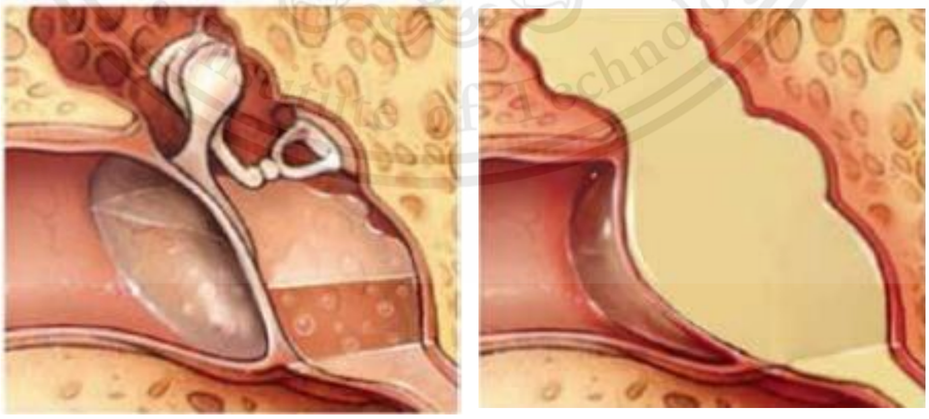


Fig. 5: left image shows Otitis media with ear fluid in tympanic cavity, right image shows acute otitis media with middle ear infected in tympanic cavity [12].

2.2.1 Causes of otitis media

The disease is categorized into acute, chronic, and middle ear effusion.

1) Acute otitis media most often occurs along with infections in the upper respiratory tract (throat and nose), such as: influenza, whooping cough, measles, etc. causing the pathogens around the throat to go through the Eustachian tube or middle ear pressure equalization tube into the middle ear and cause inflammation. This causes the epithelium inside the middle ear and the Eustachian tube to swell, and pus builds up in the middle ear since it cannot be drained through the swollen and clogged eustachian tubes. Eventually, the eardrum becomes perforated, and the pus trapped inside will flow out causing deafness.

Pathogens can enter the middle ear from these channels:

1. From an infection in the throat or nose passing through the eustachian tube to the middle ear. Which is commonly found.
2. From an ear infection passing through a perforated eardrum then enters the middle ear
3. Through the bloodstream

Around 55-75% of the pathogens found are called Streptococcus pneumoniae. And up to 90% are found to be Haemophilus influenzae and Moraxella catarrhalis. The rare ones to be found are Staphylococcus aureus, Streptococcus Group A and group B and Gram-negative bacteria such as Pseudomonas, which are often the cause in newborns. [11] On the other hand about 10-40% of viruses found are Respiratory syncytial virus, Rhinovirus, Influenza virus, and Adenovirus, respectively. (But some information states that this disease is often caused by a viral infection, often associated with the common cold. Which is usually mild and resolves on its own within a few days and is rarely caused by bacteria which must be treated with serious antibiotics because if left untreated, it can lead to serious complications) [14]

The reason why this disease is found in children more than in adults is because in infants and young children the Eustachian tube connecting the middle ear and nasopharynx is not fully developed; it is almost horizontal, unlike adults, where it is more angled. With the Eustachian tube being longer in children. From these anatomical features, pathogens in the upper respiratory tract, especially in the nasal cavity, are more likely to spread to the middle ear in children than adults. Thus, these infections can spread to the middle ear, eventually leading to acute otitis media [15].

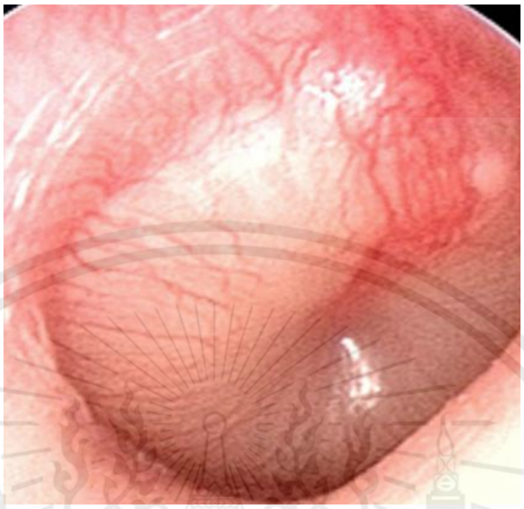


Fig. 6: Acute otitis media [6].

2) Otitis media with effusion (OME) is when there is presence of fluid in the middle ear without signs of inflammation or infection. Where most patients are about 3 to 8 years [16] they will experience decreased hearing but no ear pain and no fever. However, it will delay language development therefore decreasing the will for children to attend school [17]. When examining the ear, no swelling or redness of the eardrum will be found. But there will be a decrease in the movement of the tympanic membrane. This condition is most common in children with risk factors such as cleft lip and cleft palate or down's syndrome with abnormal facial structure [18] but if this condition is found in adults, nasopharyngeal cancer should be screened (Nasopharyngeal carcinoma), since it can block the Eustachian tube.

Fig. 7: Otitis media with effusion [12].

3) Chronic otitis media (Chronic otitis media or Chronic suppurative otitis media - CSOM) is a condition with perforation of the eardrum with chronic leakage of ear fluid (Commonly started from young where it's likely that they are malnourished or unhealthy children) which also can be a result of acute otitis media or a perforated eardrum injury. Sometimes it may be found in people with chronic sinusitis, chronic tonsillitis, crooked nasal septum, or nasal polyps, in some cases cholesteatoma may be detected, making it more dangerous to the patient.

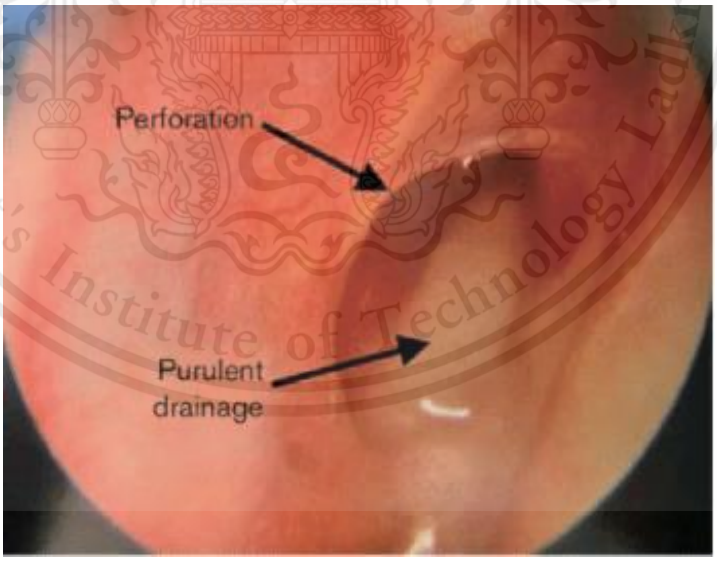


Fig.8: Chronic suppurative otitis media with tympanic membrane perforation and purulent discharge [19].

2.2.2 Risk factors that cause otitis media [11]

1) Inhalation of cigarette smoke.

2) have low or poor immunity. Such as infants who are not breastfed.

3) Situation where the Eustachian tube is blocked. Such as during the common cold or an insertion of a feeding tube through the nose.

4) Cleft lip and cleft palate.

5) Being raised by bottle feeding, pacifiers, and drinking milk while lying down.

6) Sending a child to a daycare center

7) The Eustachian tube in children differs from that of adults.

2.2.3 Symptoms of otitis media

Acute otitis media patients often develop symptoms suddenly after an upper respiratory tract infection such as the common cold, pharyngitis, or tonsillitis including pain in the ear (However, pulling the ear will not hurt like otitis externa), tinnitus, decreased hearing, high fever, chills, and some people may experience vertigo, nausea, and vomiting. As for the baby and young children, their symptoms include being awake and crying all the time due to the pain from their ears. Some may use their hands to pull on their ears. Some people may have seizures due to high fever. However, children often have flu symptoms or a cough during these episodes. [11]

acute otitis media can be categorized into 3 phases:

The red and swollen phase, while examining the ear with a medical device, the eardrum should appear red and swollen. At this stage, patients will experience ear pain or tightness in the ears, fever, and hearing loss. In infants and young children, they will cry and refuse to sleep.

The phase where fluid is present in the ear for 1-2 days, serum begins to seep from the dilated blood vessels into the middle ear and into the mastoid cavity behind the ear. At this stage, patients will begin to experience more ear pain, high fever, and decreased hearing. When examining the ear, the eardrum is swollen, red, protruding from being pushed out by the water inside.

The perforation phase is when the eardrum can no longer withstand the pressure of fluid inside the middle ear until it perforates. Causing pus to flow out to outer ear canal. In which the patient will feel that there is pus flowing from the ear for a while and the ear pain and fever will be greatly reduced. Most acute inflammation stops at this stage. The perforated eardrum will repair itself within 2 weeks and the patient's hearing will return to normal or almost normal. But in some patients, the perforation cannot be closed by itself, it will go into chronic inflammation. (In general, from the swelling and redness to the perforation period, lasts no more than 2 weeks, if treated in time it will help prevent perforation).

Chronic otitis media patients often have intermittent and persistent otitis media for more than 3 months with decreased hearing and pus leaking from the ear canal, usually when the patient has an upper respiratory infection such as a cold or after swimming. In some cases, patients may experience vertigo, nausea, and vomiting, but no fever or pain in the ear. [20]

2.2.4 Complications of otitis media

Since the ear is an organ located in the base of the skull that is close to the brain, there can be complications, where it is categorized into 2 types: extracerebral complications such as infectious inflammation of the mastoid fossa, deviated face, permanent hearing loss and intracranial complications such as meningitis, brain abscess, etc., the complications that arise can be fatal if incorrect or timely treatment [21].

2.2.5 Diagnosis of otitis media

Doctors can diagnose this disease by looking into the patient's medical history and symptoms (such as ear pain, tinnitus, fever with flu, sore throat), and physical examination using an otoscope along with the use of pneumatic otoscope to examine the movement of the eardrum, where both examinations will reveal abnormalities, such as swelling, redness or perforation. These indications suggest that the patient may be experiencing one of the following diseases: An early stage of acute otitis media, the perforation of the tympanic membrane and the middle ear effusions (which can be confirmed by examining using the tympanogram).

When examining the ear with chronic otitis media, a wide perforation of the eardrum is found along with purulent discharge, cholesteatoma, and other related symptoms. Other special examinations may be ordered additionally, such as a hearing test, x-ray, computed tomography, and tympanogram.

2.2.6 Treatment of otitis media

Treatment of acute otitis media [22]

1. Painkiller and antipyretic drugs such as paracetamol, will be prescribed. And if found to be caused by bacteria, antibiotics such as amoxicillin, cotrimoxazole or erythromycin will be prescribed in order to eliminate the bacteria, where patient are expected to take it consecutively for 10-14 days (depending on the severity of the disease). In the case where pus is found to be leaking from the ear canal ear drops will be prescribed.
2. Doctors may prescribe antihistamines, decongestants, oral decongestants, and topical decongestants (which are used to open the swollen eustachian tubes allowing the inflammation to calm down for the pus to be easily drained.
3. If symptoms improve within a few days of taking antibiotics, continue taking it until the prescription is finished. But if the symptoms have not improved your doctor may need to use a needle to drain the pus. This is called a "myringotomy", after this treatment, the tympanic membrane will heal on its own within 1-2 weeks.

Myringotomy is performed in cases when the patient's condition has not improved after medication (the patient still experiencing ear pain, and high fever), when the pus needs to be obtained in order to be stained or cultured to find the pathogen type, when the patient has immunocompromised, or when the patients has acute otitis media with complications (e.g. acute mastoiditis), ear abscess, meningitis, brain abscess, or hemiplegia.

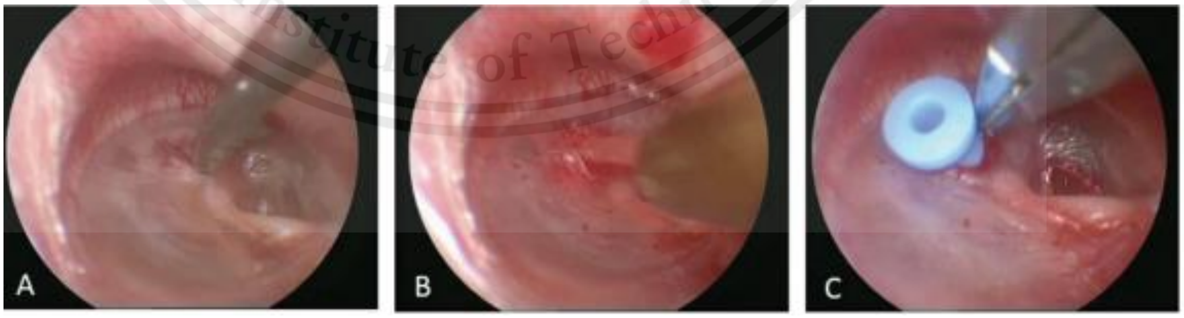


Fig. 9: Myringotomy treatment shown on A, B suction of fluid, and C grommet positioning [23].

Treatment for middle ear effusion can be treated with a short course of antibiotics. But if the symptoms do not improve, the doctor will consider performing a tympanic membrane puncture and inserting a drain tube (Myringotomy). to improve the patient's hearing.

Treatment of chronic otitis media

1. Always keep the outer ear clean and dry. Then use antibiotic ear drops prescribed by your doctor 3-4 times a day until the pus dries. If acute inflammation symptoms such as ear pain and fever are found, take antibiotics for 10-14 days.
2. If the symptoms have not improved after 1-2 weeks or if more symptoms such as deafness, perforation of tympanic membrane to the edge of the eardrum, abscess behind the ear, or hemiplegia arises, the patients are advice to go to the hospital as soon as possible where the doctor may perform computed tomography and other special examinations to detect and treat it accordingly.
3. In patients with severe headache, vomit, stiff neck, meningitis or brain abscess should urgently visit the hospital. Where mastoidectomy is often performed in cases where there is inflammation of the mastoid bone cavity where pus is trapped. The doctor will make an incision behind the ear into the cavity and drain out the pus inside.

2.3 Devices for detecting eardrum movements (Tympanometry)

Tympanometry assesses the acoustic conditions of the middle ear, tympanum, and bone conductivity to sound [24] by establishing changes in air pressure in the ear canal as an objective test. It measures the transmission of electroacoustic energy through the middle ear to assess the sound absorption of the eardrum. The tympanic membrane is stretchy when the air pressure between the two sides of the tympanic membrane in both the outer and middle ear is equal. Therefore, the presence of water behind the tympanic membrane will cause the tympanic membrane to become stiff, making the recording of the graph appear flat. The sound is measured with a microphone that is part of the instrument which is inserted into the ear canal. However, this test should not be used to assess hearing sensitivity. Since the results of this test should always be viewed along with pure tone audiometry.

Tympanometry is an important component of hearing assessment. The measuring of the eardrum allows us to differentiate between sensorineural hearing loss and conductive hearing loss when evaluating the Weber and Rinne tests came out unclear. Moreover, eardrum measurements are useful in diagnosing tympanic effusion (OME) by indicating fluid accumulation in the middle ear canal.

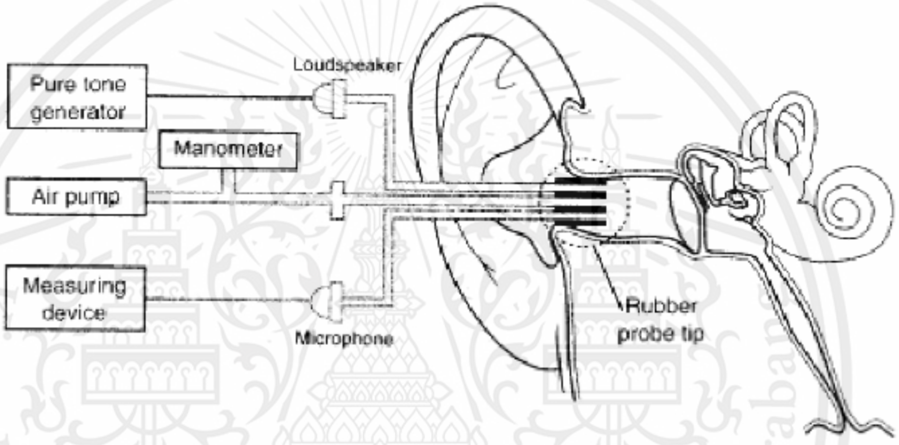


Fig. 10: Tympanometry working diagram [25].

Working principle of Tympanometry

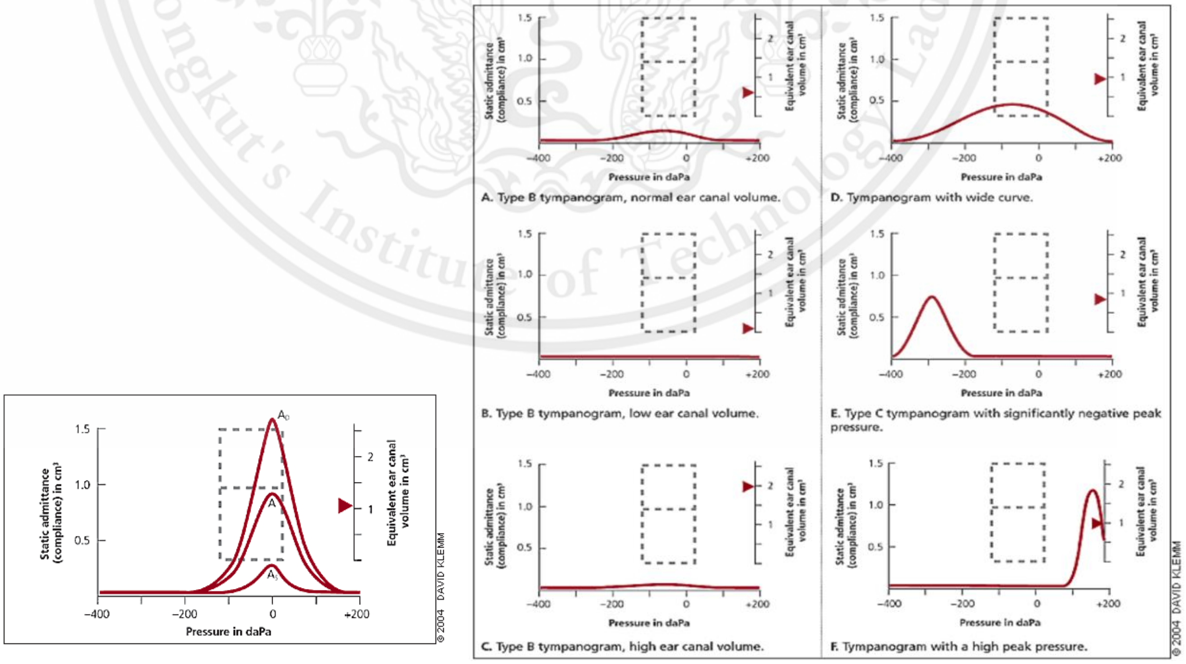
It uses a probe tip which creates a 226 Hz tone into the outer ear canal where the sound will hit the eardrum causing vibration in the middle ear which results in auditory perception, when the sound is reflected and received by the instrument. Since, if in fact there is an issue within the middle ear, the eardrum loses its elasticity, which increases the reverberation.

Even Though 226 Hz is the most commonly used frequency. Sound in other frequencies can also be used. In infants under 4 months of age, research has shown that 1000 Hz tones provide more accurate results. And with the use of multiple frequencies between 250 and 2000 Hz, ear bone abnormalities can be identified. [26] Normally, the air pressure in the ear canal is equal to atmospheric pressure. In addition, under normal conditions a healthy individual will hear most clearly when the air pressure in the middle ear is about the same as the atmospheric pressure, which is possible by the work of eustachian tubes that opens periodically in order to ventilate the middle ear and equalize the pressure.

Examination and interpretation of Tympanometry

After ensuring that the eardrum is visible and that there is no perforation via an ear endoscopy. The test (Tympanometry) is performed by inserting an instrument into the ear canal. The tool changes the pressure in the ear, create pure sound and measures the response of the eardrum to sound at various pressures. And using what it retrieved in constructing a dataset that measures how electroacoustic values vary with pressure, which shows the results as a graph according to Jerger's classification as follows: [27]

1. Type A: has normal pressure in the middle ear with movement of the eardrum and bones. However, there are two subtypes: type As, which the graph shows a lower peak suggesting that the ear bones “sticking” to one another. And type Ad, which has a higher peak suggesting that the ear bones are falling apart.
2. Type B : There is fluid in the middle ear, the eardrum is perforated, or a tumor in the middle ear.
3. Type C : Result shows negative pressure in the middle ear canal as a result of dysfunction of the Eustachian tube and tympanic membrane retraction.



A. Type B tympanogram, normal ear canal volume.

D. Tympanogram with wide curve.

B. Type B tympanogram, low ear canal volume.

E. Type C tympanogram with significantly negative peak pressure.

C. Type B tympanogram, high ear canal volume.

F. Tympanogram with a high peak pressure.

Fig. 11: Different types of Tympanometry graph [28].

2.4 Acoustic Reflectometry

Acoustic Reflectometry (AR) measures the tympanic membrane's reaction to a sound produced by a small, portable instrument to calculate the likelihood of Otitis media with effusion (OME). Since AR does not require an airtight seal in the ear canal, it is typically reliable even with children who are crying or struggling [29].

The stapedius reflex, also known as the acoustic reflex, is a reflex contraction of the middle ear's intra-aural muscle brought on by a loud sound. The eardrum is shielded from high-frequency sounds by the intra-aural muscles. It is a bilateral reflex, meaning that even if the sound only reaches one ear, it still happens in both ears. Regardless of the listener, this reflex always occurs and is automatic. The recording of acoustic reflexes is known as acoustic reflectometry. For instance, the acoustic reflex threshold is the lowest volume of sound needed to cause the stapedius muscle to contract. The acoustic reflex typically has a threshold between 65 and 90 dB [30]. Sound stimuli in acoustic reflectometry are tones with frequencies 500, 1000, 2000, and 4000 Hertz (Hz), and broadband noise. The analyzer in the middle ear automatically increases the strength (level) of the stimulus and finds the AR threshold, determining the increase in the AR amplitude as the stimulus increases.

Reflectivity is used to measure this response. Defining as the degree to which the instrument's incident sound waves are canceled out by any reflecting sound waves. The phase and frequency of the sound waves that are emitted and reflected are key factors in how much cancellation occurs. The second-generation technique, spectral gradient acoustic reflectometry (SG-AR), calculates and graphically displays the data from the incident and reflected sound (reflectivity), from which the spectral gradient angle can be determined [31]. It measures the tympanic membrane's response to a sound stimulus in the frequency range of 1.8-4.4 kHz. The tympanic membrane reflects more sound energy, and the frequency spectrum is narrow, resulting in a narrow spectral gradient angle. If the movement of the membrane is constrained by fluid in the middle ear. The spectral gradient curve can be evaluated, printed, and then categorized into various pattern categories that correspond to various probabilities of Middle Ear infection (MEF) [32].

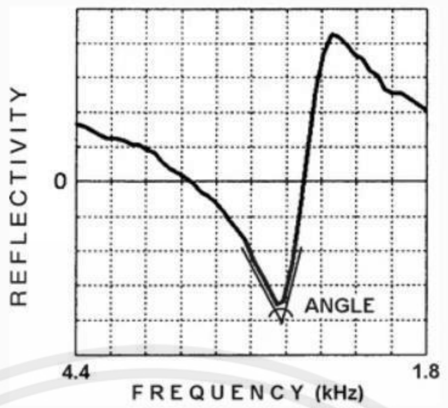


Fig. 12: The function of sound reflectivity and frequency is shown by a curve. The spectral gradient angle, which is indicated at the nadir of the reflectivity curve, becomes narrower the sounder energy is reflected by the tympanic membrane (for example, in MEF). Thus, a small or acute angle (90°) is suggestive of MEF [32].

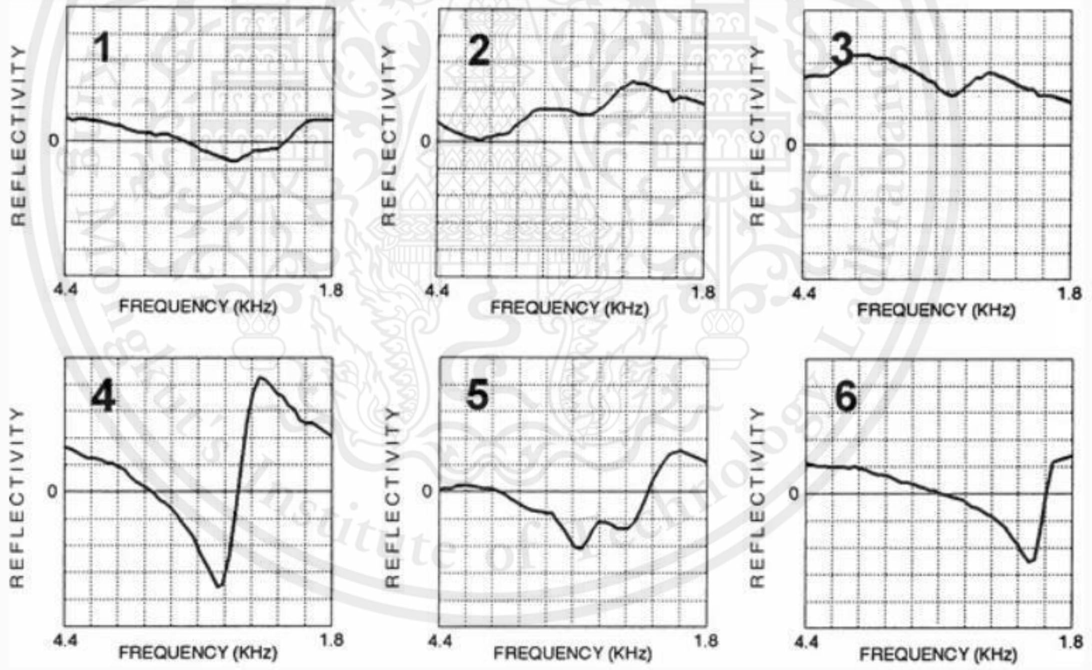


Fig. 13: The figure illustrates six different curve types, each of which indicates a different likelihood that the ear under examination contains middle-ear fluid. Pattern types 1-3 are common findings. Middle-ear fluid is indicated by type 4 narrow (90°) spectral gradient angle. Types 5 and 6 are marginally normal, have negative pressure, or have only a minor amount of middle ear fluid (rightward shift of the spectral gradient angle, or toward lower frequency) [32].

2.5 Comparison of Spectral Gradient Acoustic Reflectometry and Tympanometry for Detection of Middle-ear Effusion in Children

The purpose of this study was to compare the accuracy of otitis media diagnosis between Acoustic Reflectometry and Tympanometry. Where 600 respiratory patients with a range of ages between 6 months and 14 years are selected to go through the screening, by first being tested using Pneumatic otoscope acoustic reflectometry and tympanometry, if the result came back as negative where there no fluid found within the middle ear, patient will be instructed to come back within 5-7 days for a reevaluation. Where finally 2,152 samples from tests were collected from those 600 patients.

The result from using the Pneumatic otoscope shows that 1,922 samples (89.3%) of middle ears do not contain fluid, while the other 230 samples (10.7%) contain fluid. While the result from using the Acoustic reflectometry shows the results of the screen display where levels 1-2 indicates that there is no fluid in the middle ear, and levels 3-5 indicates the presence of fluid in the middle ear. 1,896 samples (88.1%) came out as level 1-2 and 256 samples (11.9%) came out as level 3-5.

When Acoustic reflectometry and tympanometry were compared, their results are almost identical to one another. During the examination on middle ear without fluid, the tympanometry indicates that 1,084 samples are type A and As and 853 samples are type C and Cs, while the Acoustic Reflectometry indicates 1,037 samples are level 1-2 and 734 samples are level 1-2. When examined again the tympanometry indicates 853 samples are type C and Cs, while the Acoustic Reflectometry indicates 734 samples are level 1-2. Lastly, when the tools are used on the middle ear with fluid the tympanometry indicates 215 samples are type B, while the Acoustic Reflectometry indicates 125 samples are level 3-5 [33].

2.6 Detecting Ear Infections in Children Using a Smartphone App, Exemplar project based on Ear Infection and Audio Reflectometry.

A new smartphone app created by University of Washington researchers. They used a piece of paper, a microphone, and the speaker of a smartphone to detect fluid behind the eardrum. Voices played on smartphones played toward the ear of the patient, once the sound hits the tympanic membrane, it bounces back to the phone's microphone.

Relating to the theory of audiometry, the software evaluates the likelihood of the fluid within the middle ear by observing the movement of the tympanic membrane. This group of researchers' goal is to get this application into households. To direct sound waves into and out of the ear canal, a doctor or parent may fold and cut a piece of paper into a slot that can be inserted into the outer ear. A hole in the paper allowed the phone's continuous 150-millisecond sound, which sounded like a bird tweeting, to pass through and hit the eardrum. The paper hollow serves as a conduit for sound waves that the eardrum reflects into the smartphone's microphone.

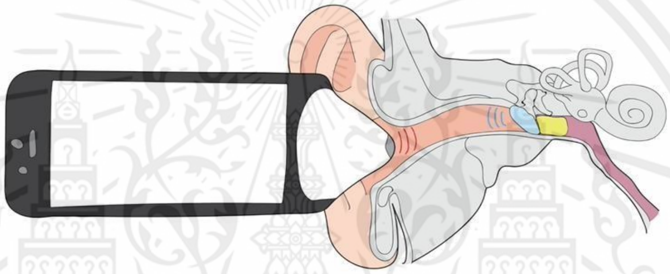


Fig.14: This figure displays the visualization of the application system [2].

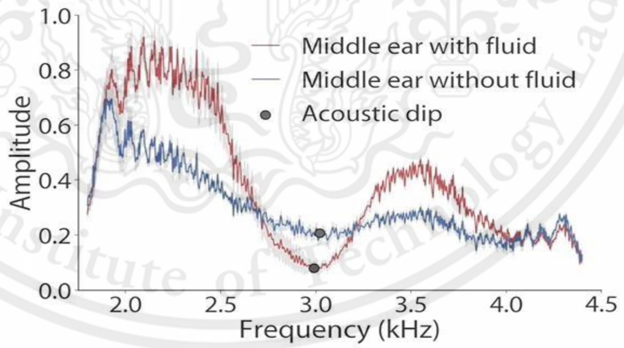


Fig.15: Acoustic dip between ear with and without fluid [2].

2.7 Imaging design theory

The radii of curvature of the surfaces, the thicknesses, the air spaces, the diameters of the various components, and the types of glass to be used must all be determined and specified before a lens can be created. The reason for the complexity in lenses is that, in an ideal world, all rays of all wavelengths originating at a given object point should be made to pass accurately through the image of that object point, and the image of a plane object should be a plane, with no appearance of distortion (curvature) in straight line images. The otoscope captures images of the tympanic membrane, which measures 7 to 9 mm in diameter. To guide image acquisition during an otoscopic examination, a clinician must be able to see not only the tympanic membrane but also some of the surrounding area. This constraint necessitates a field-of view (FOV) which is related with the aperture, which is typically can be calculated from the equation (1).

$$Angular\ field\ of\ view = 2\ x\ arctan\ (H2f)\ (1)$$

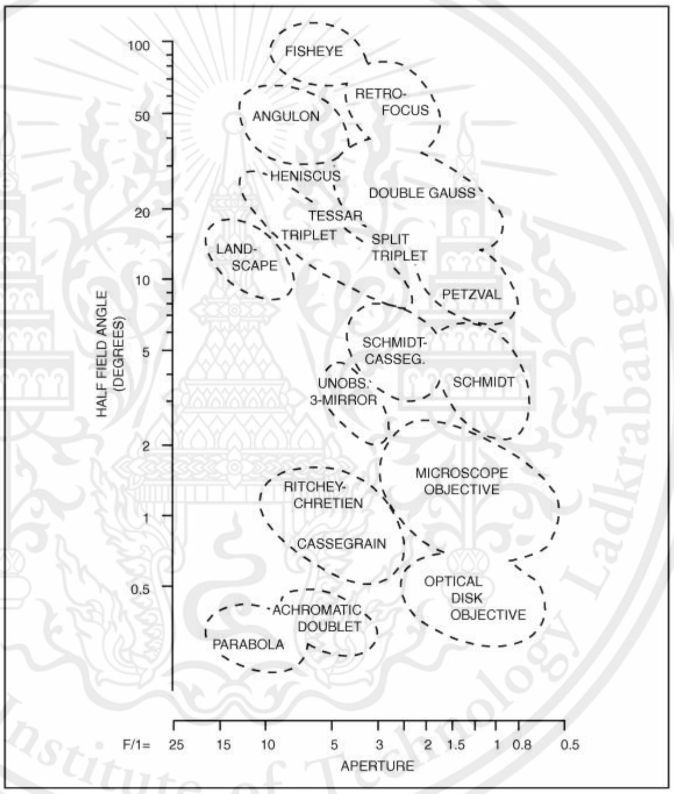


Fig. 16: Map showing the design type which is commonly used for combination aperture and FOV [34].

Moreover, to design the otoscope. A pupil conjugate is placed near the front lens to maximize image space F-number which is calculated by equation (3) where N is f number and f is focal length. And the focal length of lens can be calculated where f is focal length, n is refractive index of lens, R1 and R2 are radius of curvature from both sides of lens and t is thickness of lens. Furthermore, the wavelength, the working distances, focal length, and optical aberration are considered [35]

$$1f = (n-1)[1R1-1R2+(n-1)tnR1R2]\ (2)$$

$$N = f\phi\ entrance\ pupil\ (3)$$

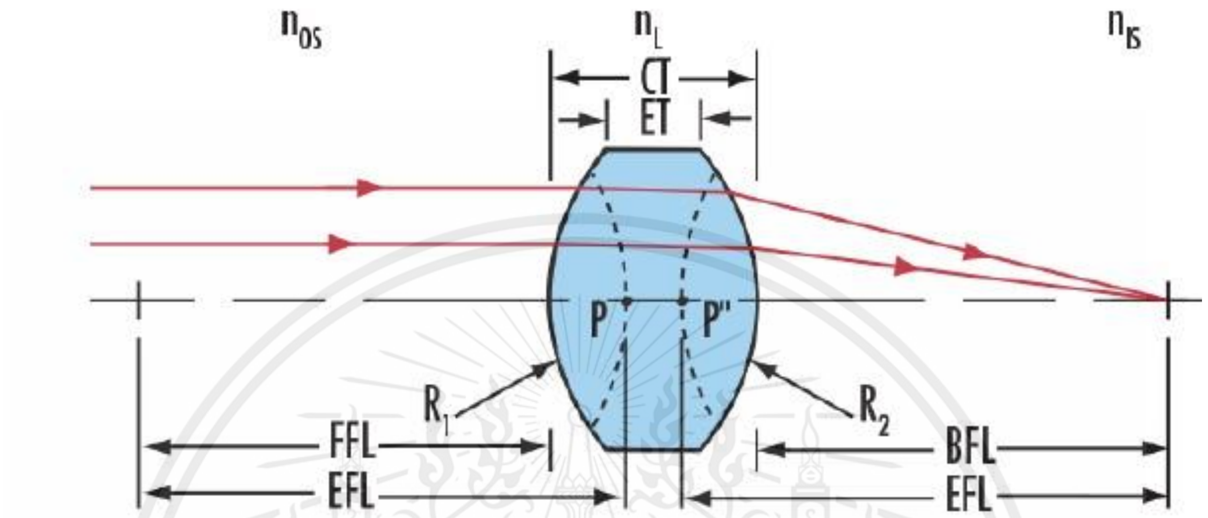


Fig.17: simple lenses' optical and mechanical parameters to facilitate integration into application assemblies.

To evaluate the focal length with respect to the simple lens diagram in figure B kwon as two lens layout of an optics system, all the equation is required to set all the mechanical parameters with fixed focal length.

Power of surface 1 at the R1 is ϕOS

$$\phi OS = nL - nOSR1\ (4)$$

power of surface 2 at the R2 is ϕIS

$$\phi IS = nIS - nLR2\ (5)$$

The optical power of two-surface of lenses is expressed as (6)

$$\phi = \phi OS + \phi IS - \phi OS\ x\ \phi IS(CTnL)\ (6)$$

The secondary principal point of lens if the power of the lenses and center of thickness are known, then it can be determined by (7)

$$P'' = -\phi OS\phi(nISnL)CT\ (7)$$

Power of the two-surface lens is known, then the effective focal length is (8)

$$EFL = 1\phi \text{ (8)}$$

To determined the front and rear focal point with EFL and object,image space index(nOS,nIS) value can be shown in (9) and (10)

$$fF = -nOS \cdot EFL \text{ (9)}$$

$$fR = nIS \cdot EFL \text{ (10)}$$

And the back focal length is given by (11)

$$BFL = fR + P'' \text{ (11)}$$

Front focal point is expressed by (12)

$$FFL = fF + P \text{ (12)}$$

The nodal point shift can be determined by front and rear focal point in (13)

$$NPS = fF + fR \text{ (13)}$$

The primary principal point of two-surface lens combination is shown as (14)

$$P = \phi IS\phi(nOSnL)CT \text{ (14)}$$

CHAPTER 3 METHODOLOGY

3.1 Introduction

In this chapter describes the design of middle ear infection screening system. The aim of this thesis is to create a middle ear infection screening tool that is noninvasive, accurate, convenient, and cost-effective for early detection and diagnosis of the infection. Additionally, the system will utilize advanced technology such as machine learning algorithms to improve the accuracy of diagnosis. A system is mainly divided into two parts, first, the otoscope part for visual inspection of the ear canal and tympanic membrane. Second, acoustic reflectometry system for testing for MEE detection. The design of Otoscope and Acoustic reflectometry systems are described in the project's design methodology section 3.2 and 3.3 respectively.

3.2 Otoscope concept and prototype

The eardrum is recorded using one of two designs. The first is a digital camera and optical zoom, and the second is a wireless Wi-Fi camera and USB port camera. To integrate with the application on the iOS system smartphone, both designs were tested to obtain the clearest image of the inner ear.

3.2.1 Optical zoom and Digital zoom system.

A type of imaging system called a zoom image system enables the user to change the image's magnification. This is typically done by using a variety of lenses or other optical components that can be moved or adjusted to alter the system's focal length and, consequently, the image magnification.

3.2.2 Optical Zoom System Design.

This zoom lens design were created by Zemax program which was set up all the optical parameter in the program and parameters were calculated by using thin lens equations.

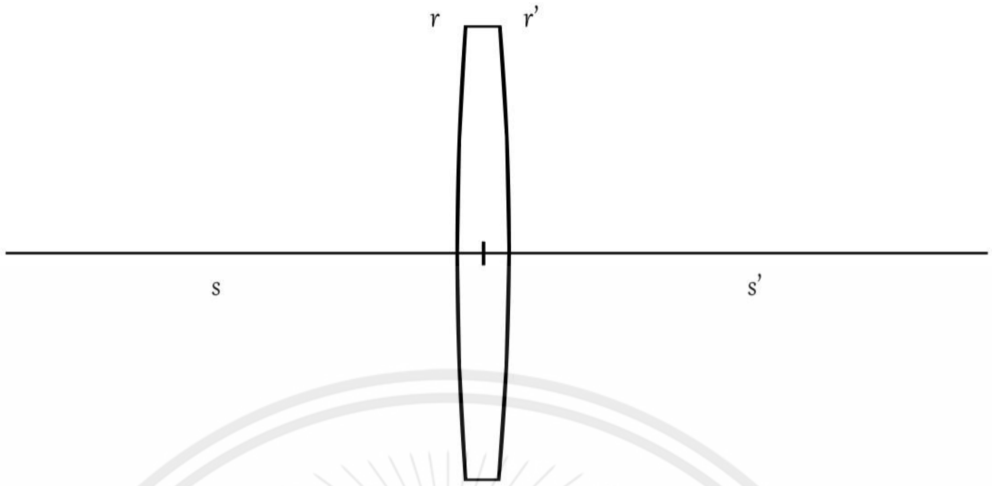


Fig.18: schematic of thin lens

The thin lens has the following conjugate equation:

$$1s' - 1s = 1f = \qquad (1)$$

where s for the object distance, s' for the image distance, f for the lens's focal length, and   for the lens's power. Also, the power of the thin lens we have

$$=(n-1)(1r-1r') \qquad (2)$$

Where n for the glass index, r' and r for are the lens's radii of curvature. The magnification m can be written as

$m = ss' = 11+s$ (3)

Two parameters (variables) were identified: X and Y. The shape parameter X can be used to describe the shape of the lens. The thin lens's shape parameter X (bending factor) is defined as

$$X = r'+rr'-r \qquad (4)$$

And Y is conjugate parameter can be expressed as

$$S = S'+SS'-S \qquad (5)$$

There is only one shape parameter X for both radii r and r0. To calculate the lens's radii of curvature using the lens power, refractive index n, and shape parameter X in the Equation (2) and (4)

$$r = 2(n-1)(X+1) , r' =2(n-1)(X-1) \qquad (6)$$

For the parameter Y can be find that

$$Y = S'+SS'-S = m+1m-1= -1-2s = -1-2s' \qquad (7)$$

From the equation, values of all parameters were calculated and inserted in the Zemax program to generate and simulate the design. To design the imaging system two parts need to be concerned for two parts, firstly is the lens system and the second is illumination system which will be combined together. For the lens system, there are ten parameters to classify the state of a single thin lens element. one for the position, one for thickness, two for the two surface radii, and several for the glass index, fields, and wavelengths In high orders, these parameters form the equation. If a lens has N spherical elements, the parameter number is multiplied by N. However, all the parameters in the lens system can be designed and simulated in the Zemax program.

Select system parameters.

The first step in lens design is to choose the system parameters, which include aperture stop type and value, field range, and wavelength range.

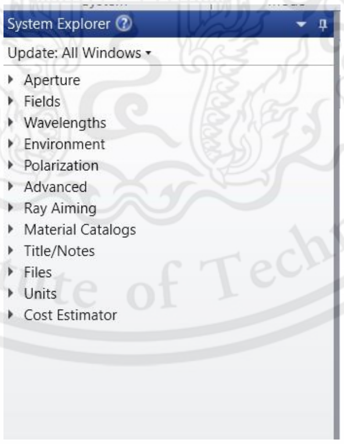
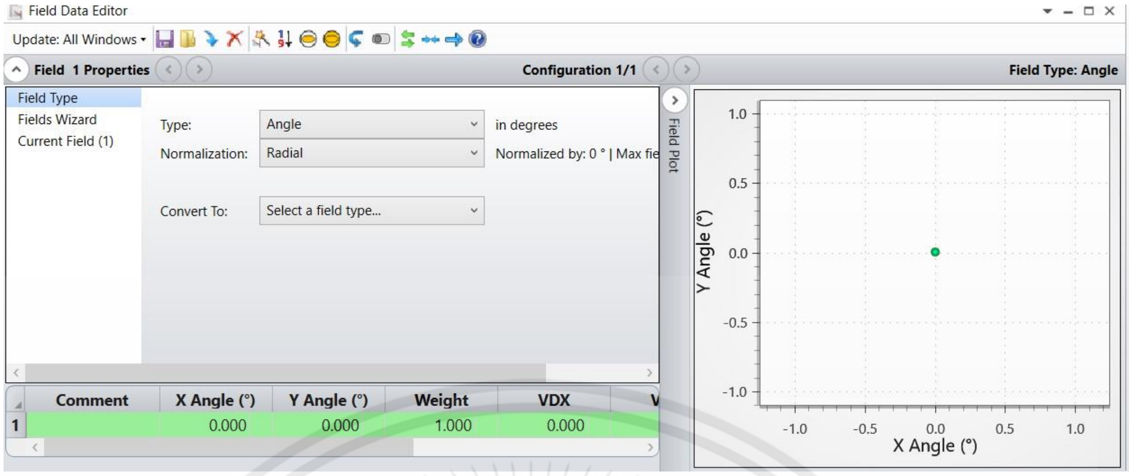


Fig. 19: system parameter in Zemax.

For the set up, the aperture was set as “object space NA” which suitable for the lens design parameter and aperture value was 0.5
After set up the aperture type, field set up is required



Type: Angle in degrees

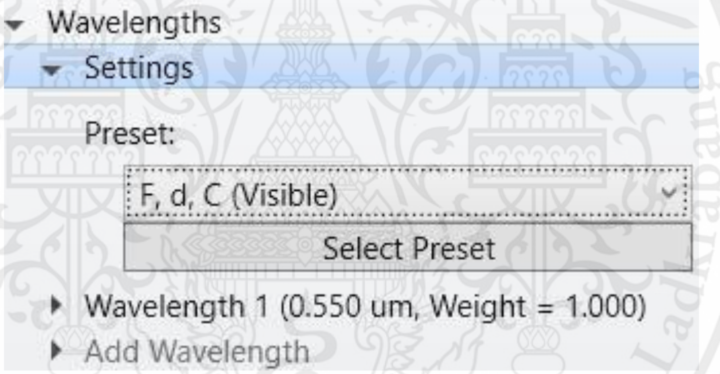
Normalization: Radial Normalized by: 0 ° | Max fie

Convert To: Select a field type...

	Comment	X Angle (°)	Y Angle (°)	Weight	VDX
1		0.000	0.000	1.000	0.000

Fig. 20: field set up and field property.

Lastly, set up the wavelength for the system parameter which is for the light source in the design.



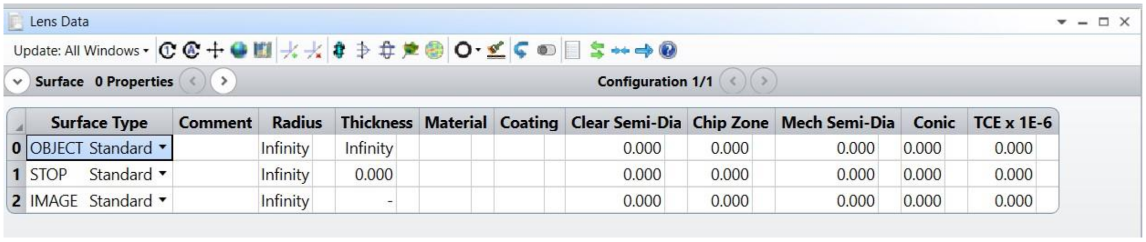
Preset: F, d, C (Visible)

Wavelength 1 (0.550 um, Weight = 1.000)

Fig. 21: wavelength settings.

Set lens start structure.

The second step in lens design is to establish the basic structure, which includes element numbers, glass types, and aperture stop position. Although it is common to add or remove lens elements and move the aperture stop position during the design process, a starting structure that is closer to the final structure will certainly speed up the optimization process. Only the spherical lens design is discussed here. Later on, we'll have an entire section dedicated to aspheric lens design. Because camera lenses are widely used, we will use some commercial camera lenses to demonstrate.



	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT Standard		Infinity	Infinity			0.000	0.000	0.000	0.000	0.000
1	STOP Standard		Infinity	0.000			0.000	0.000	0.000	0.000	0.000
2	IMAGE Standard		Infinity	-			0.000	0.000	0.000	0.000	0.000

Fig. 22: Lens datasheet, showing the surface type which is the type of surface that matches the curve of the design.

1) Digital Zoom System Design.

In digital zoom system design was completed through the smartphone camera and eartips which is designed in the Autodesk Inventor. To design ear tips, the required parameter for design are approximate values of the length of ear canal and diameter of ear canal that is 2.5 cm for the length and 0.6 cm for diameter.

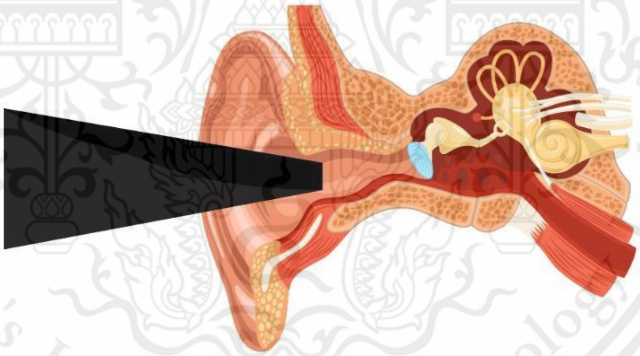


Fig. 23: Ear tips.

3.3.3 USB port camera and wireless Wi-Fi camera.

A USB port otoscope camera connects to a device directly via USB cable for easy image capture, whereas a wireless Wi-Fi otoscope camera allows for remote viewing and image capture via a Wi-Fi connection.

Fig. 24: Wireless Wi-Fi camera.

Fig. 25: USB port Wi-Fi camera.

3.4 Acoustic reflectometry system concept and prototype

The acoustic reflectometry system uses a microphone and a speaker located in a modified earphone to detect middle ear fluid levels based on tympanic membrane mobility. The system sends soft acoustic chirps into the ear, and the system microphone picks up the reflected sound waves. Then, machine learning algorithms analyze the acoustic dip that results from sound waves reflecting off the eardrum. A normal eardrum resonates well, which has a broad-spectrum, soft echo, causing a broad and shallow acoustic dip. While in the ear with MEE the fluid restricts the mobility of the eardrum, causing a reflected sound energy causing a destructive interference, resulting in narrower and deeper acoustic dip. To precisely collecting and analyzing an acoustic dip from the ear, multiple systems must be designed and constructed, including a modified earphone for emitting and collecting sound waves, an artificial tympanic cavity as a substitute for the real human ear, and machine learning algorithms for analyzing an acoustic dip.

3.4.3 Earphone design and construct

An acoustic reflectometry system uses a modified earphone. The acoustic reflectometry apparatus emits 150 MS of 1.8 to 4.4 kHz frequency-modulated continuous wave chirps into the patient's ear canal. The microphone inside the modified earphone is active while the acoustic chirp is emitting, collecting both incident and reflected sound waves from the tympanic membrane. The design of the earphones requires the placement of the speaker and microphone close to each other to allow the microphone to collect the sound at the same time as the speaker plays the sound.

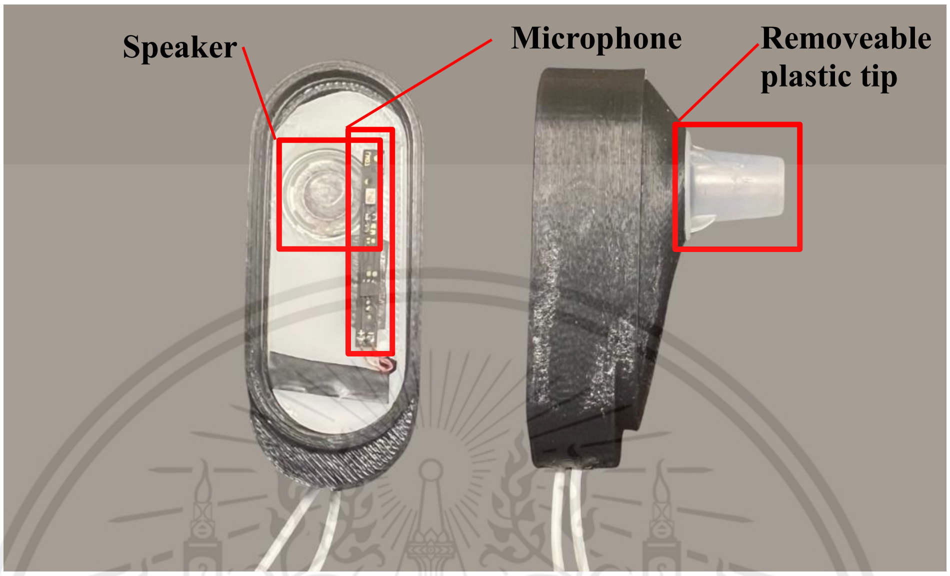


Fig. 26: Image of the modified earphone for acoustic reflectometry screening.

The modified earphone was designed using Inventor® CAD software and fabricated using 3D printing technology. The device can be segmented into two distinct parts. First, the body, which includes the speaker and microphone that are placed together. The speaker and microphone were modified from Apple® 3.5mm earphones. Second, the tips, which were modified to be replaceable for hygienic cleaning and sizing adjustment. This modified device can be connected to computers or smartphones via a 3.5mm connection.

3.4.4 Tympanic Cavity design and construct

Acoustic data collection for machine learning analysis necessitates modified earphones and middle ear subjects. To simulate different categories of patients, the middle ear samples must contain varying levels of fluid, and a large sample size is required to generate a robust data pool for machine learning analysis. However, without Institutional Review Board (IRB) approval, direct contact with patient ear canal procedures and other potential risks may raise ethical concerns regarding the collection of data from actual human subjects. In addition, it can be challenging to acquire data from actual human subjects because locating patients with middle ear fluid, a key variable of interest in certain studies, can be difficult. As a solution, fabricating an artificial tympanic cavity provides a controlled environment for data collecting and removing ethical problems. Furthermore, it allows for the replication of specific variables or scenarios that may be difficult to recreate in real human participants, allowing for precise and controlled trials to explore the effects of chirping noise on the middle ear with and without MEE.

The artificial tympanic cavity is constructed to closely mimic the structure of the human middle ear. It consists of a 3D printed tympanic cavity with a volume of 1ml, designed using Inventor® CAD software to replicate the anatomical features of the human ear. A silicone tube, with a length similar to that of the human ear canal (approximately 2mm), is attached to the tympanic cavity. The tube acts as an ear canal, allowing the acoustic chirp to enter the artificial tympanic cavity. To simulate the tympanic membrane, a layer of Parafilm® is placed between one end of the silicone tube and covers the open side of the artificial tympanic cavity. This Parafilm® acts as a membrane that mimics the acoustic properties of the human tympanic membrane. Furthermore, the artificial tympanic cavity is made with an open top that can be filled with water to mimic the different levels of fluid in the middle ear that can be found in real human ears with MEE.

Fig. 27: Artificial tympanic cavity system including ear canal, ear drum and tympanic cavity.

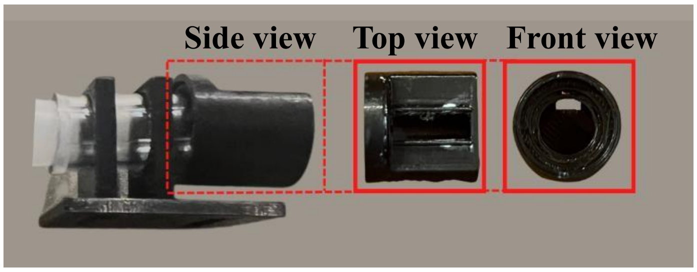


Fig. 28: Different angle of the artificial tympanic cavity.

This construction of artificial middle ear system ensures that the artificial tympanic cavity closely resembles the structure and conditions of the human middle ear. When compared our artificial tympanic cavity with real human middle ear by commercially available Earcheck^{TM} device for locating middle ear fluid, our artificial middle ear system closely emulates the functioning of a real human ear. The Earcheck^{TM} device measures the amount of middle ear fluid in a human ear using the theory of acoustic reflectometry and categorizes the results into five levels: “Fluid unlikely”, “monitor”, “consult doctor level 3”, “consult doctor level 4”, and “consult doctor level 5”, with the severity level increasing with the amount of water detected. Similarly, our artificial middle ear system replicates the acoustic reflectometry characteristics of a typical human ear. When no water is added to the artificial tympanic cavity, the Earcheck^{TM} device indicates "Fluid unlikely." As water is gradually added to the artificial tympanic cavity, the Earcheck^{TM} device displays a "monitor" indication. When 70% of the volume of the artificial tympanic cavity is filled with water, the Earcheck^{TM} device displays "consult doctor." This similarity in results demonstrates that our artificial middle ear system closely mirrors the characteristics of acoustic reflectometry, as observed in a normal human ear using the Earcheck^{TM} commercial device.

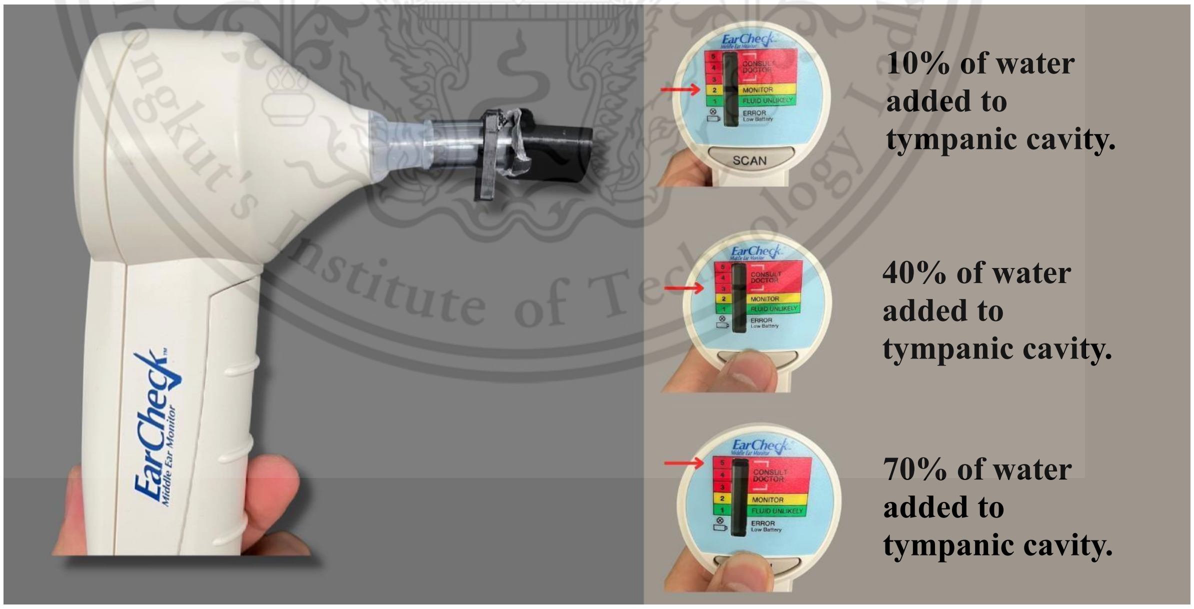


Fig. 29: Earcheck^{TM} Acoustic reflectometry device shows different results from varying water level inside artificial tympanic cavity.

3.4.5 Data collecting experiment.

We collected and preprocessed the acoustic reflectometry data using the following steps. First, we connected the Earcheck^{TM} acoustic reflectometry device to our artificial tympanic cavity. Second, we added varying amounts of water inside the artificial tympanic cavity. Third, we pressed the "Scan" button on the commercial device to diagnose the amount of water inside the sample. After the device registered the result, we placed our modified earphone into the same artificial tympanic cavity with the same amount of water. Fifth, our software ran a 150-ms chirping noise through the modified earphones. Sixth, the microphone captured both the incident waves and reflection waves from the artificial ear system as a .wav file. This process is repeated 75 times, each time, the amount of water inside the tympanic cavity vary. The goal is to collect 5 cohorts of different water levels inside the tympanic cavity. Each cohort consists of 15 datasets.

Obtaining data from the artificial middle ear system from comparing it to the commercial acoustic reflectometry device allows us to see the appearance of the acoustic waves associated with each water level recorded by the commercial device. This enables us to get data in the same categories as the commercial equipment, ensuring precise comparison and analysis.

Fig. 30: Modified earphone collecting acoustic reflectometry data from artificial tympanic ear system.

3.4.6 Data preprocessing

The acoustic chirp data contains 7200 samples that was send was emitted to the middle ear system. The total number of samples that was obtained back was 48,000 samples. We then process the .wav file into a fast Fourier transform (FFT) for extracting frequency response from the file within the range of 0-24 kHz. Then we discarded the frequency outside 0-5000 kHz range of transmitted chirp. This range was picked in order to bring only the acoustic dip area of the graph for machine learning analysis.

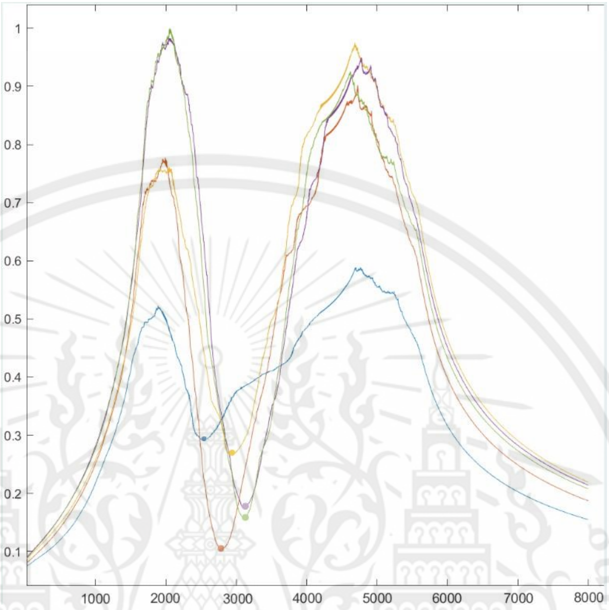


Fig. 31: Different levels of acoustic wave form obtained when chirps was played into an ear without fluid (blue), with minimal fluid (yellow), with medium fluid(purple and green) and maximum fluid (orange).

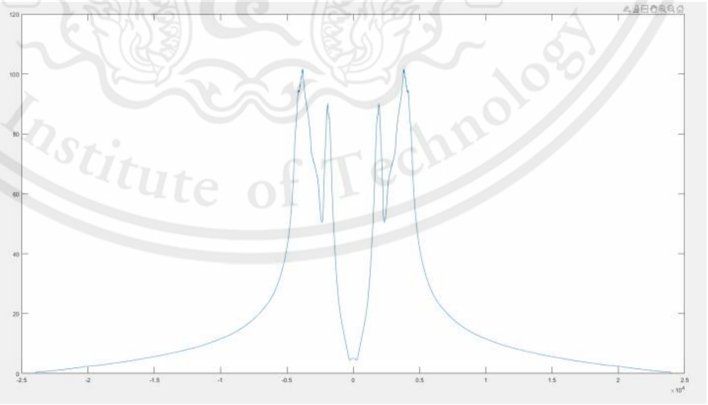


Fig. 32: FFT frequency response acoustic reflectometry wave from ear without fluid.

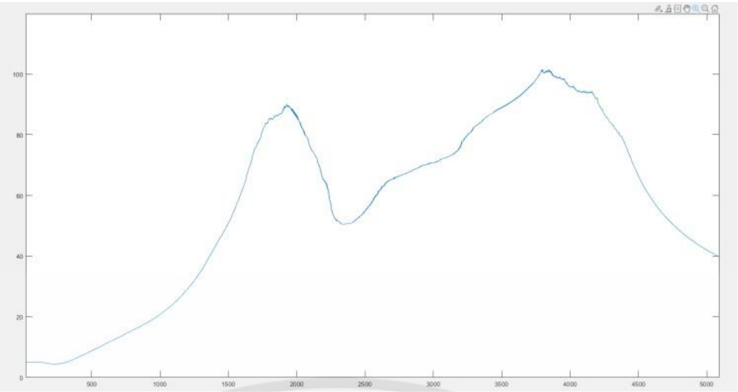


Fig. 33: Extracted frequency response wave in 0-5000 kHz range.

All 75 acoustic response data were preprocessed, including range extraction, and categorized into spreadsheets for machine learning training. There are two distinct spreadsheets used for training.

The first spreadsheet, labeled as dataset A, includes all 5 cohorts for AI training. However, cohorts ranging from "Consult doctor level 3" to "Consult doctor level 5" are combined and categorized as "Consult doctor". As a result, there will be 3 categories of water level, namely "Fluid unlikely", "Monitor", and "Consult doctor", each with 15 data points, including 5 from each "Consult doctor" level segment, forming a total of 15 data points.

The second spreadsheet, labeled as dataset B, includes all 5 cohorts, with 20 datasets from "Fluid unlikely" and 5 data points from each of the other types, forming a total of another 20 datasets for the "Fluid likely" category. Together of 40 datasets.

These spreadsheets serve as the training dataset for the machine learning model, allowing it to learn from the categorized data for accurate classification and analysis.

After forming the training datasets, the next mandatory step is to efficiently resize the datasets for machine learning algorithms. Since each data point includes 5000 frequency points, this could be too large for a laptop-based AI system to run efficiently. Therefore, a resizing software in MATLAB was used to reduce the frequency points from 5000 to 101 frequency points, while maintaining the resolution of the data, as shown in Fig. 28. The yellow and green segments on top are the dataset of “Fluid Unlikely”, the darker blue indicate the acoustic dip in the dataset.

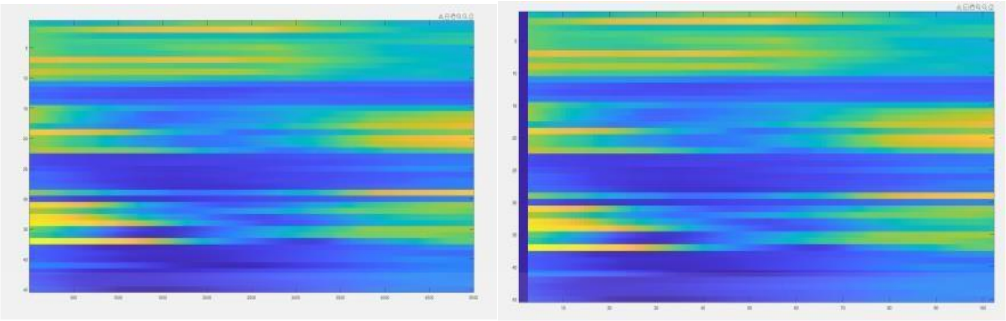


Fig. 34: Left side is the preprocess spectrogram of spreadsheet A; right side is the postprocess after resizing.

CHAPTER 4
EXPERIMENTAL RESULT AND DISCUSSION

4.1 Introduction

In the previous chapter, we presented the experimental hardware and design used to observe the tympanic membrane and collect acoustic reflectometry data from the ear.

The construction of otoscope part has been design fabricate, the result in tympanic membrane image shown in the result section 4.2.

Acoustic reflectometry screening system, we are presenting the results obtained from the experiments. Specifically, we will focus on the analysis of the obtaining using MATLAB software to identify the best-fit machine learning model which is shown in section 4.3. That can be utilized for training future data and potentially be ported out into a smartphone application.

4.2 Otoscope results

According to an earlier chapter on the methodology of the image system. The result can be expressed as follows:

4.2.1 Optical zoom lens and Digital zoom lens.

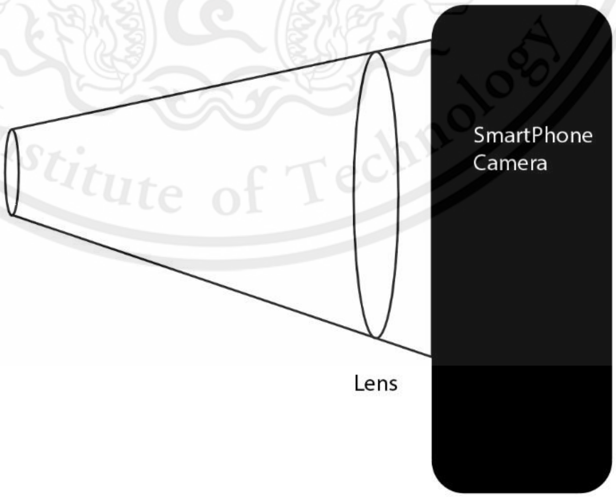


Fig. 35: Lens, Ear tips and Smartphone Diagram.

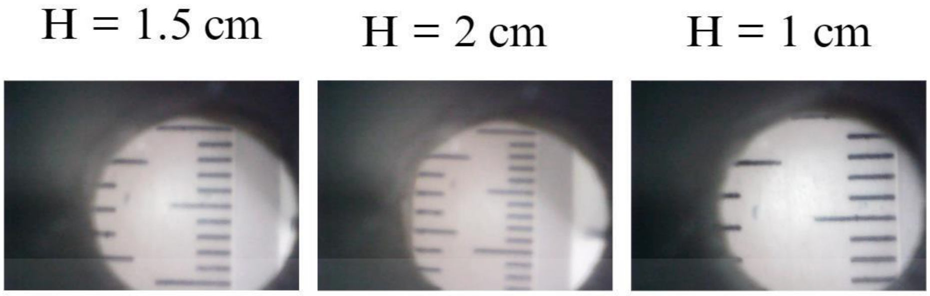


Fig. 36: Image from lens design for each range of object distance. The lens magnifies 2x at 3 ranges of object distance.

Fig. 37: Eardrum image from lens design

4.2.2. Digital zoom system

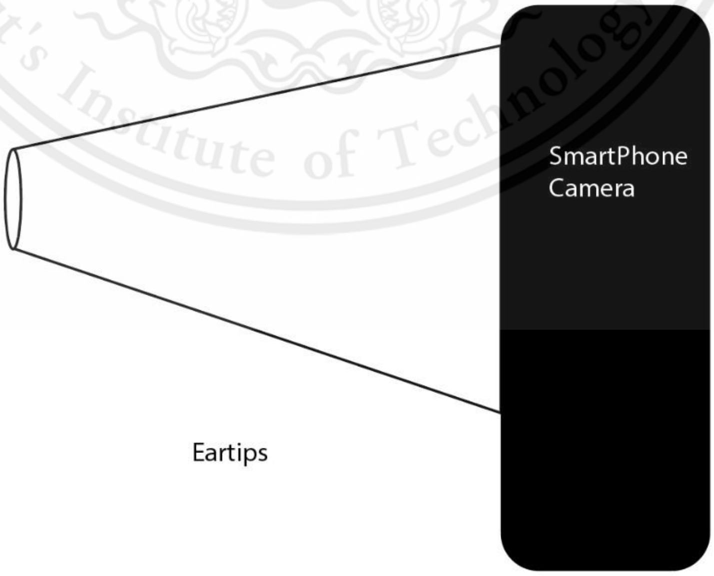


Fig. 38: Ear tips and Smartphone diagram.

The design of ear tips is the same as Fig.35, but the inside of the tips has no lens contained. Image result from this design shown by the following Fig 38.

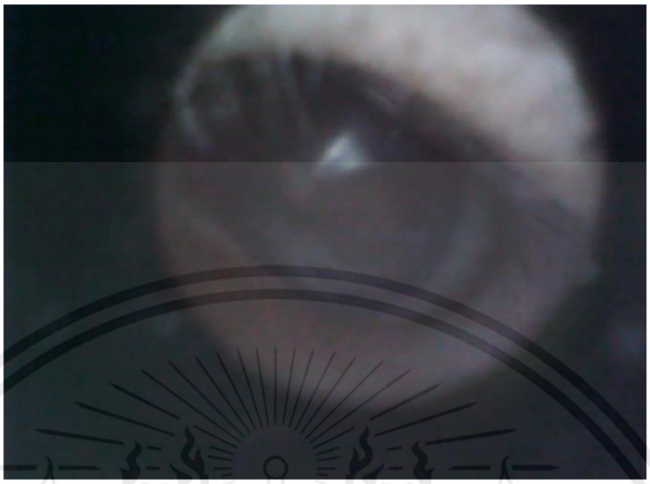


Fig. 39: Digital zoom image from a smartphone.

This can be seen that the whole eardrum area was captured but the field of view of image was limited by ear tips.

4.3 USB port camera and wireless Wi-Fi camera.

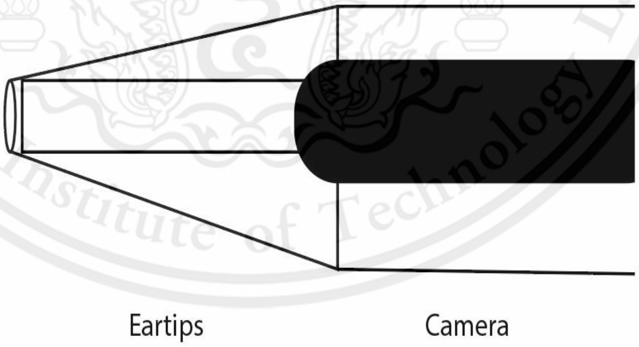


Fig. 40: USB and Wireless Wi-Fi camera diagram.

Fig. 41: USB and Wireless Wi-Fi camera.

The design of ear tips is like Fig.35 but inside of the tips has a camera contained. Image result from this shown by the following Fig 42.

Fig. 42: Eardrum image from camera.

When the camera was placed close to the mouth of ear tips, the field of view of image became larger enough to the whole area of eardrum.

4.4 Acoustic reflectometry machine learning result for Dataset A

After placing spreadsheet into MATLAB's classification learner to find the best fit machine learning model. Spreadsheet A consists of 3 categorical data, "Fluid unlikely, "Monitor" and "Consult doctor". Before placing into the classification learner, we performed *k-fold* (k = 5), three distinct machine learning models appeared to have best accuracy when testing. Including Cubic Support Vector Machine (SVM), Tri layered Neural Network, and Fine K-Nearest Neighbors (KNN), achieved high accuracy rates of 80%, 80%, and 76.7%, respectively.

Cubic Support Vector Machine (SVM) is a form of SVM that maps data into a higher-dimensional space using cubic kernels, allowing for the capturing of complicated correlations between features. Cubic SVMs can fit data that cannot be separated linearly, making them appropriate for handling nonlinear classification issues. They work by determining the optimum hyperplane to segregate the data while maximizing the margin between various classes. The capacity of Cubic SVMs to handle complex data distributions and capture nonlinear patterns results in greater accuracy rates for classification applications.

A Tri layered neural network is a neural network architecture with three layers: an input layer, a hidden layer, and an output layer. The input layer takes the input data, the hidden layer extracts and represents the features, and the output layer delivers the final prediction. Tri layered neural networks may learn complicated patterns from input and can be trained using a variety of optimization procedures, including backpropagation. The ability of a Tri layered neural network to learn hierarchical data representations allows for improved feature extraction and modeling of complicated relationships in the data, resulting in higher accuracy rates for prediction tasks.

Fine K-Nearest Neighbors (KNN) is a variation of the popular KNN method that contains extra modifications to improve its accuracy, such as weighted voting and distance-based weighting. KNN is a straightforward and user-friendly technique that can be applied to both classification and regression tasks. It works by determining the k closest neighbors of a data point using a distance metric and then making predictions based on the majority class or weighted votes of those neighbors. Fine KNN improves on the basic KNN algorithm by including new factors such as allocating higher weights to closer neighbors or utilizing distance-based weighting to prioritize neighbors that are more similar to the query point. The simplicity and interpretability of Fine KNN makes it suited for small datasets or as a baseline model. It can also be used for online learning, where new data points can be added to an existing model incrementally without retraining the entire model. However, for large datasets, it may suffer from the curse of dimensionality and be computationally expensive.

Confusion matrix, TPR, FPR, Specificity and Sensitivity table.

Table 1: Cubic Support Vector Machine (SVM) confusion matrix.

True Class					
Fluid Unlikely	100%			100%	
Monitor		70%	30%	70%	30%
Consult Doctor		30%	70%	70%	30%
	Fluid Unlikely	Monitor	Consult Doctor	True Positive rate	False Positive rate
	Predicted class				

	Specificity	Sensitivity	
Fluid Unlikely	70.6%	Fluid Unlikely	100%
Monitor	100%	Monitor	70%
Consult Doctor	100%	Consult Doctor	70%

Table 2: Tri layered Neural Network confusion matrix.

True Class					
Fluid Unlikely	100%			100%	
Monitor		60%	40%	60%	40%
Consult Doctor		20%	80%	80%	20%
	Fluid Unlikely	Monitor	Consult Doctor	True Positive rate	False Positive rate
	Predicted class				

	Specificity	Sensitivity	
Fluid Unlikely	80%	Fluid Unlikely	100%
Monitor	100%	Monitor	37.5%
Consult Doctor	100%	Consult Doctor	80.0%

Table 3: Fine K-Nearest Neighbors (KNN) confusion matrix.

True Class					
Fluid Unlikely	100%			100%	
Monitor		70%	30%	70%	30%
Consult Doctor		40%	60%	70%	40%
	Fluid Unlikely	Monitor	Consult Doctor	True Positive rate	False Positive rate
	Predicted class				

	Specificity	Sensitivity	
Fluid Unlikely	50.8%	Fluid Unlikely	100%
Monitor	100%	Monitor	41.2%
Consult Doctor	100%	Consult Doctor	60%

Table 1, 2 and 3 represent the confusion matrix of three different machine learning models which function well with the dataset A. All these three models predicted 100% accurately on classified ear without fluid data.

Table 4: Machine learning model comparison.

Model	AUC (Fluid Unlikely)	Sensitivity
Cubic Support Vector Machine (SVM)	1.0	100%
Tri layered Neural Network	1.0	100%
Fine K-Nearest Neighbors (KNN)	1.0	100%

Table 5: Acoustic reflectometry machine learning results for Dataset B.

A) Cubic Support Vector Machine (SVM)

True Class		
Fluid Unlikely	100%	
Monitor		100%
	Fluid Unlikely	Consult Doctor

B) Tri layered Neural Network

True Class		
Fluid Unlikely	92.86%	7.14%
Monitor	3.45%	96.6%
	Fluid Unlikely	Consult Doctor

C) Fine K-Nearest Neighbors (KNN)

True Class		
Fluid Unlikely	100%	
Monitor		100%
	Fluid Unlikely	Consult Doctor

CONCLUSION

5.1 Introduction

In conclusion, the ear infection detection application and system based on deep learning comprise two main parts: the otoscope part and the acoustic reflectometry part. The goal of this thesis is to develop an application system that utilizes the theory of acoustic reflectometry to screen for middle ear effusion (MEE). The system aims to have an otoscope extension connected to a smartphone, which allows for the observation of the tympanic membrane to check for any ear wax blockages that may affect the acoustic noise. Additionally, the system includes a modified earphone that plays chirping noise to analyze the acoustic characteristics and identify any abnormalities such as acoustic dips that could indicate the presence of MEE.

5.2 Conclusions & discussion

5.2.1 Otoscope implementation with application.

The image system design has yielded a conclusive result, indicating that the USB port and Wi-Fi camera design are the most efficient for image solutions. This is due primarily to its ability to provide a broad field of view, which is required for obtaining clear images of the entire tympanic membrane. It should be noted that this system will be included as a feature in mobile applications used to diagnose middle ear induction.

5.2.2 Acoustic reflectometry conclusion and discussion.

In conclusion, our research has successfully developed a middle ear screening tool which will further working with an application that incorporates acoustic reflectometry theory into the system comprised of an artificial tympanic cavity, modified earphone, and chirping noise, with promising results obtained through machine learning using MATLAB. However, it is important to note that our experiment's data gathering technique was limited to the artificial tympanic cavity, which may have introduced biases into the results. Future study should focus on gathering data from real human samples, after receiving relevant ethical clearances such as Institutional Review Board (IRB) clearance from KMITL, to further improve the accuracy and usefulness of our technology. We can address potential biases and improve the validity and generalizability of our findings by using real human data.

The creation of a middle ear screening application based on acoustic reflectometry theory has tremendous potential for the early detection of middle ear effusion (MEE), a prevalent ailment that, if left untreated, can lead to hearing loss and other consequences. Our system may be modified to better adapt to the complexities of real-world events by gathering data from real human samples, and its sensitivity can be further examined and confirmed. This study is an important step toward the practical application of acoustic reflectometry for MEE screening, and it has the potential to significantly impact clinical practice in the field of otology.

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