University of Split School of Medicine
Medical physics and biophysics

PRACTICAL EXERCISES GUIDE

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Contents

Processing of Measurement Results

Why is it important to quantify uncertainty?

Quantifying uncertainty is crucial in the field of measurement and data analysis. By doing so, we can better understand the reliability and consistency of our measurements, which allows for more accurate and informed decision-making. Additionally, it enables comparisons with measurements from other groups or devices, ensuring that we can benchmark our findings and identify potential areas for improvement. Consequently, uncertainty quantification makes our results credible and transparent and enables data-based decision making.

Measurement errors are inevitable, and they can be classified into three main types: systematic errors, random errors, and gross errors. While it is often impossible to completely eliminate these errors, statistical analysis can help to determine their impact on measurement results.

One practical example can be seen in weather forecasting, such as predicting the probability of rain. Weather models use a vast array of data from various sources, including satellite images, ground stations, and historical records. Despite sophisticated algorithms, there is always a level of uncertainty due to the complexity of weather systems. Systematic errors might arise from biased data sources, such as a weather station placed in an atypical microclimate, while random errors could stem from unpredictable atmospheric fluctuations.

Another example involves voting polls. Pollsters gather data from a sample of the population to predict election outcomes. Systematic errors might occur if the sample is not representative of the overall population, such as underrepresenting certain demographics, leading to skewed results. Random errors are introduced by the inherent variability in human responses and the sampling process itself. By quantifying the uncertainty in these polls, we can better gauge the reliability of the predicted outcomes and understand the potential margin of error.

Measurement Errors

Systematic Errors:

Systematic errors, caused by identifiable factors, result in measurements that are consistently too high or too low and can be corrected. These errors often stem from instrumental issues, environmental conditions, or procedural flaws. For example, a miscalibrated scale may give heavy readings, or an unadjusted thermometer might show incorrect temperatures. Unlike random errors, which vary unpredictably, systematic errors can be detected and minimized through careful calibration, maintenance, and methodological adjustments. Addressing these errors is crucial for accurate and reliable measurements in scientific research and other precision-dependent fields.

Examples with respect to the cause of the systematic error:

- **Instrument**: A poorly calibrated instrument, e.g., a thermometer that shows 102°C in boiling water and 2°C in frozen water at a standardized atmospheric pressure. Such an instrument will show measured values that are consistently too high.
- **Observer**: Reading a meter scale or water level at an angle.
- **Environment**: Example: Voltage drop in the city network, as a result of which the measured currents will be constantly too low.
- **Theory**: Due to the simplification of the model or approximations in the equations that describe it. For example, if according to the theory the ambient temperature does not affect the readings, but in reality it does, this factor will be a source of error

Random Errors:

These errors vary unpredictably from one measurement to another. They are inherent in any measurement process and can often be minimized through repeated measurements and statistical analysis.

Examples with respect to the cause of the random error:

- **Observer:** An error in the judgment of an observer when reading values at the smallest subdivision of the scale.
- **Environment:** Unpredictable fluctuations in the voltage, temperature or mechanical vibration of the device.

Gross Errors:

These are significant mistakes such as recording incorrect values or taking incorrect readings. They usually stand out from other measurements and should be excluded from data analysis if verified.

Example: An observer may record an incorrect value, take an incorrect reading from the scale, forget a digit when reading from the scale, or make another similar omission.

Quantifying the effect size

When dealing with random errors in an ideal experiment, the arithmetic mean ($\overline{X}$) is used to obtain the actual value of the property measured through multiple successive measurements (X_i). This value is calculated by summing up all measurements and dividing that value with the total number of measurements (N) using the following equation:

$$\overline{X} = \frac{\sum_{i=1}^{N} X_i}{N}$$

Example of calculation:

Consider a set of measurements: 2, 3, 4, 5, 6. The mean value ($\overline{X}$) of these measurements is calculated as:

$\overline{X}$ = (2 + 3 + 4 + 5 + 6) / 5 = 20 / 5 = 4

Quantifying uncertainty

Merely presenting the mean result is insufficient as it does not provide information on the consistency of the measurements. For example, the mean value of the sequences 1, 1, 3, 5, 5 and 3, 3, 3, 3, 3 is the same, but we can be more confident in the result of the second set of measurements due to their consistency.

Her we will quantify uncertainty using the mean absolute error (MAE). MAE provides a measure of the average magnitude of errors in a set of measurements, calculated using the following equation.

$$MAE = \frac{\sum_{i=1}^{N} \left| X_i - \overline{X} \right|}{N}$$

Example of calculation:

Consider a set of measurements: 2, 3, 4, 5, 6. The mean value ($\overline{X}$) of these measurements is calculated as:

$\overline{X}$= (2 + 3 + 4 + 5 + 6) / 5 = 20 / 5 = 4

Next, we calculate the absolute errors for each measurement:

|2 - 4| = |-2| = 2

$|3 - 4| = |-1| = 1$

$|4 - 4| = |0| = 0$

$|5 - 4| = |1| = 1$

$|6 - 4| = |2| = 2$

Now, sum these absolute errors and divide by the total number of measurements (N = 5):

MAE = (2 + 1 + 0 + 1 + 2) / 5 = 6 / 5 = 1.2

This MAE value represents the average magnitude of errors in the set of measurements.

MAE interpretation:

To understand the interpretation of Mean Absolute Error (MAE), let's consider two sets of measurements that have identical means but different MAE values.

First, calculate the mean ($\overline{X}$) for both sets of measurements:

Set 1: {2, 3, 4, 5, 6}

$\overline{X}_1 = (2 + 3 + 4 + 5 + 6) / 5 = 20 / 5 = 4$

Set 2: {3, 3, 5, 5, 4}

$\overline{X}_2 = (3 + 3 + 5 + 5 + 4) / 5 = 20 / 5 = 4$

Even though both sets have the same mean ($\overline{X}$ = 4), the MAE will differ.

Next, calculate the absolute errors for each measurement in Set 1:

$|2 - 4| = 2$

$|3 - 4| = 1$

$|4 - 4| = 0$

$|5 - 4| = 1$

$|6 - 4| = 2$

Sum these absolute errors and divide by the total number of measurements (N = 5):

MAE_1 = (2 + 1 + 0 + 1 + 2) / 5 = 6 / 5 = 1.2

Now, calculate the absolute errors for each measurement in Set 2:

$|3 - 4| = 1$

$|3 - 4| = 1$

$|5 - 4| = 1$

$|5 - 4| = 1$

$|4 - 4| = 0$

Sum these absolute errors and divide by the total number of measurements (N = 5):

$MAE_2 = (1 + 1 + 1 + 1 + 0) / 5 = 4 / 5 = 0.8$

Interpretation:

MAE provides a measure of the average magnitude of errors in a set of measurements, ignoring their direction (positive or negative). It helps in understanding the accuracy of predictions or measurements.

When comparing two sets with identical means, but one has a smaller MAE, we can conclude that the set with the smaller MAE has less variability in its measurements. This indicates that the errors are generally smaller and closer to the mean value, suggesting higher accuracy in the measurements or predictions. In essence, a smaller MAE signifies more consistent and reliable data.

It is important to note that while MAE is a valuable metric for understanding error magnitude, examining the distribution of errors can offer a deeper understanding of the data's characteristics.

General information on the practical exercises

Practical Exercises

- All exercises will be performed in laboratory A426
- Students are to work in pairs as designated in the schedule posted on the course website.
- Each pair is required to complete five exercises, with three school hours designated for each exercise.
- A handwritten report must be submitted to the teacher upon completion of each exercise.
- Preparation for each exercise should include reading the practical exercise guide and the relevant materials from the textbook.
- Exercises will be conducted cyclically, so it may be necessary to read some materials before they are covered in lectures and seminars.
- Swaps between students are permitted only if the group size remains unchanged and both students are performing the same exercise. Both teachers must be informed of the swap via email.

Colloquium

If a student skips an exercise or submits an unsatisfactory report, they must take a colloquium. The colloquium will consist of five multiple-choice questions, with only one correct answer per question. To pass, at least three answers must be correct. Failure to pass the colloquium means the student cannot take the written exam for that term and must retake the colloquium before the next exam term.

Report Format

Reports should be written legibly on A4 paper and include:

- Student's name and surname
- Date of the exercise
- Ordinal number and title of the exercise
- Objective of the exercise in 1-2 sentences
- Exercise hypothesis
- Summary description of the measurement procedure
- Tabular record of the measurement results with units
- Calculated quantities with clearly indicated calculation procedures
- Graphical representation of results if necessary
- Personal comment on the exercise including whether or not the results are in line with the initial hypothesis and what were the potential sources of measurement error

Practical Exercise 1: Diagnostic Ultrasound

An echogram records ultrasound echo patterns occurring at the boundary between two media with different acoustic impedances. Acoustic impedance is the product of a medium's density and the speed of sound in that medium.

Resolution of the ultrasound display refers to the capability to distinguish two closely spaced details. It is the smallest distance at which two adjacent objects can be identified as separate entities. There are two primary types of resolution in ultrasound imaging: axial resolution and lateral resolution (Figure 1).

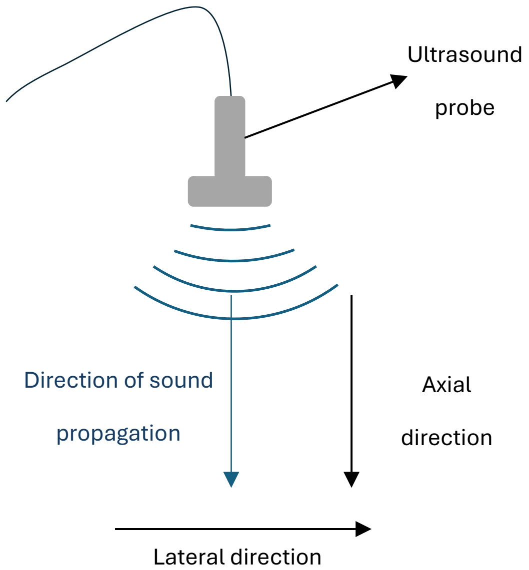

Figure 1: Type of resolution with respect to the direction of sound propagation.

Axial resolution is defined as the ability to distinguish two structures that are close to each other along the direction of the ultrasound beam. It is primarily determined by the spatial pulse length (SPL), which is the length of a single ultrasound pulse. Shorter pulses result in better axial resolution. Axial resolution affects the image clarity in the direction of the ultrasound beam, meaning that objects aligned with the beam can be more accurately distinguished.

Lateral resolution, on the other hand, is the ability to differentiate two structures that are close to each other in a direction perpendicular to the ultrasound beam. This type of resolution is determined by the beam width; narrower beams lead to better lateral resolution. The lateral resolution affects the image clarity across the width of the ultrasound beam, allowing for better differentiation of side-by-side structures.

Resolution measurement:

In order to measure the ultrasound resolution, you will use two wooden sticks connected on one side and separated on the other. Immerse the wooden sticks in the water-filled container. To see the ultrasound image, touch the water surface with the probe. Make sure not to immerse the probe too deeply into water to avoid frying the electrical parts. **The probe should never be immersed in water by more than half a centimetre**. Place the probe over the part where the sticks are separated the most and then slowly move the probe to the other side. As you move over to the part where the sticks are connected, the lines on the ultrasound image corresponding to the signal from the two sticks should get closer together as well (Figure 2). At some point the lines on the ultrasound image will overlap. When this happens, stop moving the probe and mark the place on the sticks under the current position of the probe. Then take out the sticks and measure the gap between them at the marked position using a ruler. The obtained measurement is the axial resolution limit.

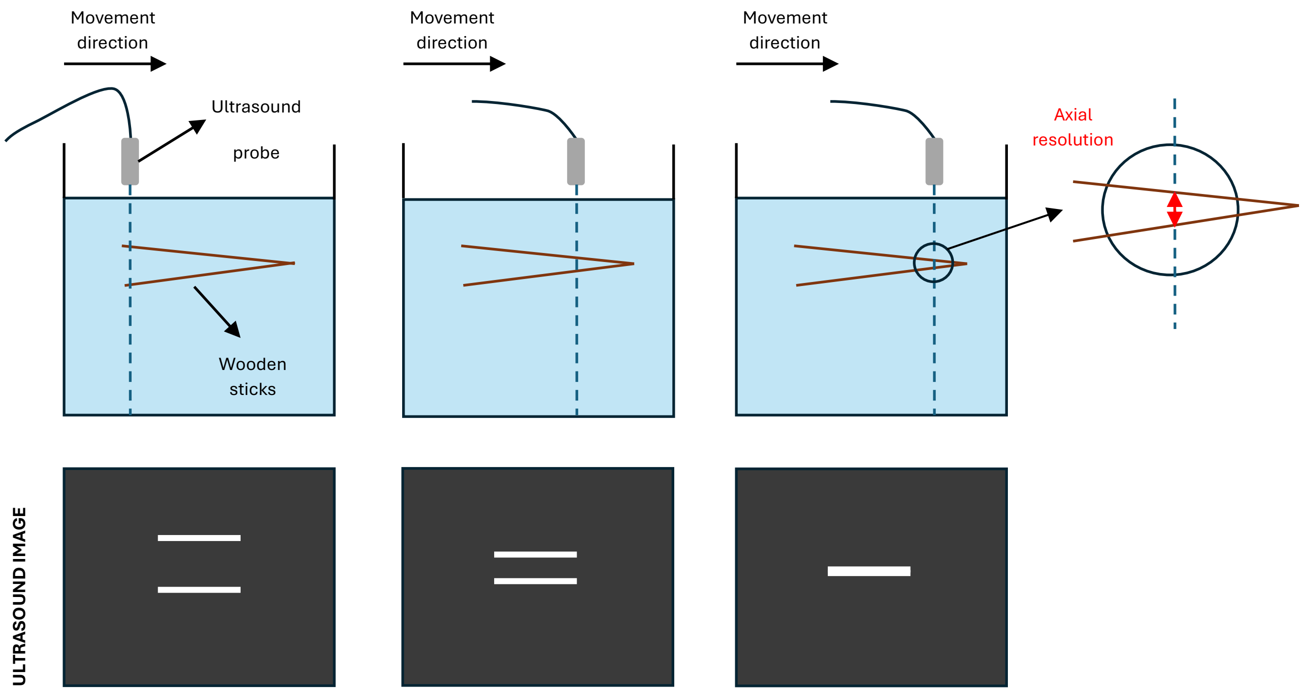

Figure 2: The process of axial resolution measurement. As the probe is moving over to the part where the wooden sticks are connected, the corresponding lines on the ultrasound image get closer together.

The separation between the sticks when the lines on the image start overlapping is the axial resolution limit.

In order to measure the lateral resolution, rotate the sticks by 90 degrees so that the gap between the sticks is in a direction perpendicular to the direction of sound propagation. Then go through the process of finding the lateral resolution by repating the steps described above for the axial resolution measurement.

Tasks:

1. Fill the plastic container with water and then immerse a metal ball in the water. Inspect the ball under ultrasound and comment on the appearance of the signal and explain the cause. What artifacts can be seen?
2. Immerse the wooden sticks in the water at the depth of 3 cm (measure the depth using a ruler). Place the probe over the part where the sticks are separated the most and then move the probe to the other side and determine the point at which the signal from the sticks are no longer distinguishable on the monitor. Remove the sticks from the water and measure the distance between them. The obtained measurement is the resolution limit. Perform three measurements for both the axial and lateral resolutions and use the measurements to calculate the mean and MAD values for each resolution type.
3. Change the depth of the sticks to 7 cm (measure the depth using a ruler) and repeat the measurements and calculations for both resolution types. How do the average values change? How do the results align with your initial hypothesis?
4. Compare the axial and lateral resolutions and how they change with increasing depth. Comment on the differences and trends in view of the facts from the course textbook.

Measurements table:

Depth (cm)	Measurement	Axial resolution (mm)	Mean axial resolution (mm)	MAE axial resolution (mm)	Lateral resolution (mm)	Mean lateral resolution (mm)	MAE lateral resolution (mm)
	1						
	2						
	3						
	1						
	2						
	3						

Practical Exercise 2: Audiometry

The human auditory system

The human ear is a highly sophisticated organ that captures sound waves from the environment and converts them into electrical signals that the brain can interpret. The auditory system consists of three main parts: the outer ear, the middle ear, and the inner ear. Each section plays a crucial role in the process of hearing. The outer ear collects sound waves and funnels them to the eardrum, which vibrates in response. These vibrations are then transferred through the ossicles of the middle ear to the cochlea in the inner ear, where they are converted into electrical signals. These signals travel via the auditory nerve to the brain, where they are perceived as sound.

The human auditory system is extremely sensitive, capable of detecting a broad range of sound frequencies and intensities. However, our perception of sound follows a nonlinear relationship with frequency. This nonlinear relationship is primarily due to the ear's varying sensitivity to different frequencies. The human ear is most responsive to frequencies between 2,000 and 5,000 Hertz (Hz), where most of human speech occurs. Consequently, sounds within this range are perceived as louder and clearer than those at higher or lower frequencies, even with identical sound pressure levels. This phenomenon is attributed to the resonant properties of the outer and middle ear, as well as the mechanical and neural characteristics of the inner ear.

Introduction to audiometry

Audiometry is a technique utilized to evaluate the hearing ability of an individual. This process involves the measurement of a person's ability to hear various sound frequencies and intensities. The primary aim of audiometry is to identify any hearing loss, its severity, and its potential causes. Audiometry is a fundamental tool in audiology and is used extensively in both clinical and research settings to understand the auditory capabilities of individuals.

There are multiple types of audiometry because hearing loss can manifest in various forms and affect different parts of the auditory system. Each approach is designed to evaluate specific aspects of hearing ability and to identify the types of hearing impairments.

Pure tone audiometry

Pure tone audiometry is the most common method of hearing assessment. It involves the use of an audiometer to deliver sounds at various frequencies and intensities to the patient through headphones. The patient indicates whether they can hear each sound, and the results are plotted on a chart called an audiogram. This type of audiometry helps in identifying the specific frequencies that an individual can hear and determining the degree of potential hearing loss.

Speech audiometry

Speech audiometry evaluates an individual's ability to hear and understand speech. This method uses recorded or live speech instead of pure tones. The patient listens to words or sentences at different volumes and repeats them back to the examiner. The results provide information about speech recognition thresholds and the clarity of speech perception, which are crucial for understanding everyday communication abilities.

Bone conduction audiometry

Bone conduction audiometry assesses hearing by bypassing the outer and middle ear and directly stimulating the inner ear. A bone vibrator is placed on the mastoid bone behind the ear, and sounds are transmitted through the bone to the cochlea. This method helps to determine whether hearing loss is due to problems in the outer or middle ear (conductive hearing loss) or in the inner ear (sensorineural hearing loss).

Immittance audiometry

Immittance audiometry includes tympanometry and acoustic reflex testing. Tympanometry measures the movement of the eardrum in response to changes in air pressure, providing information about the condition of the middle ear and eustachian tube function. Acoustic reflex testing evaluates the reflexive contraction of the middle ear muscles in response to loud sounds, helping to assess the integrity of the auditory pathway.

Sound liminal audiometry

In this exercise, sound liminal audiometry, also known as threshold audiometry, will be performed. This type of audiometry focuses on determining the faintest sound that an individual can hear at various frequencies. This approach is critical for establishing the hearing threshold.

Procedure for Sound Liminal Audiometry

The procedure for sound liminal audiometry involves several steps:

- Calibration: The audiometer must be calibrated to ensure accurate measurements. This involves setting the sound intensity at the threshold of audibility for each frequency by adjusting the volume indicator on the computer.
- Initial Setup: The subject is seated in a quiet environment, and headphones are placed over their ears. The test begins with the calibration of the audiometer to determine the hearing threshold for each frequency.
- Determining Hearing Threshold: The subject listens to a series of tones at varying frequencies and intensities. They indicate when they can hear the sound by pressing a button. The software adjusts the intensity until the quietest sound that the subject can detect is found.
- Data Recording: The results are recorded on an audiogram, which plots the hearing thresholds across different frequencies. The chart contains two curves, one for each ear. The values for the left ear are usually displayed in blue, and for the right in red color.

By understanding the specific frequencies at which hearing loss occurs, audiologists can tailor interventions such as hearing aids or other assistive devices to improve the patient's quality of life.

Audiogram interpretation

Interpreting an audiogram requires understanding the values plotted on the graph, which represent the hearing thresholds at various frequencies. The horizontal axis of an audiogram shows the frequency of sounds in Hertz (Hz), ranging from low to high frequencies. The vertical axis represents the intensity of sound in decibels (dB), with values ranging from -10 dB to 120 dB.

On the vertical axis, 0 dB is a reference point that indicates the weakest sound that a person performing the calibration could hear. To draw relevant conclusions about the test subject's hearing quality, calibration should be conducted by a young adult with normal hearing. If there is uncertainty regarding the hearing ability of the individual performing the calibration, we can only infer the test subject's hearing relative to that individual, without making definitive conclusions about their absolute hearing capabilities. The value of 0 dB on an audiogram does not indicate the absence of sound but rather the threshold of hearing for the person which performed the calibration. Values below 0 dB show that the test subject has more sensitive hearing, while higher dB levels indicate less sensitive hearing compared to the calibrator. When a person's hearing threshold is plotted at higher dB levels, it reveals the need for louder sounds for them to detect, indicating hearing impairment.

For example, assuming the test was calibrated correctly, and the test subject has normal hearing, the audiogram should look like the right chart on Figure 1. A threshold at 20-25 dB indicates mild hearing loss, whereas thresholds at 40-55 dB suggest moderate hearing loss. Severe hearing loss is represented by thresholds at 70-90 dB, and profound hearing loss is indicated when thresholds are above 90 dB (Figure 1). The audiogram thus provides a visual representation of the degree and configuration of hearing loss, helping audiologists to diagnose and recommend appropriate interventions.

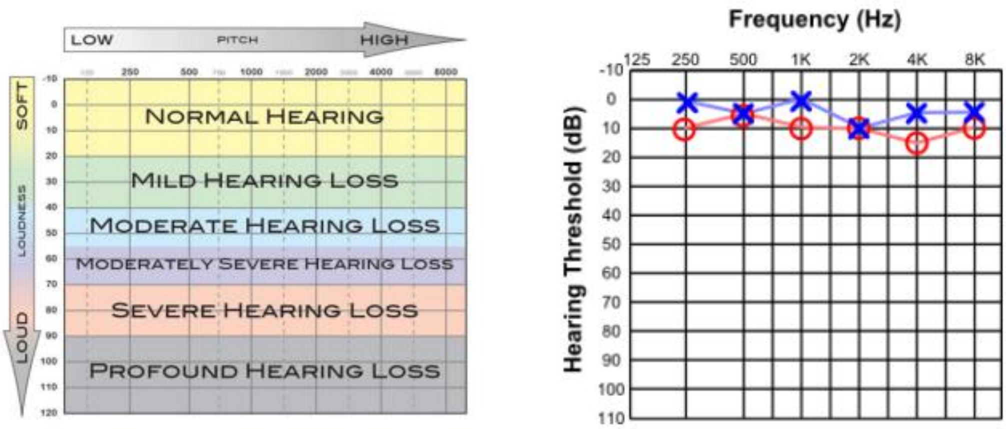

Figure 1: Quality of hearing with respect to values recorded on an audiogram (left) and a normal audiogram (right).

Tasks

1. Turn on the computer, put on the headphones, and start the Esser home Audiometer Hearing Test. Before the audiometry itself, it is necessary to calibrate the system by determining the sound intensity at the threshold of audibility for each frequency by moving the volume indicator on the computer. To start the calibration, click on Calibration -> New calibration by ear. On the next two pop-up prompts regarding the sound card compatibility test, select “No” both times. Then, two sound control columns will appear on the screen. Maximize the values in both columns, then set the hearing thresholds by lowering the left column only (the right column should always remain at the maximum value). The threshold is determined by selecting the lowest value at which you can still hear the sound (not the first one you cannot hear). After setting the value for one frequency, click Next and set all the remaining frequencies for one ear, and then for the other. When

finished, save the calibration data to the Desktop in the Audiometry folder. Create a new subfolder with the current date and save the calibration under your initials.

2. After both students have completed the calibration, load the first student's calibration into the software by clicking on Calibration -> Load Calibration Data and selecting the calibration with the appropriate initials. Then the other student (not the one whose calibration was loaded) can start the test. What would happen if you only used your own calibration? How would the audiogram look?
3. Now you can start the actual test. Click on Hearing Test -> New Test. You will first be shown the "Familiarization" window. This window will display a curve whose values will correspond to the loudness of the sound displayed in your earphones. The curve is controlled using the "Ctrl" button located in the bottom left corner of the keyboard. Your task is to press and hold the butto as long as you hear a sound in the earphones. This will cause the software to reduce the loudness and the curve will start going up. Once you can no longer hear a sound in the earphone, let go of the "Ctrl" button. The software will respond by increasing the loudness again and the curve will start going down again. Once you start hearing the sound again, press and hold "Ctrl" again. Repat the above process until you are ceertain that you understand the testing procedure.
4. Once you are confident you understand how the testing procedure works, click "Next" (or "OK", or "Continue", which ever appears). A pop-up message will appear notifying you that the next step is the actual hearing test. Procede and use the same approach as the on described in task 3. The hearing test will generate audiometric curves as shown in Figure 1 right.
5. After the first student completes the test, take a screenshot of the obtained result, load the second student's calibration, and switch places with your colleague so they can also take the test. Once finished, again capture the resulting audiogram.
6. Paste the cropped images of the audiometry results into a Word document and comment on the results below them. Which student heard better, at which frequencies, and how do you conclude this from the given graphs?
7. What are the possible sources of error, and in which areas of the graph do you suspect they might have occurred?

Practical Exercise 3: Optical Bench

Lenses are fundamental optical components utilized in various scientific and medical applications. They are primarily categorized into two types: converging lenses (also known as convex lenses) and diverging lenses (also known as concave lenses). Understanding the properties and behavior of these lenses is essential for practical experiments, particularly for medical students who will encounter a wide array of optical instruments in their careers.

Converging lenses:

Converging lenses are thicker at the centre than at the edges, causing parallel rays of light to converge at a single focal point on the other side of the lens (Figure X). This property makes them ideal for applications requiring magnification, such as microscopes and magnifying glasses. Converging lenses are also used in corrective eyewear for individuals with hyperopia (farsightedness), as they help focus incoming light directly onto the retina.

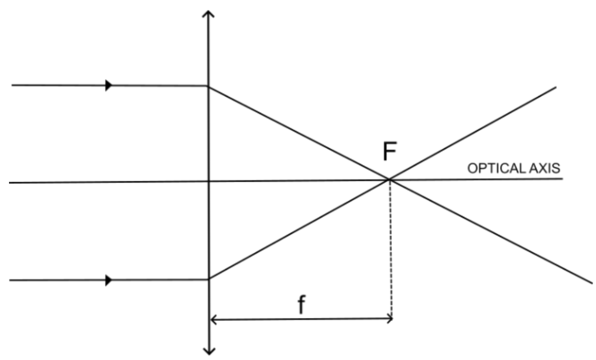

Figure 1: The refractive effect of a converging lens on parallel rays of light. The focal point (F) is the point at which light perpendicular to the lens are refracted after passing through the lens. The focal distance (f) is the distance from the lens to the focal point.

Depending on the lens-object distance, different image sizes can be obtained on the screen, with no image being created if the distance is smaller than the focal distance, a magnified image appearing if the distance is between one and two focal distances, and a reduced image forming if the lens-object distance is greater than two focal distances. The summary of these relationships is presented in Table 1. Notice that knowing these relationships and the focal length of the lens allows us to know a priori how far away the lens should be placed with respect to the object in order to get an image of a certain magnification.

Table 1: Image characteristics with respect to the magnitude of x_1 and x_2.

X_1	X_2	Image
$\infty > \mid x_1 \mid > 2f$	$f < x_2 < 2f$	real, inverted, smaller than the object
$\mid x_1 \mid = 2f$	$x_2 = 2f$	real, inverted, the same size as the object
$2f > \mid x_1 \mid > f$	$x_2 > 2f$	real, inverted, larger than the object
$\mid x_1 \mid < f$	$x_2 < 0$	imaginary, upright, larger than the object

Diverging lenses:

Diverging lenses, on the other hand, are thinner at the center and thicker at the edges. These lenses cause parallel rays of light to diverge away from a common focal point, effectively spreading the light rays (Figure Y). Diverging lenses are commonly used in applications where the reduction of image size or the control of light dispersion is necessary. Diverging lenses are used in glasses for individuals with myopia (nearsightedness), aiding in the proper focusing of light before it reaches the retina.

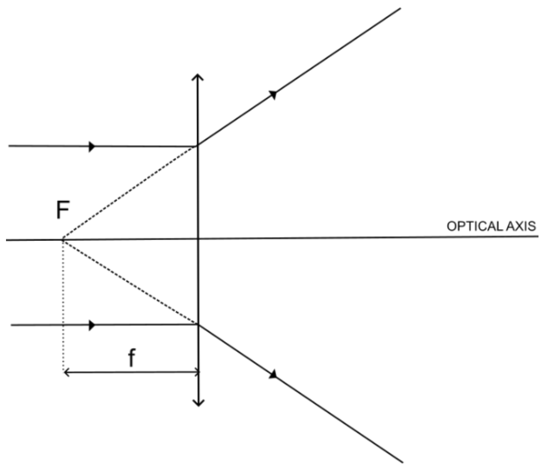

Figure 2 The refractive effect of a diverging lens on parallel rays of light.

Both types of lenses have unique focal properties that are crucial for various practical applications. The behaviour of light through these lenses is governed by the lens equation. The lens equation enables calculation of the focal distance of the lens by measuring the distance from the lens to the object (x_1) and from the lens to the image (x_2) once there is a sharp image on the screen. The equation is $\frac{1}{f} = -\frac{1}{x_1} + \frac{1}{x_2}$, or equivalently, $f = \frac{x_1 x_2}{x_1 - x_2}$.

Depending on the circumstances, in the above equation x_1 and x_2 can be entered with either positive and negative signs. The sing is determined with respect to the direction of the light rays illuminating the object, which is taken to be the positive direction (in the case of Figure 3, the light falling on the object is traveling from left to right, so we take that direction as the positive one). If the distance is measured in that positive direction, its value is entered into the equation with a positive sign, and if not, with a negative sign. Using the example from Figure 3, and knowing that x_1 is the distance measured from the lens to the object, and x_2 the distance measured in the direction from the lens to the image, it follows that the measured value of x_1 should be inserted into the equation with a negative sign, and the value of x_2 with a positive sign

Quantities that have the same direction like the light beam have positive sign. If they have opposite direction the sign is negative. According to this, the distance x_1 in this case will have negative, and x_2 positive sign (Figure 3).

Aside from focal distance, the lens' ability to refract light is often expressed through power calculated as the reciprocal of focal distance in metres: $j = \frac{1}{f}$. The lens power is expressed in diopter units (dpt). Image magnification is determined by the ratio of the image and object size, and it should be equal to the ratio of lens-image distance to lens-object distance, or mathematically expressed, $m = \frac{y_2}{y_1} = \frac{x_2}{x_1}$.

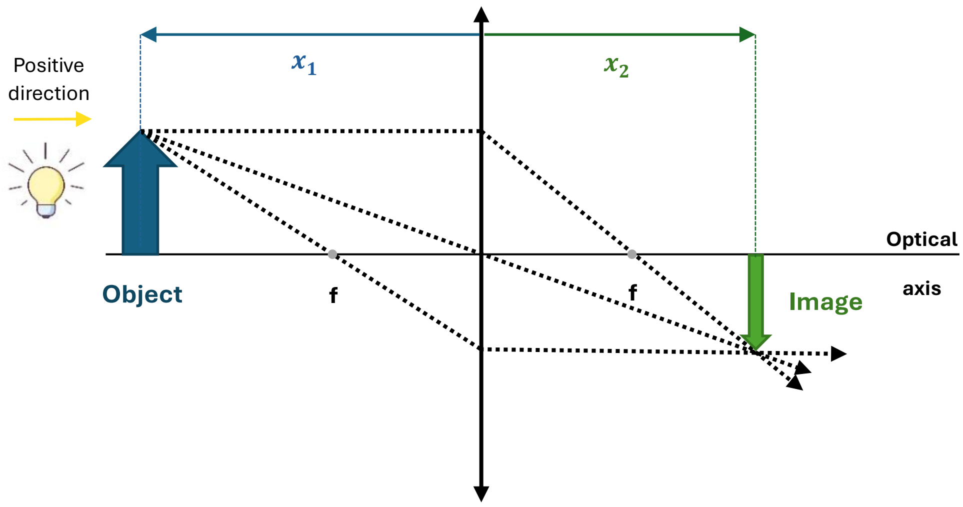

Figure 3: Schematic depiction of the image formation process for the single lens approach.

Single-lens measurement method:

The object (O) is an arrow shaped hole cut in a piece of cardboard and illuminated by a light source for the experiment. The object and source are placed on the optical bench together with the lens (L) and screen (S) (Figure 3). Holders (H) are used to slide the optical elements along the bench in order to find a sharp image on the screen. Once the sharp image is found, the millimetric scale on the optical bench is used to read the lens-object (x_1) and lens-image (x_2) (Figure 3, Figure 4). Once these distances are recorded, they can be used to calculate f and j using the lens equation.

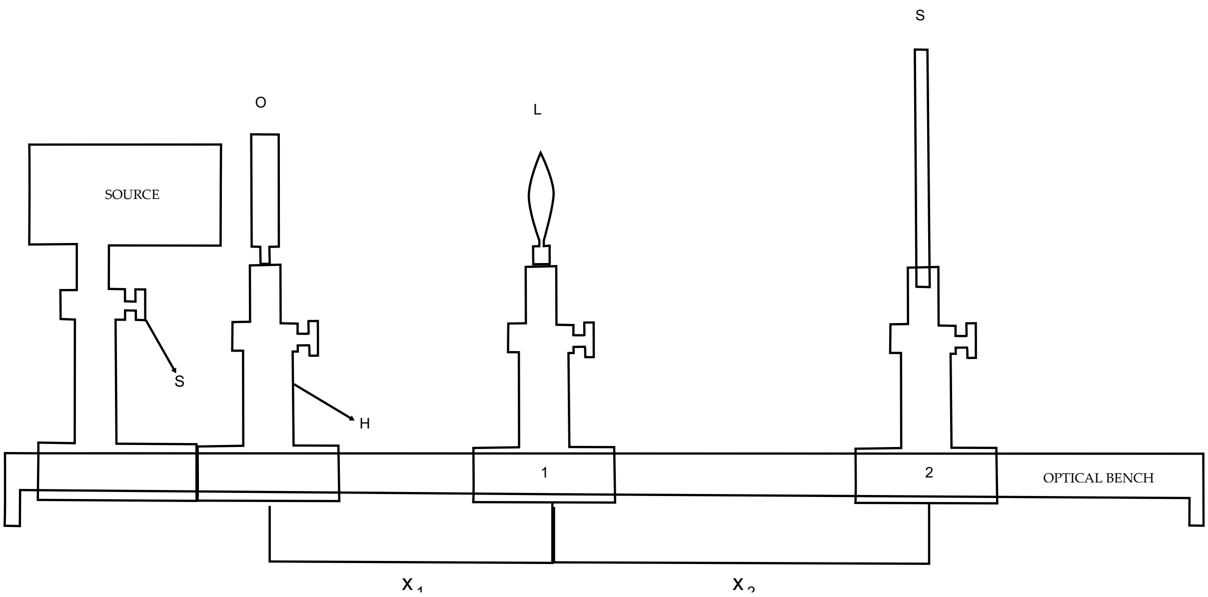

Figure 3: Measurement process using the single-lens approach.

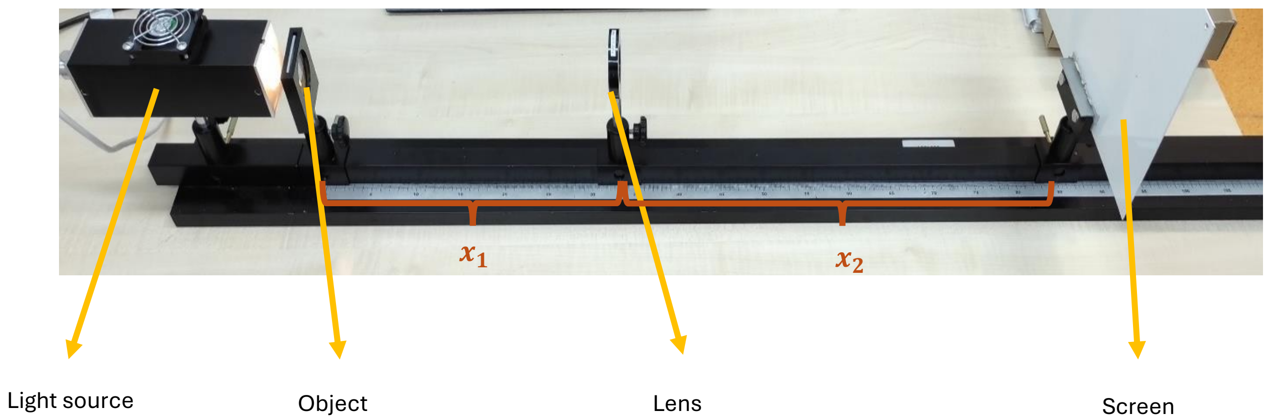

Figure 4: Experimental setup for the single-lens approach.

Virtual object method (two-lens method):

Since the single-lens approach requires the formation of a sharp image, and that can only be achieved using a converging lens, the single-lens method cannot be used to calculate the power of a diverging lens. To be able to measure the power of a diverging lens, we would have to use a two-lens setup in which the sum of refractive powers of both lenses is positive. This means that the diverging lens should be paired with a more powerful converging lens in order to enable the production of a sharp image on the screen and measurement of the lens-image distance necessary for the lens equation to be used.

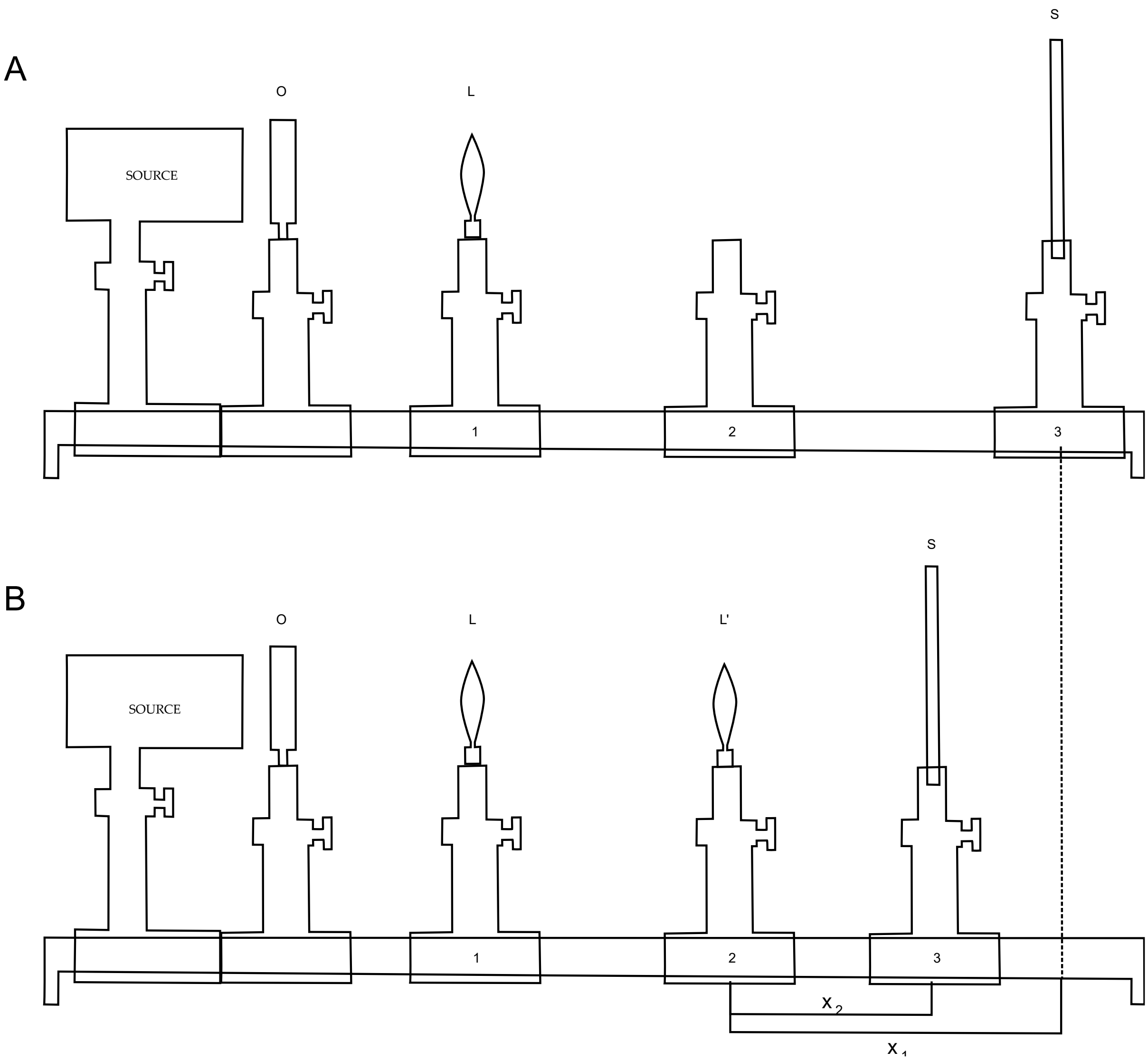

Figure 5: Measurement process using the virtual object approach. **A** The relative position of optical elements after finding a sharp image of the lens L. **B** The placement of elements after finding the image produced by the combined effect of lenses L and L′.

The measurement process is described in Figure 5. First repeat the same process like the one described in the single-lens approach in order to find a sharp image on the screen using just the lens L (Figure 5A). Then write down the position of the sharp image on the optical bench (dashed vertical line on Figure 5). This is the position of the virtual object for the second lens. Following that, place the second lens L′ in the holder 2 anywhere between the lens L and the screen S and measure x_1 as the distance from the lens L′ to the current screen position. The image on the screen should become blurred. Now move the screen holder until a sharp image reappears and measure x_2 as the distance from the lens L′ to the new screen position. Use the obtained measures to calculate the focal distance and power of the lens L′.

Tasks:

1. Take a lens with a focal length of 10 cm and determine the parameters from the table below once a sharp image of the object is found on the screen. Use the single-lens technique to calculate the focal distance.

2. Repeat the measurements using the same technique, but for a lens with a focal length of 20 cm.

3. Measure the same parameters as in the first task for a lens with a focal length of 10 cm, but this time using the virtual object method (two-lens method).

4. Compare the measurement values for a 10 cm lens using the single-lens and two-lens method. Which method is more reliable and why?

5. Comment on the similarity of the two-lens method with correcting for farsightedness.

6. What are the primary and secondary sources of error in the process of calculating the focal distances?

Measurements table:

Method	Image size	x_1	x_2	y_1	y_2	$\frac{x_2}{x_1}$	$\frac{y_2}{y_1}$	f (cm)	$\bar{f}$ (cm)	MAE f (cm)	j (dpt)	$\bar{j}$ (dpt)	MAE j (dpt)
Single-lens, f = 10 cm	Larger												
	Similar												
	Smaller												
Single-lens, f = 20 cm	Larger												
	Similar												
	Smaller												
Two-lens, f = 10 cm	Similar												
	Smaller												

Practical Exercise 4: Viscosity

Viscosity is a fundamental property of fluids that describes their resistance to deformation or flow under an applied force. It essentially measures the internal friction between fluid layers as they move past one another. In simple terms, viscosity can be thought of as the "thickness" or "stickiness" of a fluid. For example, honey has a higher viscosity than water, meaning it flows more slowly and resists motion more than water does.

Viscosity arises from the interactions between molecules within a fluid. When a force is applied to a fluid, such as when stirring a liquid or when it flows through a pipe, the molecules within the fluid move relative to each other. These molecular movements create internal frictional forces that resist the motion, giving rise to viscosity. The degree of this internal friction depends on several factors:

- Temperature: In general, as the temperature of a fluid increases, its viscosity decreases. This is because higher temperatures give molecules more kinetic energy, allowing them to move more freely and reducing internal friction.
- Molecular composition: The nature of the molecules and their interactions affect viscosity. Fluids with larger, more complex molecules tend to have higher viscosities.

Measuring viscosity using the Poiseuille equation and Ostwald viscometer:

The Poiseuille equation, describes the laminar flow of a viscous fluid through a cylindrical pipe. It is fundamental in fluid dynamics and provides a direct method for determining viscosity. The equation relates the volume of fluid (V) which flows through a cylindrical tube of radius r and length l during time t if the fluid has a viscosity η:

$$V = \frac{\pi r^4}{8\,\eta} \cdot \frac{\Delta p}{l} \cdot t$$

In this exercise, viscosity will be measured using the Ostwald viscometer (Figure 1) that consists of a U-shaped glass tube with two bulbs connected by a capillary tube. The fluid is drawn into the upper bulb and allowed to flow through the capillary under gravity. Three types of fluid will be used throughout the exercise: water, Coca-Cola and dextran. Dextran is a polysaccharide e composed of many glucose molecules. It is used in a variety of biomedical and research applications due to its viscosity and biocompatibility.

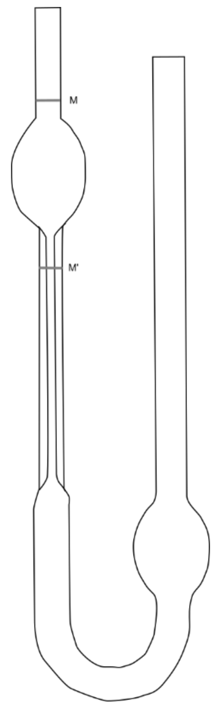

Figure 1: Ostwald viscometer.

If we wanted to measure the absolute value of the viscosity coefficient, we would need to know the values of all the parameters in the Poiseuille equation. To make things simpler, we will calculate relative viscosities of fluids compared to water. If we approximate the fluid densities to be approximately equal, and since the tube length and radius are always the same and an identical volume of fluid will always be used, all parameters except time will cancel each other. This leaves us with an intuitive expression showing that the higher the viscosity of a fluid, the longer it takes for that fluid to flow through the tube. Consequently,we can approximate the relative viscosity of a fluid compared to water to be:

$$\eta_{relative,fluid} = \frac{\eta_{fluid}}{\eta_{water}} \approx \frac{t_{fluid}}{t_{water}}$$

Measuring procedure:

1. Fill the viscometer with the fluid to be tested.

2. Draw the fluid into the upper bulb using suction.

3. Allow the fluid to flow freely through the capillary.

4. Measure the time it takes for the fluid to pass between two marked points M and M′ on Figure 1. Use the time to calculate the relative viscosity by dividing the obtained value with the mean value for water.

Tasks:

1. Conduct three measurements for the flow time of water. Average the measurements for water and calculate the corresponding uncertainty.
2. Conduct measurements for Coca-Cola. Use the average value of water to calculate the relative viscosity for each Coca-Cola measurement. Average the relative viscosities and calculate the uncertainty. After the Coca-Cola measurements, rinse the viscometer with water, followed by ethanol, and then again with water to remove traces of the fluid and prevent contamination for the next task with dextran.
3. Conduct measurements for different volume concentrations of dextran as shown in the table, and after all measurements are completed, plot the corresponding graph. Begin measurements from the lowest to the highest concentration. After measuring the last concentration, rinse the viscometer with water, followed by ethanol, and then again with water to remove traces of sugar and prevent clogging of the viscometer.

Measurements table:

Solution	t_1 (s)	t_2 (s)	t_3 (s)	Mean t	Mean η	MAE η
Water						
Coca-Cola						
Dextran 10%						
Dextran 30%						
Dextran 50%						
Dextran 70%						

Practical Exercise 5: Hemodynamics

During the systole, the heart pumps blood forcefully into the arteries, causing the arterial walls to expand. During exercise, the body demands more oxygen and nutrients, necessitating an increase in blood flow. To accommodate this, blood vessels, particularly in the muscle tissues, undergo vasodilation, which is the widening of the blood vessels. This vasodilation reduces the overall resistance within the peripheral vessels.

The goal of this exercise is to quantitatively demonstrate this effect using basic hemodynamic equations and certain approximations. Since vasodilatation is directly related to the increase in aortic volume, we start with the equation for aortic compliance $C = \frac{\Delta V}{\Delta P}$ which is the ratio of the systolic increase in aortic volume (ΔV) to the pulse pressure ($\Delta P = P_{systolic} - P_{diastolic} = P_s - P_d$). It follows that

$$\Delta V = C \cdot \Delta P \tag{1}$$

Aside from the above relationship(1), the systolic increase in aortic volume must also be proportional to the stroke volume (SV), so we can write $\Delta V = SV \cdot k$, where k is the proportionality constant approximately equal to 0.7. This value is lower than 1 for two reasons. Firstly, the aortic volume reaches its maximum value within the initial third of the systolic phase (during the rapid ejection phase) because the left ventricle expels most of its stroke volume (approximately 80%) during that time. Secondly, not all of that 80% actually contributes to an increase in the aortic volume because some of the ejected blood leaves the aorta and flows to more distant parts of the circulatory system. Since peripheral perfusion is approximately constant, we can assume that the amount of blood leaving the aorta is proportional to the duration of the fast ejection phase. Since the fast ejection phase is one third of the systolic phase, and the systolic phase lasts for one third of the total heart cycle, we conclude that the amount of blood contributing leaving the aorta during that time is $\frac{1}{3} \cdot \frac{1}{3} = \frac{1}{9}$ of the stroke volume. In other words, the fraction k of SV can be calculated by multiplying the fraction of SV

occurring during the rapid ejection phase with a corrective factor of $1 - \frac{1}{9} \approx 0.89$. Going back to the original equation, this yields

$$\Delta V = SV \cdot k = SV \cdot 0.8 \cdot 0.89 \approx SV \cdot 0.7 \tag{2}$$

Equalizing the equations (1) and (2) for ΔV, we get $C \cdot \Delta P = SV \cdot k$, so it follows that

$$\mathrm{SV} = \frac{C \cdot \Delta P}{k} \tag{3}$$

Unfortunately, this equation is not of much practical use because the values of both C and k change between different hemodynamic states (resting vs exercising), and C also displays a large interpersonal difference as it decreases with age. Luckily, both of them decrease during physical stress. The constant k decreases because the duration of the systole becomes a larger fraction of the total heart cycle and the volume expelled during the rapid ejection phase decreases as well. Aortic compliance C decreases with stress because of the greater contribution of harder-to-stretch collagen fibers at larger arterial pressures. This is where we introduce our approximation as the same direction of change during physical exercise allows us to **assume that the $\frac{C}{k}$ ratio will remain constant between two different hemodynamic states** even though their absolute values will certainly change. Consequently, taking the ratio of stroke volumes at two hemodynamic states (stress and rest), we get

$$\frac{SV_{stress}}{SV_{rest}} = \frac{\Delta P_{stress}}{\Delta P_{rest}} \tag{4}$$

Since cardiac output (CO) is the product of SV and heart rate (f), the above equation can also be written as

$$\frac{CO_{stress}}{CO_{rest}} = \frac{\Delta P_{stress}}{\Delta P_{rest}} \cdot \frac{f_{stress}}{f_{rest}} \tag{5}$$

Normally, measuring the SV and CO involves invasive procedures, but with the approximation used here, we were able to get information on those properties using only non-invasive measures such as the blood pressure and heart rate values.

Knowing that flow is a ratio of pressure an resistance (R), we can also relate CO to mean arterial pressure (P_a) so that

$$CO = \frac{P_a}{R} \tag{6}$$

Inserting equation (6) into equation (5) e, we obtain the following expression for the ratio of resistances in two hemodynamic states (rest and stress):

$$\frac{R_{stress}}{R_{rest}} = \frac{\Delta P_{rest}}{\Delta P_{stress}} \cdot \frac{f_{rest}}{f_{stress}} \cdot \frac{P_{a,stress}}{P_{a,rest}} \tag{7}$$

Notice that this equation contains a dependence on arterial pressure which can't be measured continuously using readily available equipment. **Fortunately, it can be approximated by calculating the weighted mean of systolic and diastolic pressure, where the weights are relative durations of each stage in a heart cycle.** The relative duration of the systole can be approximated as $\frac{1}{3}$ during rest, and $\frac{1}{2}$ during exercise. Using this approximation, we get the final equation for the resistance ratio:

$$\frac{R_{stress}}{R_{rest}} = \frac{P_{s,rest} - P_{d,rest}}{P_{s,stress} - P_{d,stress}} \cdot \frac{f_{rest}}{f_{stress}} \cdot \frac{\frac{1}{2} \cdot P_{s,stress} + \frac{1}{2} \cdot P_{d,stress}}{\frac{1}{3} \cdot P_{s,rest} + \frac{2}{3} \cdot P_{d,rest}} \tag{8}$$

Tasks:

1. Measure the systolic and diastolic blood pressure and heart rate at rest. To calculate the frequency of heart beats per minute, measure the number of beats in 30 seconds and multiply it by 2. Measure the systolic and diastolic pressure using a stethoscope and a sphygmomanometer. Instructions on how to measure the blood pressure and heart rate can be found at the following links: blood pressure measurement, heart rate

measurement. The heart rate is measured by the student performing the exercise, and the blood pressure is measured by the other student. For adequate precision, the measurements should be performed as fast as possible following the exercise. Consequently, the heart rate and blood pressure measurements should be taken simultaneously.

2. Repeat the measurements after exercising for 30 seconds by running in place and lifting your knees to a 90-degree angle at a frequency of about 3 "steps" per second. To measure the heart rate after exercising, record the number of heart beats during 10 seconds and multiply that number with 6.

3. If you are performing the exercise by yourself, wait for long enough so that your heart rate and blood pressure return to their basal values and then perform the resting measurements again followed by the exercise measurements.

If the exercise is performed in pairs of two as intended, while waiting for the hemodynamic parameters to return to normal for the first student, perform the resting and exercise measurements on the second student.

4. After both students have performed two sets of rest-exercise measurements, perform two more sets in the same manner but with a tougher exercise where you should again run in place for 30 seconds lifting your knees to a 90-degree angle, but now at a frequency of about 6 "steps" per second.

5. Comment on the differences in peripheral resistances with respect to the level of exercise and the differences between students for the same exercise levels. What are the possible sources of error?

Measurements table:

Exercise	Student	Measurement	State	f $\left(\frac{\text{beats}}{\text{min}}\right)$	P_s (mmHg)	P_d (mmHg)	$\frac{R_{stress}}{R_{rest}}$	Mean $\frac{R_{stress}}{R_{rest}}$	MAE $\frac{R_{stress}}{R_{rest}}$
3 steps per second	1	1	Rest						
			Exercise						
		2	Rest						
			Exercise						
	2	1	Rest						
			Exercise						
		2	Rest						
			Exercise						
6 steps per second	1	1	Rest						
			Exercise						
		2	Rest						
			Exercise						
	2	1	Rest						
			Exercise						
		2	Rest						
			Exercise						