

Mechanical Waves: Applications in Medicine

Purpose

This lesson is meant to increase students' understanding of mechanical waves and provide them with examples of medical applications of mechanical waves.

Audience

This lesson is designed for use in an introductory high school physics class.

Lesson Objectives

Upon completion of this lesson, students will be able to:

- explain the relationship between a mechanical wave's speed and the medium through which it is traveling.
- calculate wave speed given frequency and wavelength.
- describe medical applications of mechanical waves.

Key Words

elasticity, elastography, fibrosis, palpation, shear wave

Big Question

This lesson addresses the Big Question “*What does it mean to observe?*”

Standard Alignments

- **Science and Engineering Practices**
 - **SP2.** Developing and using models
 - **SP5.** Using mathematics and computational thinking
 - **SP8.** Obtaining, evaluating, and communicating information
- **MA Science and Technology/Engineering Standards (2016)**
 - **HS-PS4-1.** Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling within various media. Recognize that electromagnetic waves can travel through empty space (without a medium) as compared to mechanical waves that require a medium.
 - **HS-PS4-5.** Communicate technical information about how some technological devices

use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.

◉◉ NGSS Standards (2013)

- ◉◉ **HS-PS-4-1.** Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media.
- ◉◉ **HS-PS4-5.** Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.

◉◉ Common Core Math/Language Arts Standards

CCSS.ELA-LITERACY.RST.9-10.1. Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.

Misconceptions Addressed

This lesson addresses some common misconceptions about waves, including:

- ◉◉ Mechanical waves do not need a medium to travel through. (Question 6)
- ◉◉ The frequency of mechanical waves changes based on the properties of the material the wave travels through. (Question 11)

Primary Sources

- ◉◉ **Bite** "[Making Waves to Detect Illness](#)" based on:
 - ◉◉ Dhyani, Manish, Joseph Grajo, Atul K. Bhan, and Anthony E. Samir. 2017. "[Validation of Shear Wave Elastography Cutoff Values on the Supersonic Aixplorer for Practical Clinical Use in Liver Fibrosis Staging](#)." *Ultrasound in Medicine and Biology* 43(6): 1125–1133.
 - ◉◉ Parker, Kevin J., Marvin M. Doyley, and Deborah J. Rubens. 2010. "[Imaging the elastic properties of tissue: The 20 year perspective](#)." *Physics in Medicine and Biology* 56(1):R1.
- ◉◉ **Additional information provided by**

Mariappan, Yogesh, Kevin Glaser, and Richard Ehman. 2010. "[Magnetic Resonance Elastography: A Review](#)." *Clinical Anatomy* 23(5): 497–511. <http://doi.org/10.1002/ca.21006>

Materials

- ◉◉ Copies of the Student Handout and Science Bite for each student
- ◉◉ Means to show liver images and soccer ball video

Time












This lesson should take approximately one 50-minute class period.

Student Prior Knowledge

It would be helpful if students have learned about properties of mechanical waves and waves in general (period, frequency, amplitude, and speed).

Instructions and Teacher Tips

General Procedure

-  Project the slow motion video of a man being hit in the face by a soccer ball (<https://www.youtube.com/watch?v=On1CsbTwIDs>). You can show the entire video or just from 3:43 to 4:25 to show the wave pulse that travels through the man's face when he is hit.
-  Ask students to describe what they notice about the man's facial tissue in the moments after he is hit with the soccer ball. Students should see that his face is contorted. They may note that it looks like a wave is traveling through his face. If they don't, you may mention before giving students the student document.
-  Provide each student with a copy of the student document. Have students read through the introduction and answer Questions 1–2.
-  Review student responses for Questions 1–2 with the class.
-  Have students read the Bite and respond to Questions 3–12.
-  Project Figure 7 from "Magnetic Resonance Elastography: A Review."
 -  Paper: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3066083/>
 -  Direct Link to Figure: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3066083/figure/F7/>
-  Help students develop an understanding of the image.
 -  Tell students that the rows show images of the same liver (two different livers) and the columns show images using the same technique. The first column of images (a and d) shows images of livers taken using traditional MRI techniques and the second column (b and e) shows images taken using magnetic resonance elastography (MRE). Images c and f show stiffness estimates of the livers based on the elastography data. Ask students to describe what they see in the images. The livers look nearly identical in images a and d, but the differences become clear with the elastography data.
 -  Tell students that another way researchers look at elastography data is to measure the shear modulus (an indication of rigidity) in kPa. The higher the kPa of a substance, the more rigid it is. Ask students if they can use this information to determine which liver is fibrotic (the bottom liver is fibrotic, there is a large area of highly rigid tissue due to liver cirrhosis).

◉◉ Tips, Extensions, and Variations

- ◉◉ As an exploration before the lesson, you can have students observe the properties of tuning forks. Have students gently hit the tines of the tuning forks with rubber mallets and ask them to describe what happens when they touch the tines and what it feels like when they do. You can also have students place a vibrating tuning fork in water to observe what happens. Students should realize that the tuning fork is vibrating. This will help them make the connection that mechanical waves are due to the disturbance of some medium. If you wish to talk more about sound, you can describe how the tuning fork causes the air molecules to vibrate. The vibrations in the air cause the bones in the middle ear to vibrate. Sensory neurons are stimulated by the vibrations and pass the signals to the brain, which interprets the information as sounds.
- ◉◉ To shorten the lesson, you can skip showing the students the images of the two livers from “Magnetic Resonance Elastography: A review” at the end of the lesson.
- ◉◉ Many students have the misconception that the frequency of a wave changes and not the wave’s speed when it goes through different media. This lesson drives home the point that the frequency of a wave doesn’t change, but its speed does as it moves through materials with different properties. Take the time to emphasize this point: As a liver gets stiffer, the wave is able to travel more quickly, but the frequency of the wave does not change.
- ◉◉ You may wish to show this video about magnetic resonance elastography from the Mayo Clinic before you have students analyze the images from “Magnetic Resonance Elastography: A review”: https://www.youtube.com/watch?v=CcmZi0J_u3Y

🧑‍🔬 Background Information and Research Details

- ◉◉ In addition to diagnosing liver fibrosis, elastography is being used for the assessment of breast cancer. Elastography has been shown to increase doctor’s ability to distinguish cancerous tumors from harmless lumps. This is important because 8 out of 10 lumps found in breasts are not cancerous and over diagnosis leads to unnecessary biopsies.
- ◉◉ Elastography also has the advantage that it allows a physician to measure and track changes in the tissue over time. For example, in patients with liver disease, monitoring the elasticity of liver tissue can help doctors track the progression of the disease and determine the effectiveness of treatment.
- ◉◉ The speed of mechanical waves is closely tied to the medium’s elasticity and density. As the rigidity of a substance increases the speed at which mechanical waves travel through it increases. A material that is more rigid has particles that will return to their original position faster than a material that is more flexible. If the particles return to their original position faster, they are then able to move again faster. It is this property that allows these materials to vibrate quicker. On the other hand, as the density of a substance increases, the speed at which mechanical waves travel through it decreases. The elastic properties of a substance tend to have a greater effect on mechanical waves speed and therefore even very dense materials like gold allow mechanical waves to travel inside of them much more quickly than

less dense materials like air.

Big Question Discussion

This lesson addresses the Big Question “*What does it mean to observe?*” Specifically, students should come to understand that observations are not limited to just things we experience with our five senses. It is important to take multiple observations of something as someone’s life might depend on repeatable observations. If you choose to delve into the Big Question, consider the following ideas:

- When showing the initial video of the person getting hit in the face with a soccer ball, note how viewing that in high speed allowed us to see the wave pulse traveling through his facial tissue. If we did not have that technology, we would not be able to make those observations.
- When discussing the MRI and elastography images of the two different livers, why some observations are more useful than others in certain situations.
- After students have completed the activity or if they are struggling with the last question, prompt them with questions such as:
 - What information does palpation provide? How can elastography provide similar information? Which one more directly involves one of our five senses?
 - What advantages does elastography have over palpation?
 - How do doctors use observations to diagnose patients? What limitations do these observations have?

Answers

1. Define *elasticity* in your own words. Give an example of a solid with high elasticity that is not mentioned in the introductory text.

Sample answer: Elasticity is a measure of how well a material bounces back after being deformed. The egg white of a cooked egg or a piece of Spandex fabric is another example of a material that has high elasticity.

2. What is palpation and why do doctors use it? What are the limits of palpation as a diagnostic technique?

Palpation involves physically touching a person’s tissue in order to assess its elasticity. Doctors perform palpation to assess the health of a tissue or organ. You normally can’t or don’t want to use palpation on internal organs as that would endanger the patient. Palpation is also not precise.

 & read  **Science Bite:** [Making Waves to Detect Illness](#)

3. Describe elastography in your own words. What are some advantages of elastography over other types of medical diagnosis procedures such as ultrasound or a biopsy? Cite specific

evidence from the text to support your answer.

Elastography is the study of how elastic a substance is. Elastography is less invasive and safer than other types of procedures such as biopsies. As noted in the text, biopsy can lead to internal bleeding which puts the life of the patient in danger. By using elastography a doctor can avoid those complications. Additionally, elastography can also reveal information that other procedures like ultrasound and MRI can't.

4. A shear wave does not just travel on the surface of an object, but travels through the entire body of the object. Why do you think shear waves are used to study body tissues instead of waves that just exist on the surface of an object? Explain your answer.

Shear waves are used to study body tissues instead of waves that just exist on the surface, because if you only gather information about the surface of an organ you aren't capturing information about the entire organ. The organ could have a cancerous growth on the inside and you wouldn't know it if you only tested the surface of the organ.

There are four types of seismic waves, the waves responsible for earthquakes. Diagrams of each type of wave are shown in **Figure 1** below.

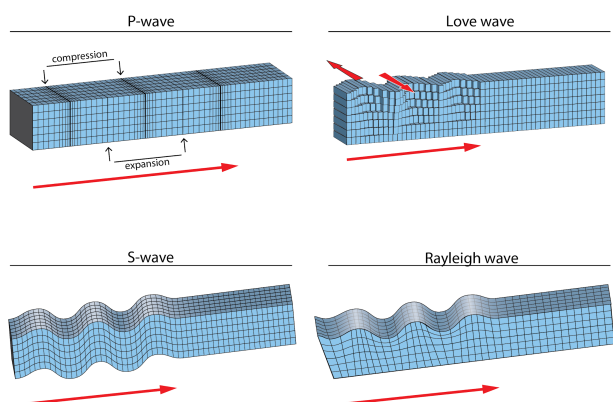


Figure 1. The Four Main Types of Seismic Waves. Two types of seismic waves, s-waves and p-waves, travel through Earth while Love waves and Rayleigh waves travel along Earth's surface. S-waves and p-waves travel faster than Love and Rayleigh waves, but Love and Rayleigh waves tend to do the most damage to structures.

5. Examine the wave diagrams in **Figure 1**.

- a. Which type or types of seismic waves are transverse? Justify your response with evidence from **Figure 1**.

S-waves, Love waves, and Rayleigh waves are all transverse waves. As shown in Figure 1, for each of these types of seismic waves, the direction particles in the medium move is perpendicular to the direction the wave is propagating.

- b. Which type or types of seismic waves are longitudinal? Justify your response with evidence from **Figure 1**.

P-waves are longitudinal waves. As shown in Figure 1, the direction particles in the medium move is parallel to the direction the p-wave is propagating.

- c. Which type of seismic wave is most similar to the shear waves used in elastography? Justify your answer with evidence from **Figure 1** and the Science Bite.

As noted in the Science Bite, shear waves are transverse waves and they travel through both the inner and outer parts of the objects. These properties most closely match the s-waves shown in Figure 1. The s-waves are also transverse (the particles in the medium move perpendicular to the direction the wave moves) and they travel through the body of the Earth, not just the Earth's surface.

6. As noted in the introduction, the waves used in elastography are mechanical waves. What property or properties of the waves used in elastography makes them mechanical waves?

A mechanical wave is one that requires a medium to travel through. The waves used in elastography require a medium, such as a patient's liver, to travel through.

7. In your own words, describe how shear wave elastography (SWE) data is collected.

First, you create a shear wave inside of a patient by shaking the organ or tissue you are interested in. Then you take pictures of the organ very quickly using some other technology like ultrasound or MRI. Finally, you use those images to determine the speed or length of the wave.

8. What do researchers look for when they are diagnosing liver fibrosis using SWE? Why do they look for this?

Researchers look for higher wave speeds when they are diagnosing liver fibrosis. They look for these higher wave speeds, because that is an indication of stiffer tissue and as a liver becomes fibrotic it gets stiffer.

9. How did the researchers assess the validity of SWE as compared to liver biopsy? Cite specific evidence from the text to support your answer.

As described in the text, the researchers performed both SWE and a liver biopsy on over 300 patients. They compared having a 2.7 m/s wave speed in a patient's liver to the results of a liver biopsy. They found that 95% of the time when a patient's liver has a wave speed of 2.7 m/s or above, the liver biopsy also indicated that the liver was highly fibrotic.

10. Analyze the data in **Table 1** to answer the following questions.

- a. Determine the wave speed for each of the wavelengths provided. Show all work and include units in your answer.

$$\text{Trial 1: } v = \lambda f = 0.0468 \text{ m} \times 60 \text{ Hz} = 2.87 \text{ m/s}$$

$$\text{Trial 2: } v = \lambda f = 0.0476 \text{ m} \times 60 \text{ Hz} = 2.86 \text{ m/s}$$

$$\text{Trial 3: } v = \lambda f = 0.0442 \text{ m} \times 60 \text{ Hz} = 2.65 \text{ m/s}$$

$$\text{Trial 4: } v = \lambda f = 0.0421 \text{ m} \times 60 \text{ Hz} = 2.53 \text{ m/s}$$

$$\text{Trial 5: } v = \lambda f = 0.0456 \text{ m} \times 60 \text{ Hz} = 2.80 \text{ m/s}$$

- b. Based on your minimum wave speed value, does the patient have severe liver fibrosis? Explain your answer.

No, my minimum value is 2.53 m/s and the cut-off value for severe liver fibrosis is 2.7 m/s, so this value would indicate that the patient does not have severe liver fibrosis.

- c. Take the average of your wave speed values. Based on that information does the patient have severe liver fibrosis? Explain.

$$\frac{2.87 \text{ m/s} + 2.86 \text{ m/s} + 2.65 \text{ m/s} + 2.53 \text{ m/s} + 2.80 \text{ m/s}}{5} = 2.74 \text{ m/s}$$

Yes, based on the average wave speed, the patient does have severe liver fibrosis, because the average is higher than the cut-off value of 2.7 m/s.

- d. Determine the median of your wave speed values. Based on that information does the patient have severe liver fibrosis? Explain.

The median wave speed value is 2.80 m/s. Based on this value, the patient does have severe liver fibrosis as this value is higher than the cut-off value of 2.7 m/s.

- e. Do you think the patient has severe liver fibrosis? Provide evidence and reasoning for your claim.

Yes, I do think the patient has severe liver fibrosis, because three of the experimental values are above the cut-off value for severe liver fibrosis and the mean and median are also above the cut-off value. Even though there are two experimental values below the cut-off value the evidence points to the patient having severe liver fibrosis.

- f. Typically, when conducting an elastography analysis of someone's liver, the technician will take at least ten different readings in up to three different locations on the body. Why do the results shown above demonstrate the importance of taking multiple trials when conducting an experiment, especially one used in diagnosis?

Trials 3 and 4 have wave speed values lower than the cut-off value for severe liver fibrosis, but the rest of the trials indicate that the patient has severe liver fibrosis. If Trial 3 or 4 was the only measurement the technician took, they might wrongly diagnose the patient as not having severe liver fibrosis. When we are thinking about someone's health it is important to do everything we can to make an accurate diagnosis as it can have a large impact on their life.

The study described in the Bite investigated the average speed of the shear wave in patients with varying levels of liver fibrosis, shown in the table below.


Least Fibrotic  Most Fibrotic				
1.52 m/s	1.60 m/s	1.79 m/s	2.16 m/s	2.81 m/s

Table 2. Average Shear Wave Speed in Livers with Different Levels of Fibrosis.

Source: Dhyani et. al. 2017.

11. Examine Table 2 above.

- a. Describe the trend in wave speed as the severity of liver fibrosis increases. Why does that make sense? Cite specific evidence from the introduction and Bite.

As the level of fibrosis increases, so does the wave speed. This makes sense, because in the introduction we were told that as the stiffness of a material increases, so does the speed of a mechanical wave in that material. In the Bite we are told that fibrosis is the hardening of the liver, so as you have more fibrosis your liver is getting stiffer. Therefore as the severity of the fibrosis increases so should the shear wave speed.

Suppose researchers used the Fibroscan to collect the data shown in **Table 2**.

- b. What would be the average wavelength of the shear wave in the least fibrotic livers?

$$\lambda = \frac{v}{f} = \frac{1.52 \text{ m/s}}{50 \text{ Hz}} = 0.0304 \text{ m}$$

- c. What would be the average wavelength of the shear wave in the most fibrotic livers?

$$\lambda = \frac{v}{f} = \frac{2.81 \text{ m/s}}{50 \text{ Hz}} = 0.0562 \text{ m}$$

- d. What is the relationship between wavelength and wave speed? Why does that make sense based on the equation for wave speed?

As wave speed increases, so does wavelength if frequency is kept the same. That makes sense, because the equation for wave speed shows that wavelength and wave speed are directly proportional.

- 12. Connect to the Big Question** In this lesson, we learned how scientists use their observations to determine if someone is ill. Compare and contrast the different types of observations you learned about in this lesson. How does this change your personal definition of “observe”? What types of observations should doctors rely more on? Why do you think so?

Sample answer: There are specific types of observations doctors use in order to diagnose a patient. These observations can be invasive, like a biopsy or minimally so like using elastography. They can also be fairly complex like ultrasound or MRI or something as simple as feeling a tissue for differences in tissue stiffness. Often, we think of observations as just things we see, but there is so much more to observations than just what we can perceive with our eyes. We need to use the multitude of information available to us in order to make decisions. I think doctors should use observations that reliably diagnose a patient as determining if a patient is actually sick or not and what illness they have is of the utmost importance when treating them. Where possible, doctors should use observations that are minimally invasive as to minimize injury and discomfort for patients.