Wavelet transform based decomposition of ultrasound signals for cortical bone model evaluation

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Outline

- Motivation
- Bone structure
- Current state-of-the-art
- Methodology
- Bone models
- Axial scanner
- Signal decomposition
- Acquired bone model parameters
- Results
- Conclusion

Motivation

- Fragility-related fractures have surged;
- By 2050, the global population aged 60 and above is expected to reach 2.1 billion, compared to 901 million in 2015;
- Precise bone evaluation is crucial to meet this growing demand.

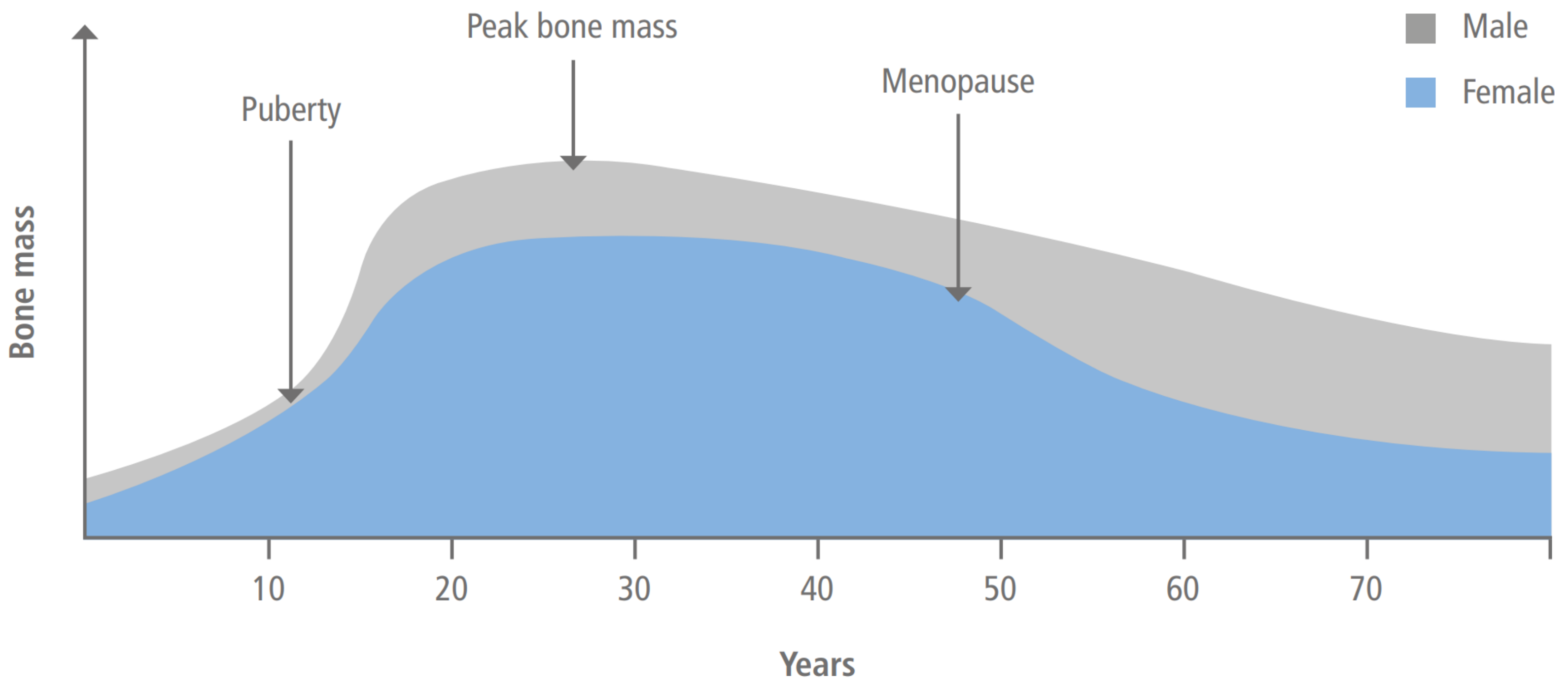

Figure 1: Bone mass throughout the life cycle [1]

Bone structure

- Long bones consist of:
  - Cortical bone;
  - Trabecular bone;
  - Bone marrow.

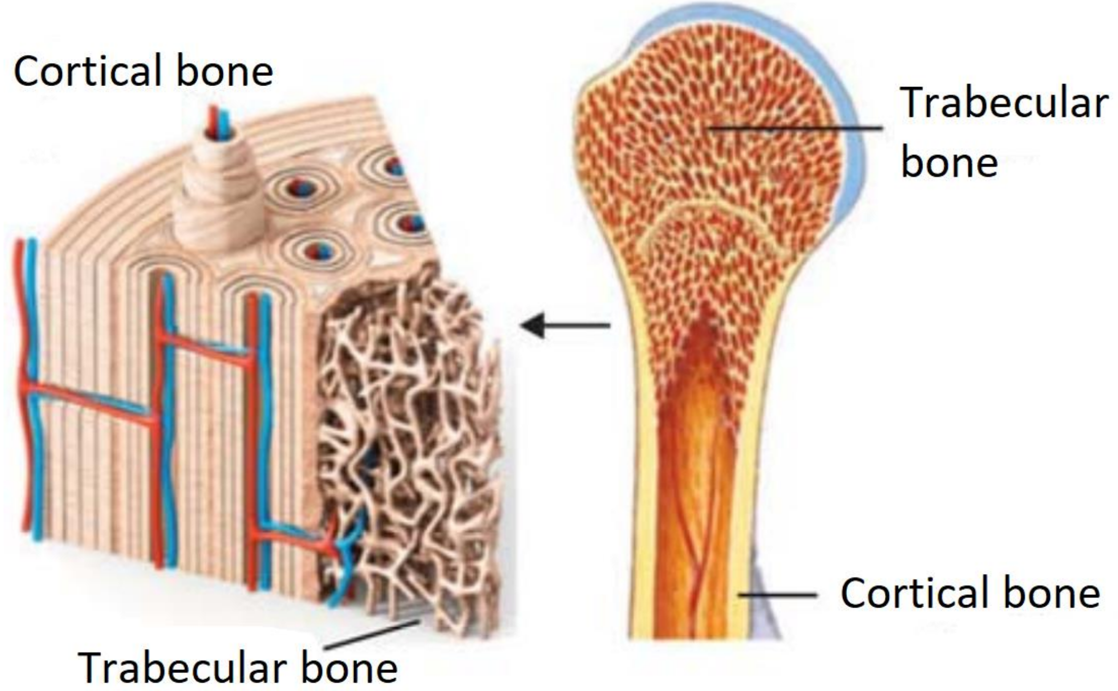

Figure 2: Bone macrostructure [2]

Current state-of-the-art

- Dual-energy X-ray absorption (DXA);
- Quantitative computed tomography (QCT);
- Downsides of: ionizing radiation, expensive;
- More research is needed to better evaluate with ultrasound diagnostics;
- Frequency spectrum analysis to create dispersion graphs.

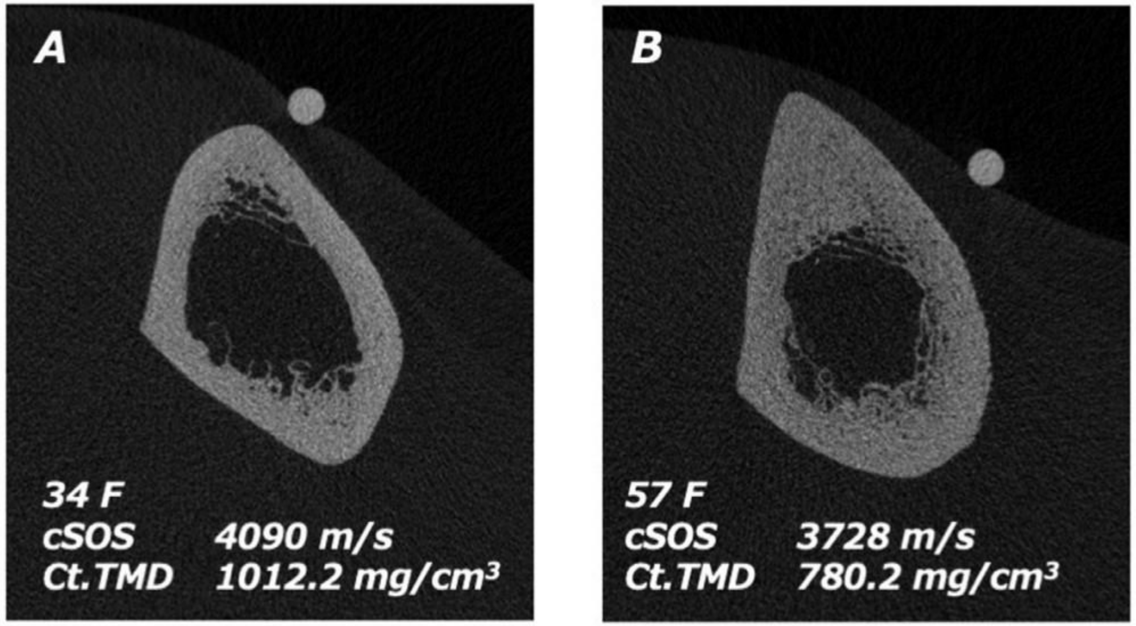

Figure 3: High resolution QCT 2D images, A- adult female, 34 year old, B – older female, 57 year old. Ct. TMD – cortical bone bone mineral density [2] cSOS – cortical speed of sound

Methodology

- **BM development:** Creation of cortical BM, which included an additional layer of soft tissue (STL), effectively simulating human soft tissue;
- **Scanning of BM**: BM surfaces underwent scanning using a custom-developed device that transmitted ultrasound signals through them;
- **Signal processing:** Signals underwent various processing steps;
- **BM parameter extraction**: Processed signals were then leveraged for parameter extraction related to the characteristics of the BM.

Modeling of osteoporosis

- Use of cortical bone models (BM) with parameters:
  - cortical thickness (CTh);
  - porosity thickness (PT) of BM.

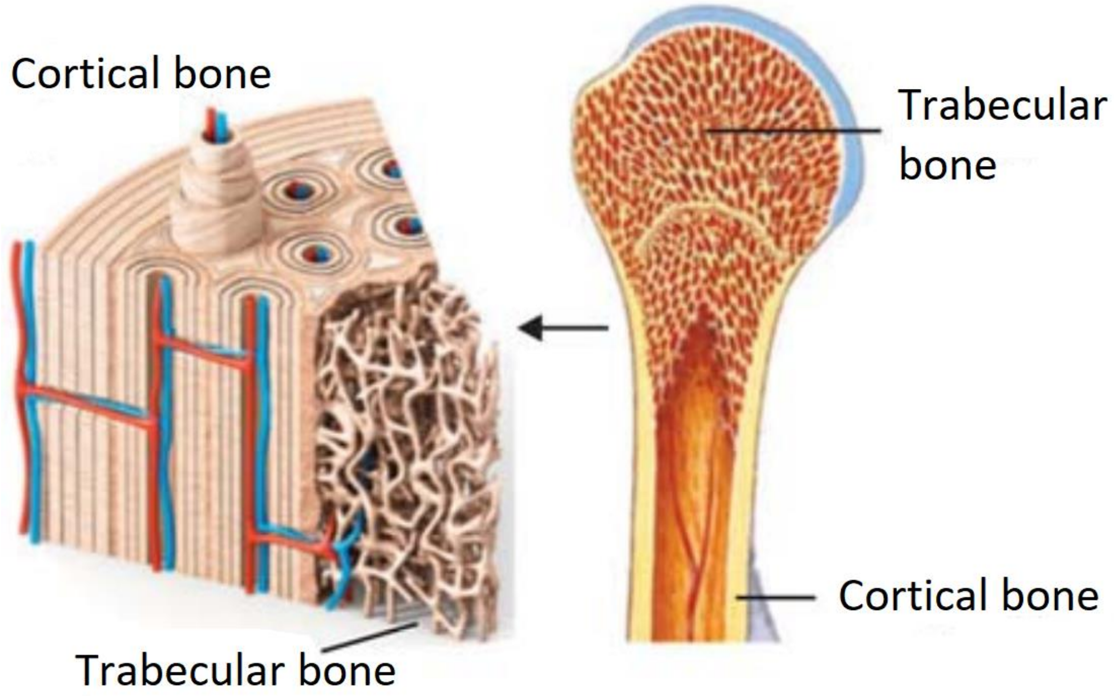

Figure 2: Bone macrostructure [2]

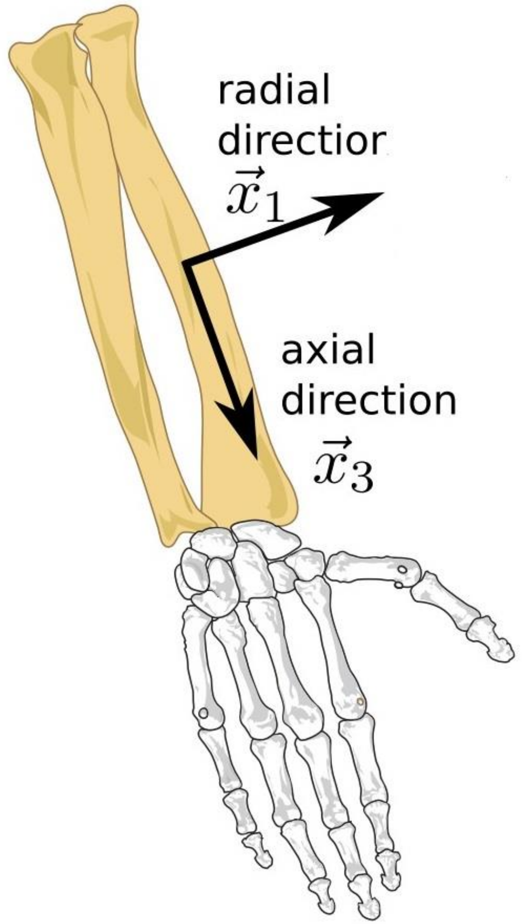

Figure 4: Axial and radial direction vectors [3]

Models of cortical bone and soft tissue

- Polymethyl methacrylate (PMMA):
  - high speed of sound (2750 m/s);
  - high hardness;
- Dense part consisting of PMMA and a porous part;
- Osteoporosis simulation by modification of two parameters (CTh and PT).

BM thickness, mm	2	3	4	5	6
Dense part:porous part ($mm : mm$)	2:0	3:0	4:0	5:0	6:0
	1:1	2:1	3:1	4:1	5:1
	0:2	1:2	2:2	3:2	4:2
		0:3	1:3	2:3	3:3
			0:4	1:4	2:4
				0:5	1:5
					0:6

Table 1: Cortical bone model classification table

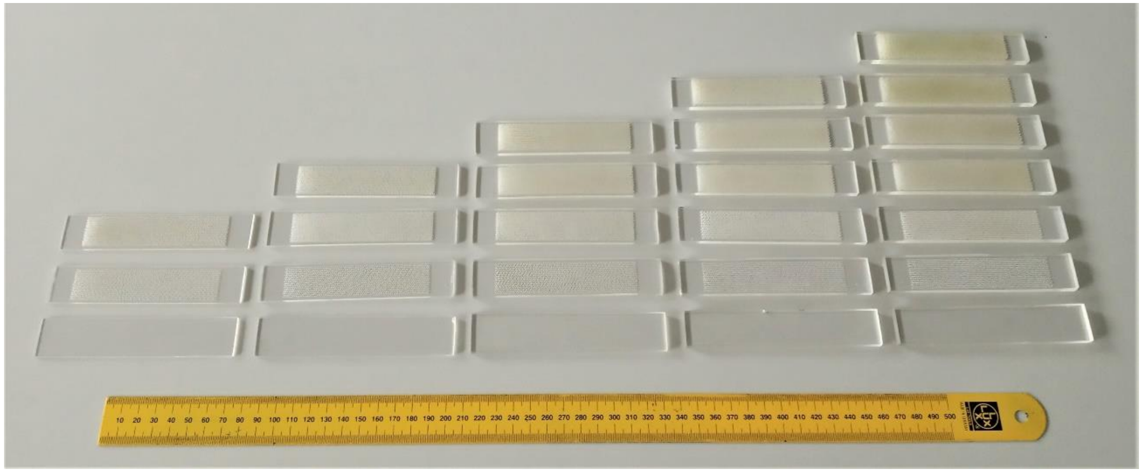

Figure 5:Bone model samples

Axial scanning

- Custom-made surface scanner;
- Stationary transducer and a receiver that is incrementally moved;
- Chirp signal with a frequency sweep ranging from 50 kHz to 500 kHz.

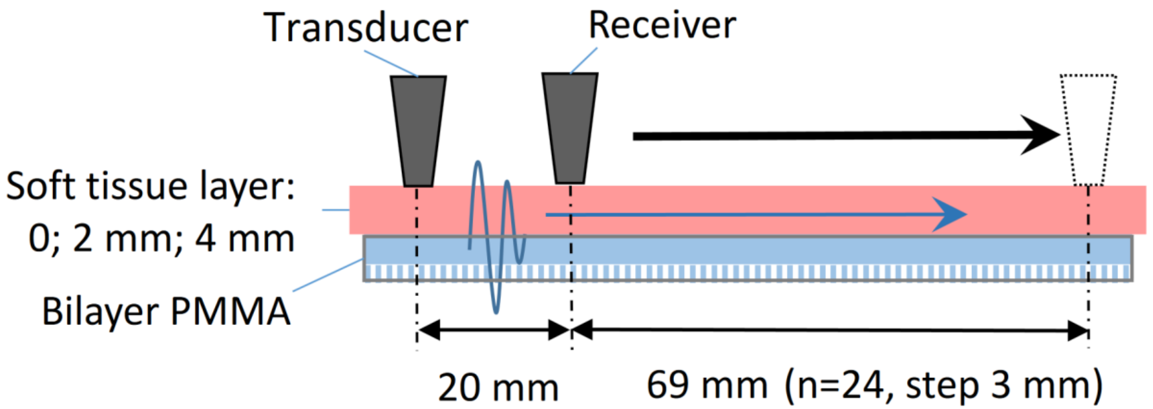

Figure 6: Diagram of axial scanning (*AS) methodology*

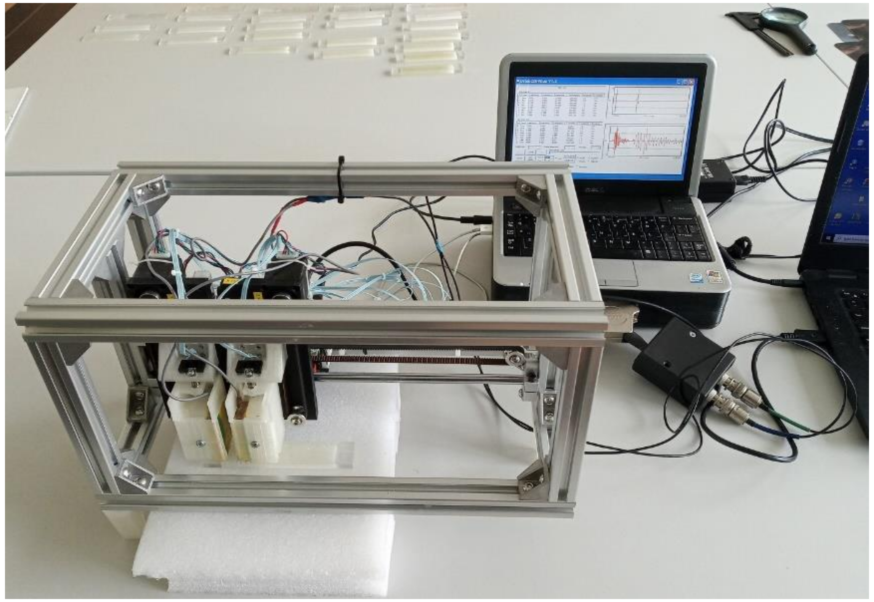

Figure 7: Developed AS device

Signal decomposition with wavelet transform

- gaus3 wavelet for signal processing;
- Analysis of frequency range 50 – 500 kHz;
- Two distinct patterns: at 60 and 300 kHz.

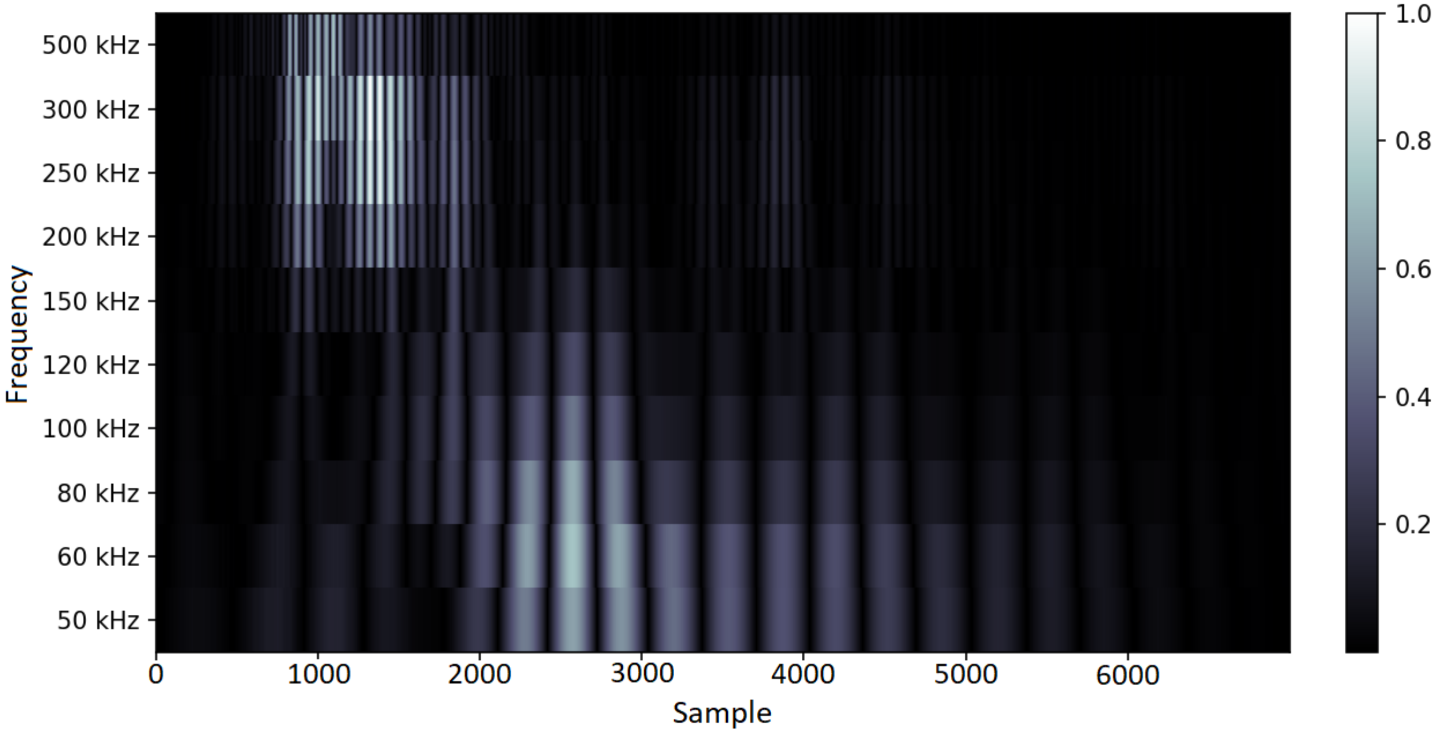

Figure 8: Spectrogram of decomposed received chirp signal for BM with a CTh of 2 mm, no porosity, and without STL

Axial scanning

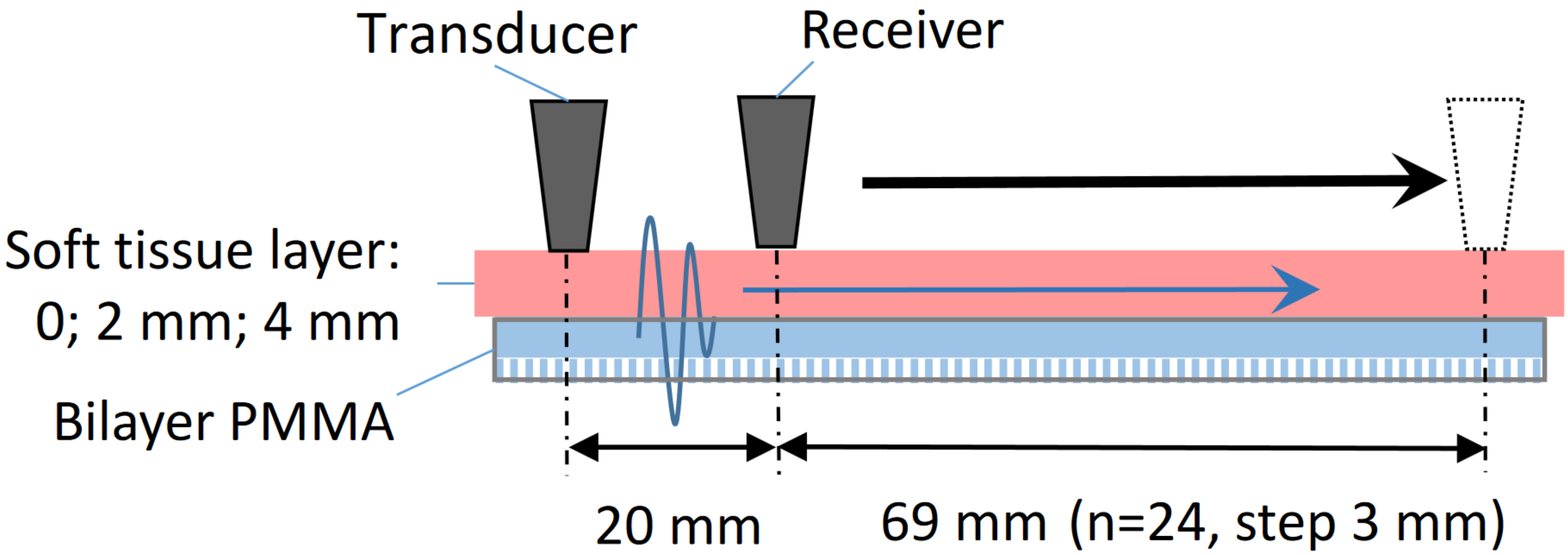

Figure 6: Diagram of axial scanning *(AS) methodology*

Cortical speed of sound

- The calculation of cSOS involves drawing a wave propagation line;
- To compute cSOS, we used formula:

$$cSOS = \frac{\Delta d}{\Delta t}$$

where Δd - the difference between the closest and farthest transducer-receiver positions and Δt - the time difference to receive the transducer signal when the transducer and receiver are at their closest and farthest positions

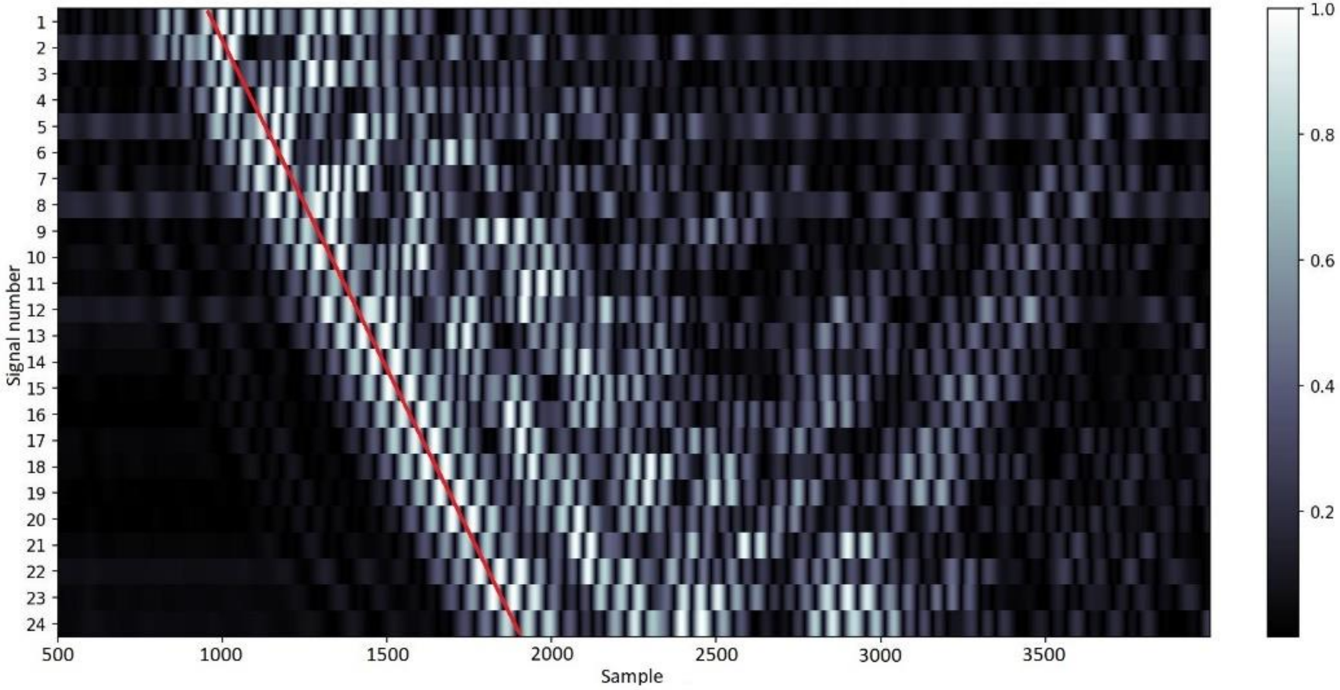

Figure 9: Spatiotemporal image of BM with a CTh of 2 mm, no porosity, and STL of 2 mm. Used gaus3 wavelet with a 300 kHz frequency. The red line represents cSOS. Each signal is normalized to a range from 0 to 1, facilitating the identification of signal maximum and minimum values.

Cumulative magnitude sum

- Bone model (BM) parameters will influence energy dissipation within BM;
- Cumulative magnitude sum (CMS) of all signals in a 2D matrix X:

$$CMS = \|X\|_1$$

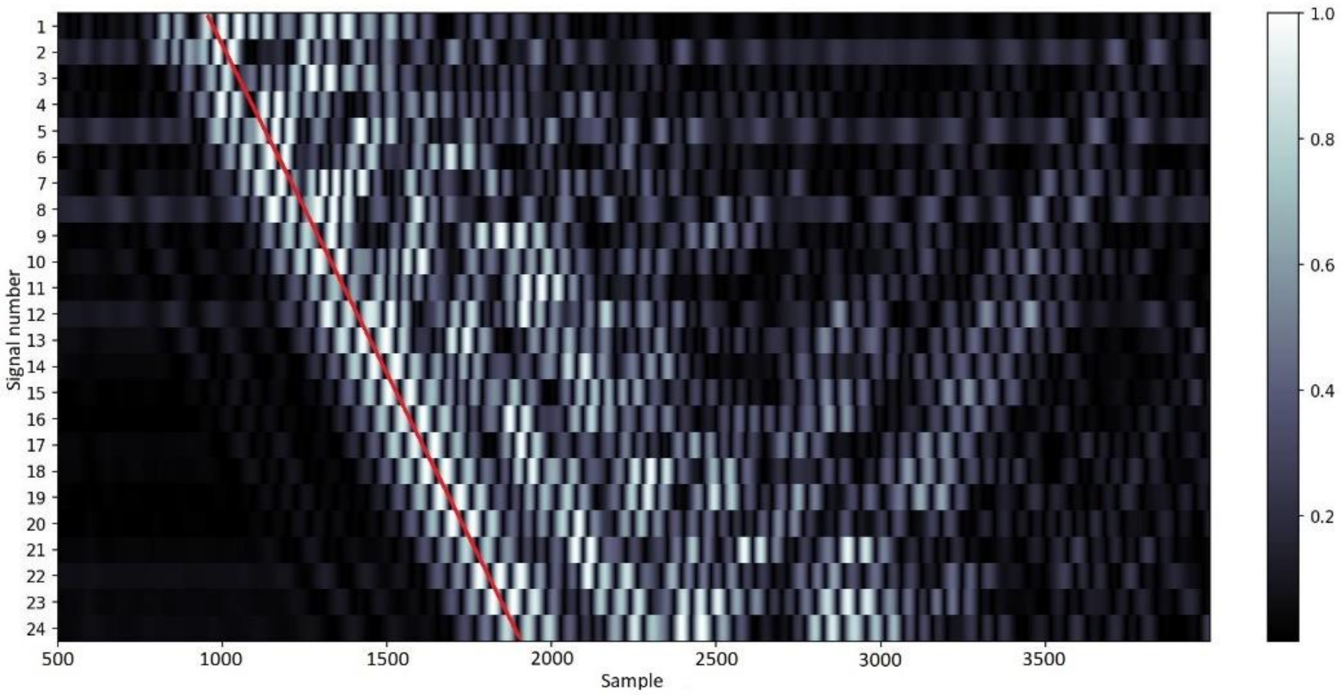

Figure 10: Spatiotemporal image of BM with a CTh of 2 mm, no porosity, and STL of 2 mm. Used gaus3 wavelet with a 300 kHz frequency. The red line represents cSOS. Each signal is normalized to a range from 0 to 1, facilitating the identification of signal maximum and minimum values.

cSOS results

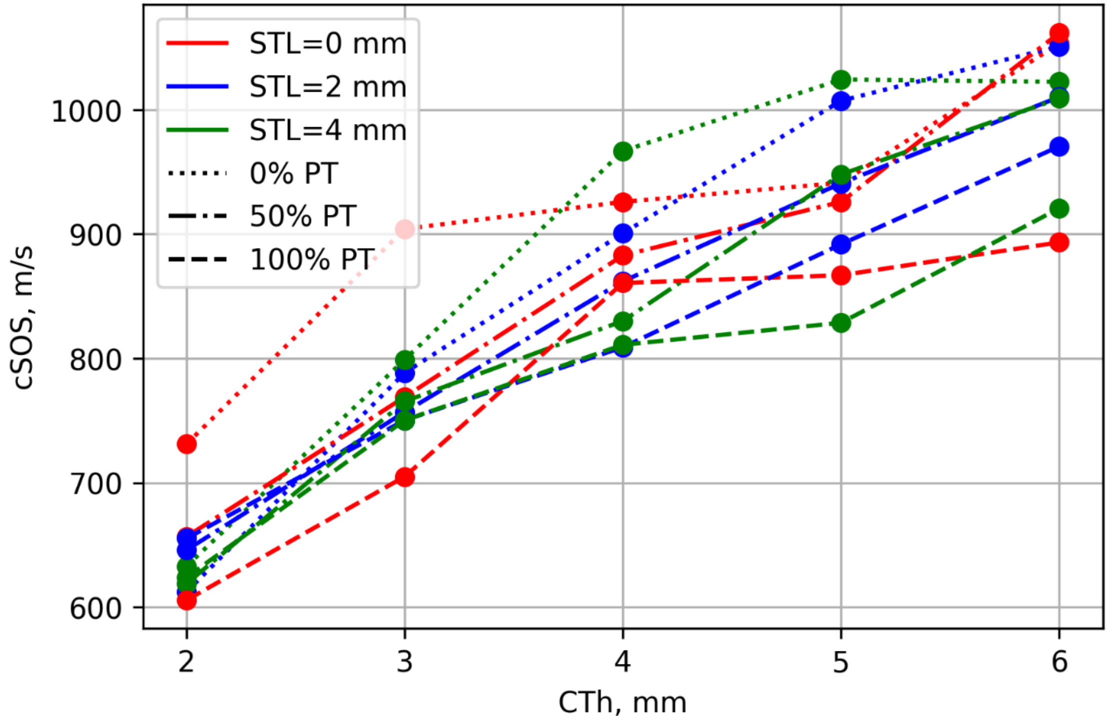

Figure 11: cSOS with varying BM cortical thickness (CTh). PT as a percentage of bone model thickness. The cSOS calculations were performed using a 60 kHz continuous wavelet transform (CWT) frequency.

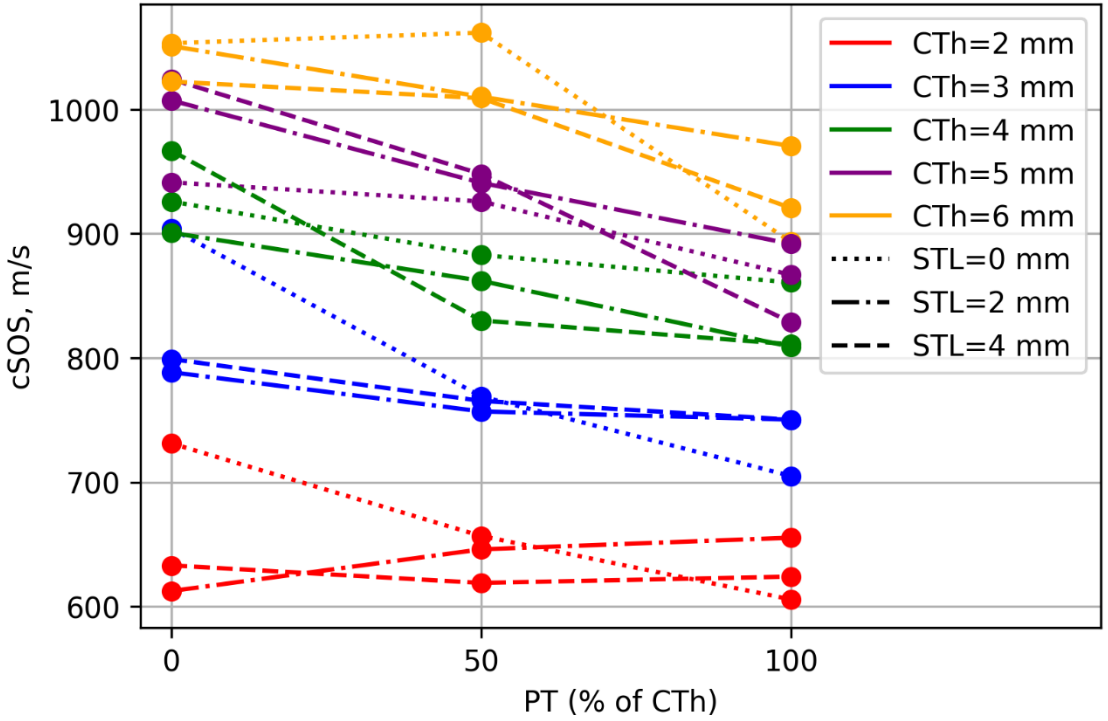

Figure 12: cSOS in BM with varying porosity thickness (PT), considering different STL thicknesses (0 mm, 2 mm and 4 mm). The cSOS calculations were performed using a 60 kHz continuous wavelet transform (CWT) frequency.

CMS results

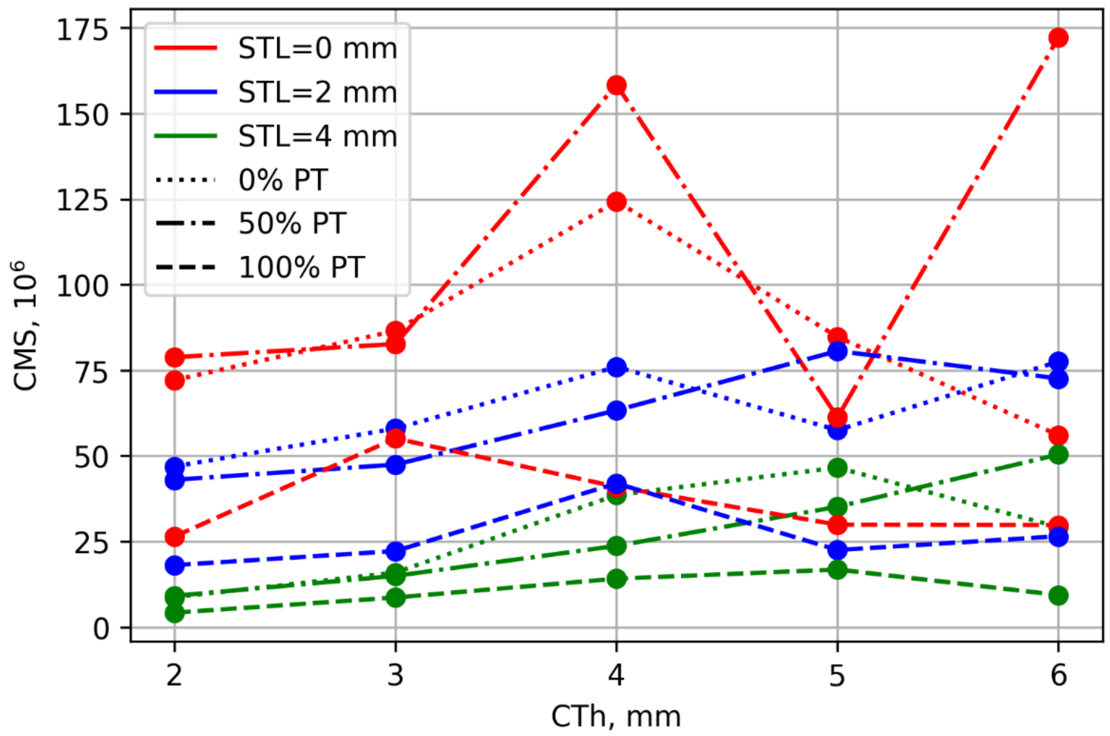

Figure 13: CMS when signals are processed with 60 kHz wavelet. Porosity thickness (PT) as a percentage of bone model thickness.

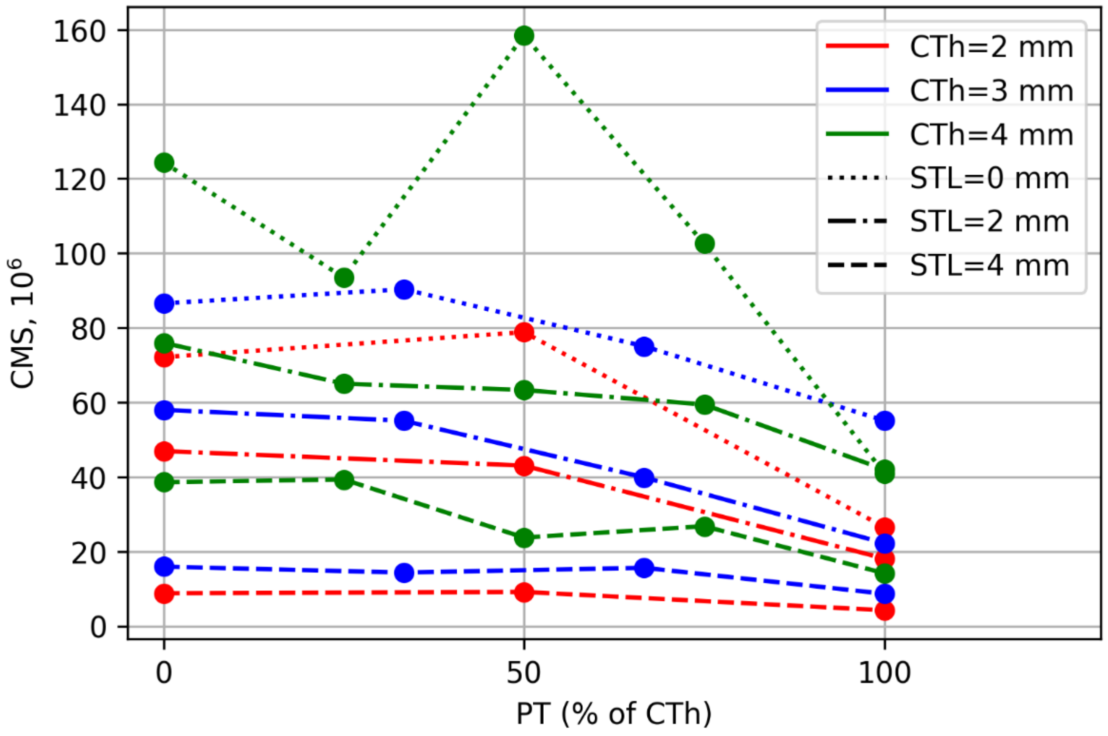

Figure 14: CMS when signals are processed with 60 kHz wavelet. STL thicknesses = 0 mm, 2 mm, 4 mm.

Conclusion

- CWT is a promising way of acquiring BM parameters;
- Two different patterns of how signals propagate at different frequencies;
- Acquired parameters (cSOS and CMS) are related to both CTh and PT;
- Use of real human subjects in the future.

References

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Thank you for your attention!

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