QMSKI 2022

In conjunction with the ISUCB

June 13 - 17

Noordwijk, Netherlands

Identification of Osteoporosis Diagnostic Signs in Cortical Bone Models Examined by Axial Transmission Ultrasound

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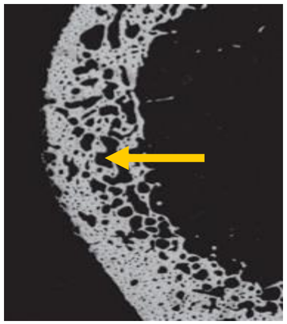
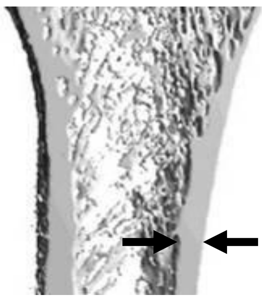
INSTITUTE OF ELECTRONICS AND COMPUTER SCIENCE

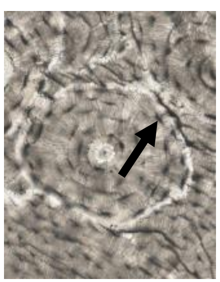
1. Introduction: Osteoporosis signs in cortical bone



Intracortical porosity

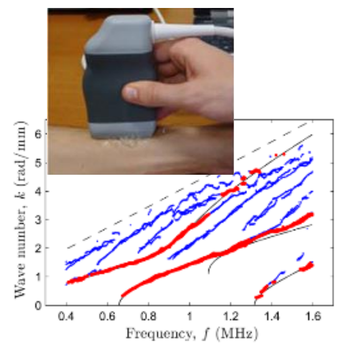


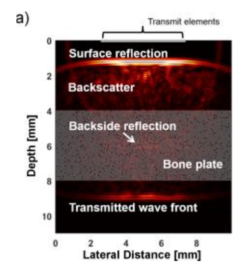
Cortical thickness

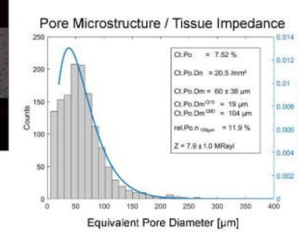


Material quality: mineralization, microstructure, collagen defects, microcracks

1st generation axial QUS:
SoS = C_{FAS} = UPV







Advanced development:

1. Modal analysis of guided waves (GW)
2. Ultrasound backscattering

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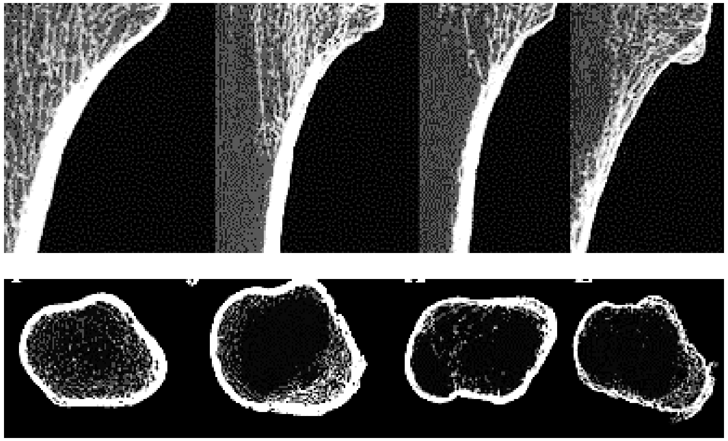
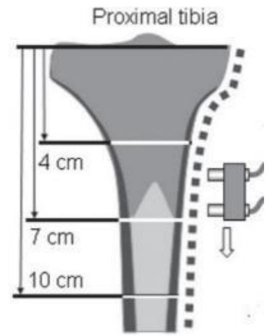
1. Introduction: Topographical features of GW

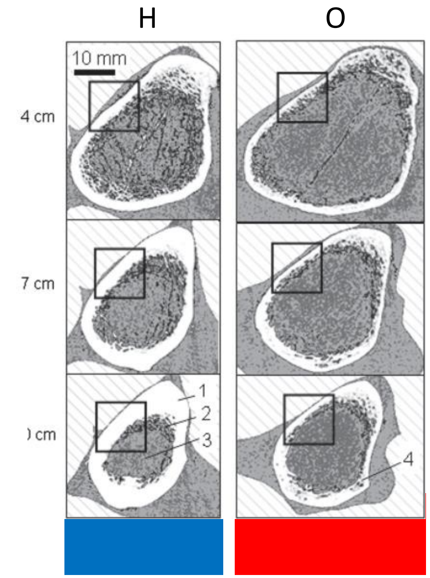


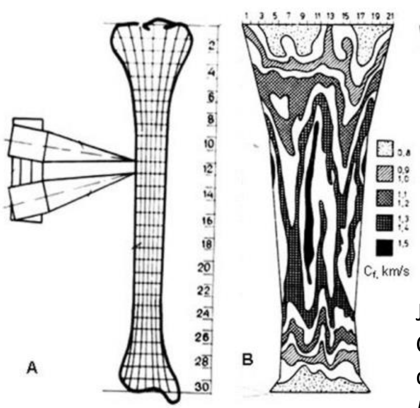
Surgical neck of the humerus:
<44, **45–64,** **65–79,** **80–100** years

Helfen T, Sprecher, C.M., Eberli, et al. High-Resolution Tomography-Based Quantification of Cortical Porosity and Cortical Thickness at the Surgical Neck of the Humerus During Aging. *Calcified Tissue International, 2017, 101(3)*

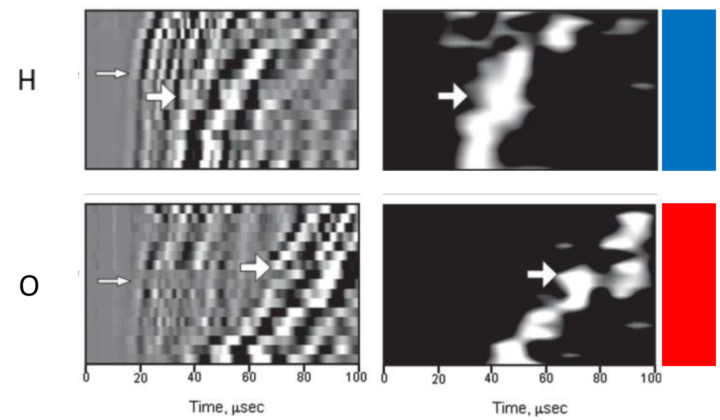


Tatarinov A, Sarvazyan A, Beller G, Felsenberg D. Comparative examination of human proximal tibiae in vitro by ultrasonic guided waves and pQCT. *Ultrasound Med Biol. 2011, 37(11)*





Jansons H, Tatarinov A, V Dzenis V, Kregers A. Constructional peculiarities of the human tibia defined by reference to ultrasound measurement. *Biomaterials, 1984, 5(4)*



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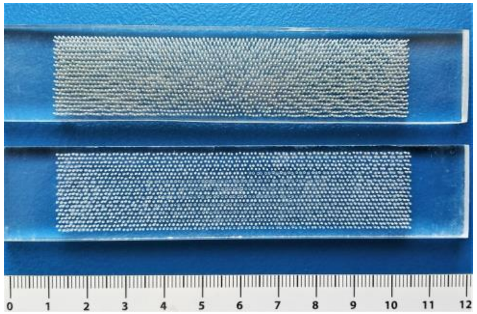
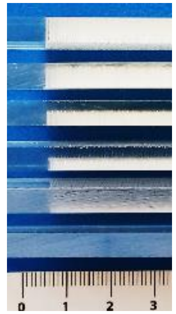
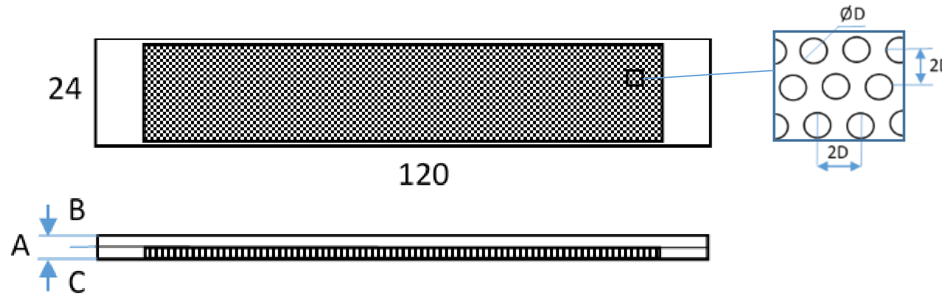
2. Aim of the study

Using **synthetic phantoms of cortical bone** simulating changes of the **cortical thickness** and the **progressing of intracortical porosity**, to test experimentally the hypothesis that the **differential assessment** of the both factors is possible by means of **axial ultrasonic testing** and application of **pattern recognition** approaches to the acquired ultrasonic signals.
To show that it can be done through the covering layers of **soft tissues** of different thickness.

3. Materials and Methods: phantoms of cortical bone





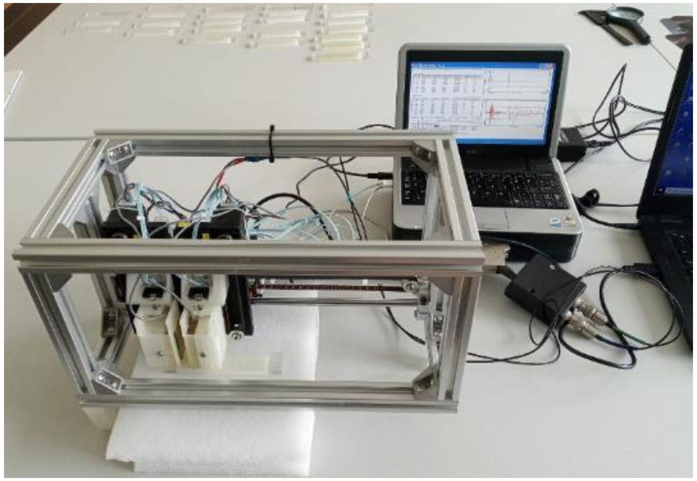


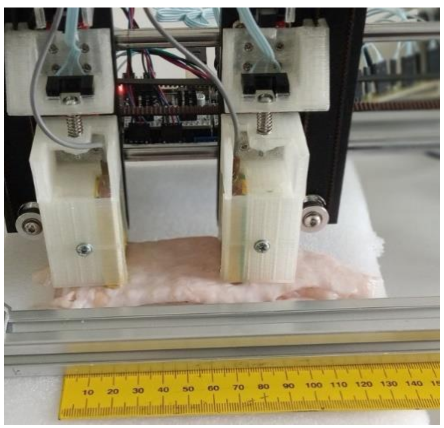
Bilayer PMMA phantoms with gradually varied thickness of solid and porous layers

Volumetric porosity in porous layer ~20%

Overall thickness A	2 mm	3 mm	4 mm	5mm	6mm
Solid : Porous B:C (mm)					0 : 6
				0 : 5	1 : 5
			0 : 4	1 : 4	2 : 4
		0 : 3	1 : 3	2 : 3	3 : 3
	0 : 2	1 : 2	2 : 2	3 : 2	4 : 2
	1 : 1	2 : 1	3 : 1	4 : 1	5 : 1
	2 : 0	3 : 0	4 : 0	5 : 0	6 : 0

3. Materials and Methods: Ultrasonic testing

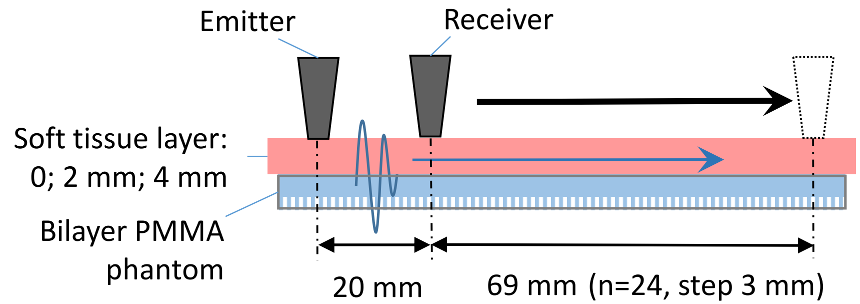




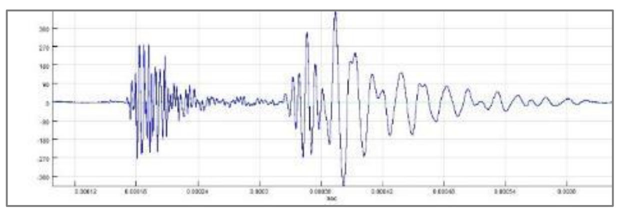
<u>Ultrasonic aquisition</u>:

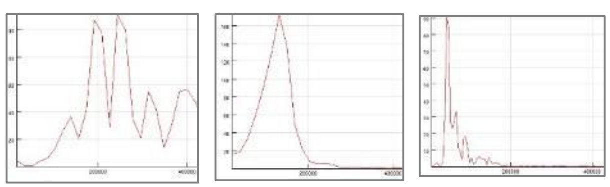
Excitation: train of 2 tone-bursts at 300 and 100 kHz
Digitizing: 30 Msps

<u>Surface profiling</u>

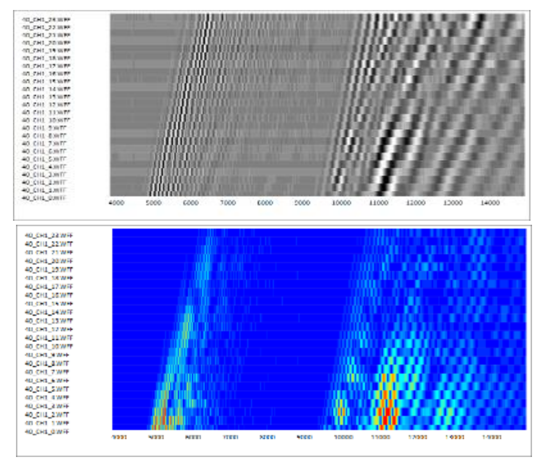


<u>Typical signal and its spectrum</u>





<u>Spatiotemporal waveform profiles</u>:



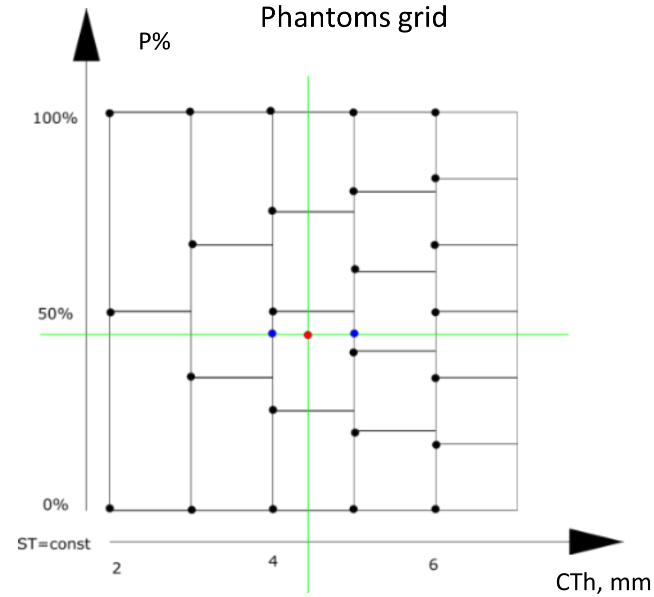
3. Materials and Methods: Data processing

Pattern recognition. Creation of decision rules.

Two factors of interests:

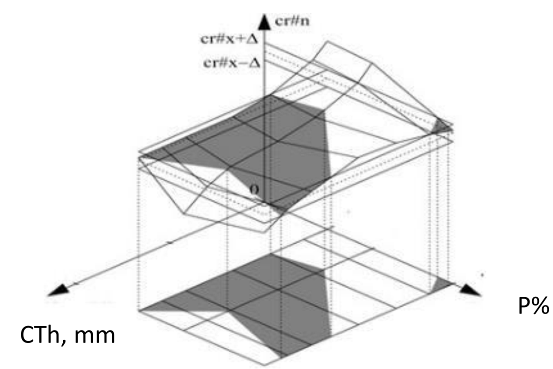
- Overall cortical thickness CTh (range 2-6 mm) ;
- Expansion of porosity P% (range 0 – 100% (at volumetric porosity ~20%);

[Soft tissues layer = constant, cases 0, 2, 4 mm]



Evaluation procedure:

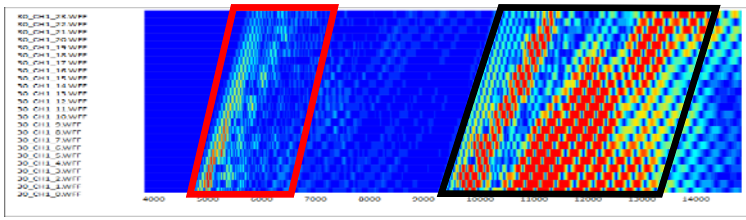
- Bilinear interpolation of the used criteria, creation of decision rules for training set
- Determination of the area of probabilistic solution within the set interval of criteria for testing set
- Alternation of specimens in training and testing sets



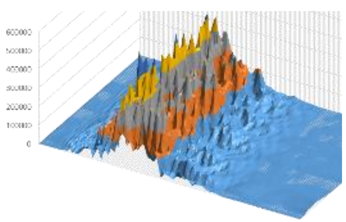
Data processing

Pattern recognition. Criteria.

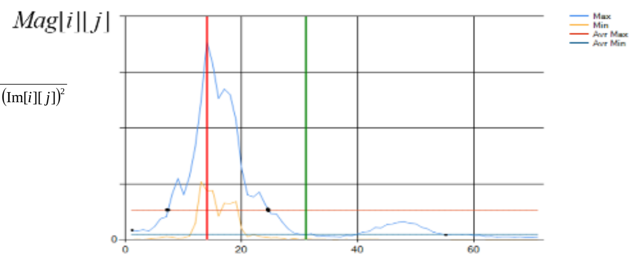
Approach 1:
Discrete Fourier Transform (DFT)
Calculation of statistical criteria



Region 1 (300 kHz)   Region 2 (100 kHz)



$Mag[i][j] = \sqrt{(\mathrm{Re}[i][j])^2 + (\mathrm{Im}[i][j])^2}$



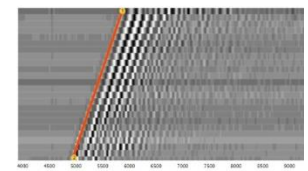
- $cr\#1$= the number of ω;
- $cr\#2 = \frac{max(F\_min(\omega))}{max(F\_max(\omega))}$;
- $cr\#3 = \frac{max|dF\_max(\omega)|}{max(F\_max(\omega))}$;
- $cr\#4 = \frac{max|dF\_avr(\omega)|}{max(F\_max(\omega))}$;
- $cr\#5 = \frac{max|dF\_min(\omega)|}{max(F\_max(\omega))}$;
- $cr\#9 = \frac{max(F\_avr(\omega))}{max(F\_max(\omega))}$;
- $cr\#10 = \frac{S_{min}}{S_{max}}$;
- $cr\#11 = \frac{S_{avr}}{S_{max}}$;
- $cr\#12 = \frac{S_{max}-S_{avr}}{S_{max}}$;
- $cr\#13 = \frac{S_{avr}-S_{min}}{S_{max}}$;

$$\begin{pmatrix} cr\#6 \\ cr\#7 \\ cr\#8 \end{pmatrix} = \begin{pmatrix} \sum_i \omega_i^4 & \sum_i \omega_i^3 & \sum_i \omega_i^2 \\ \sum_i \omega_i^3 & \sum_i \omega_i^2 & \sum_i \omega_i \\ \sum_i \omega_i^2 & \sum_i \omega_i & \omega_{max} - \omega_{min} \end{pmatrix}^{-1} \cdot \begin{pmatrix} \sum_i \omega_i^2 \cdot F\_max(\omega) \\ \sum_i \omega_i \cdot F\_max(\omega) \\ \sum_i F\_max(\omega) \end{pmatrix}$$

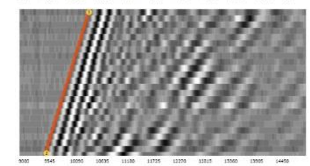
Sisojevs, A.; Tatarinov, A.; Kovalovs, M.; Krutikova, O. and Chaplinska, A. (2022). An Approach for Parameters Evaluation in Layered Structural Materials based on DFT Analysis of Ultrasonic Signals. In Proceedings of the 11th International Conference on Pattern Recognition Applications and Methods, ISBN 978-989-758-549-4, ISSN 2184-4313, pages 307-314.

Approach 2:
Measurable physical parameters

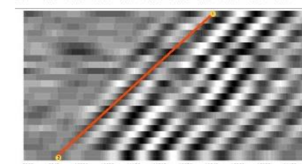
$cr\#27 = C_{300\ kHz}$ FAS



$cr\#28 = C_{100\ kHz}$ FAS



$cr\#29 = C_{45\ kHz}$ After low pass filtering



$cr\#30 = I_{300\ kHz} / I_{45\ kHz}$ After low pass filtering

$cr\#31 = ([I_{300\ kHz\ far} / I_{300\ kHz\ near}) / ([I_{45\ kHz\ far} / I_{45\ kHz\ near})$ After low pass filtering

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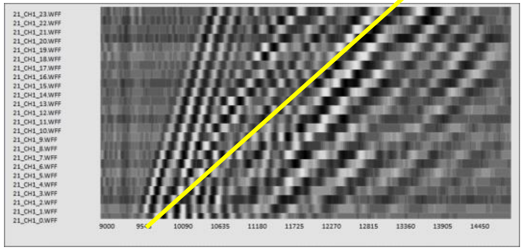
4. Experimental results

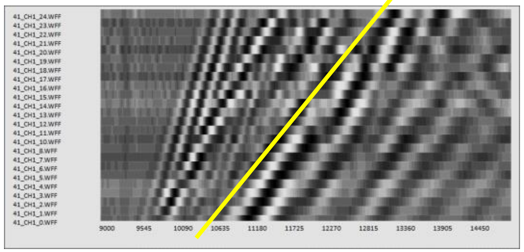
Ultrasonic waveform profiles as source data.

Effect of CTh

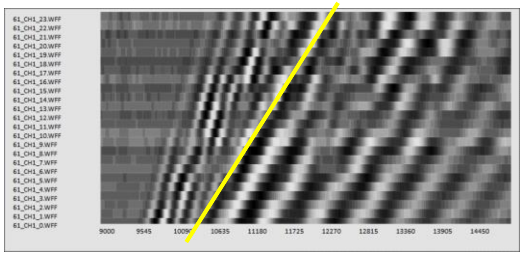
CTh = 2 mm, P% = 30%, ST = 2 mm



CTh = 4 mm, P% = 30%, ST = 2 mm

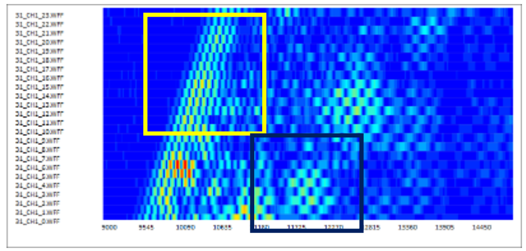


CTh = 6 mm, P% = 30%, ST = 2 mm

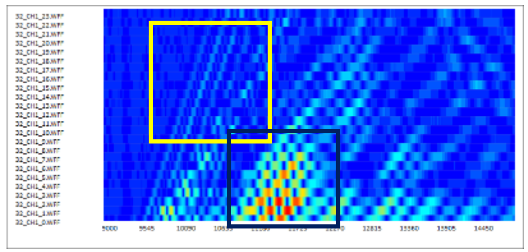


Effect of P%

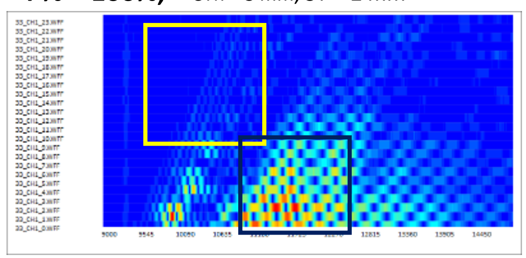
P% = 33%, CTh = 3 mm, ST = 2 mm



P% = 66%, CTh = 3 mm, ST = 2 mm

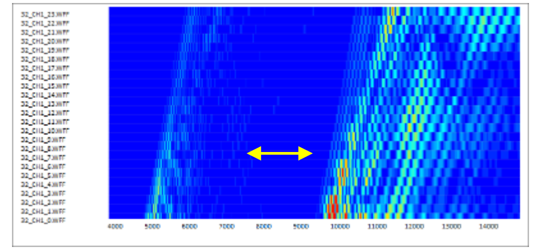


P% = 100%, CTh = 3 mm, ST = 2 mm

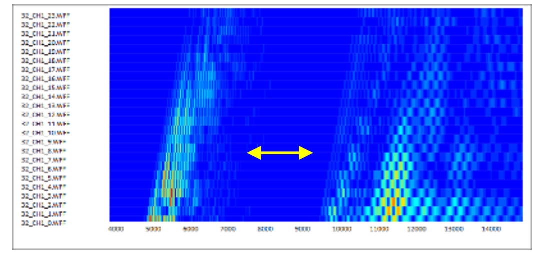


Effect of soft tissues

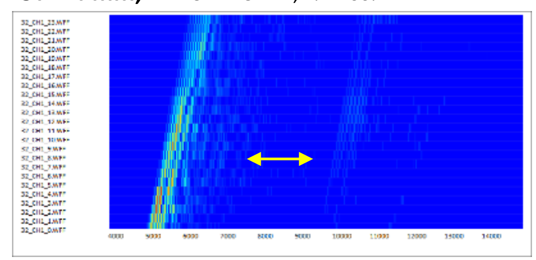
ST = 0 mm, CTh = 3 mm, P% = 66%



ST = 2 mm, CTh = 3 mm, P% = 66%

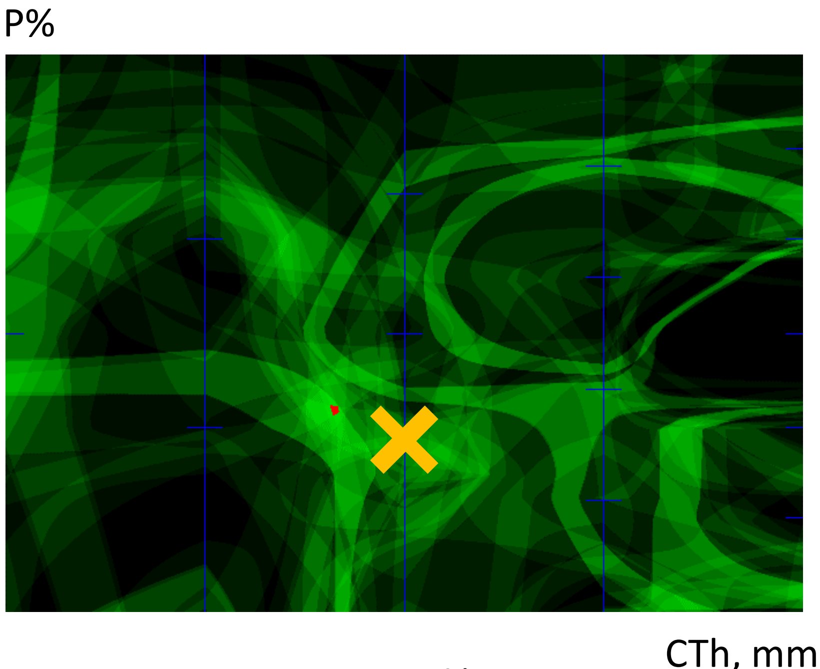


ST = 4 mm, CTh = 3 mm, P% = 66%

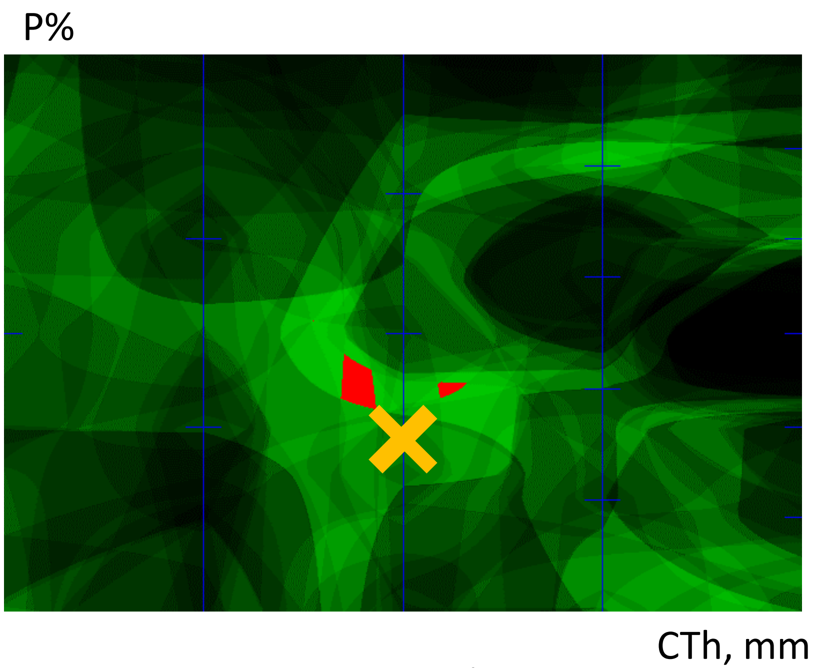


Recognition by DFT criteria: bilinear interpolation

Test object: CTh = 4 mm, P% = 25%, ST=4 mm



ε = 5%

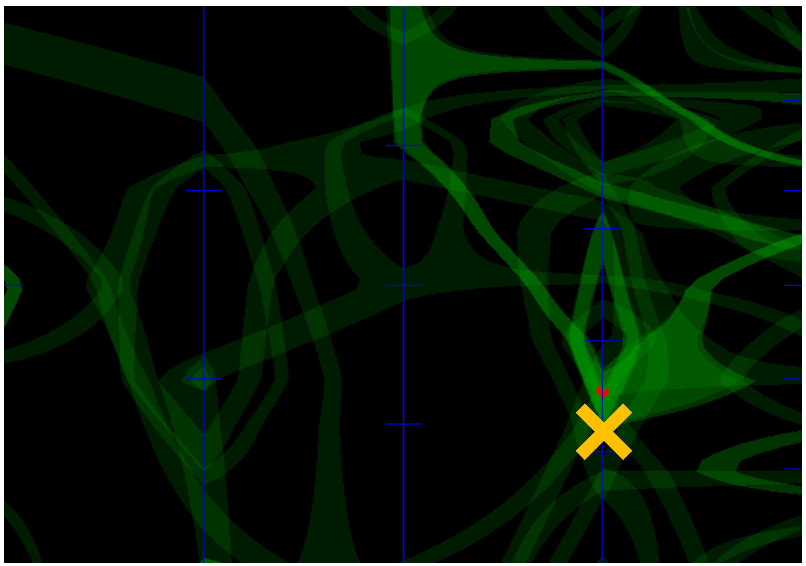


ε = 25%

Recognition by DFT criteria: bilinear interpolation

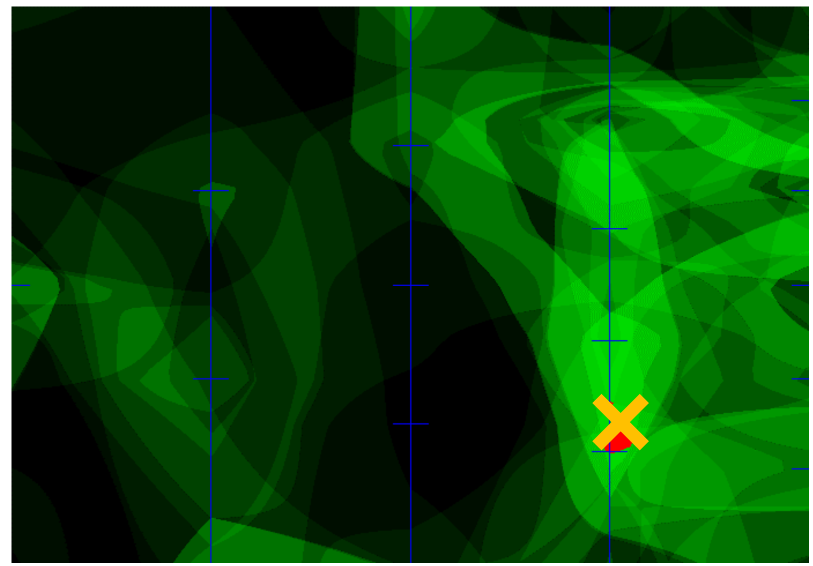
Test object: CTh = 5 mm, P% = 20%, ST = 2 mm

P%



ε = 5%   CTh, mm

P%

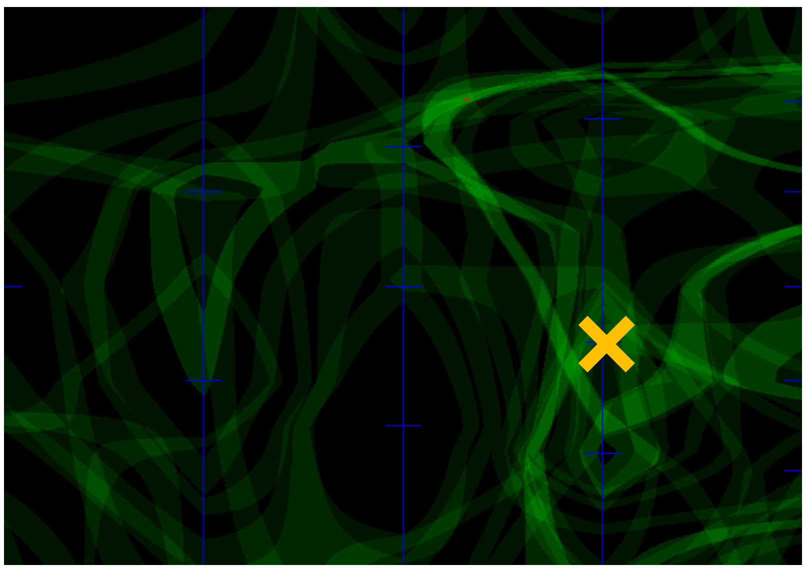


ε = 25%   CTh, mm

Recognition by DFT criteria: bilinear interpolation

Test object: CTh = 5 mm, P% = 40%, ST = 2 mm

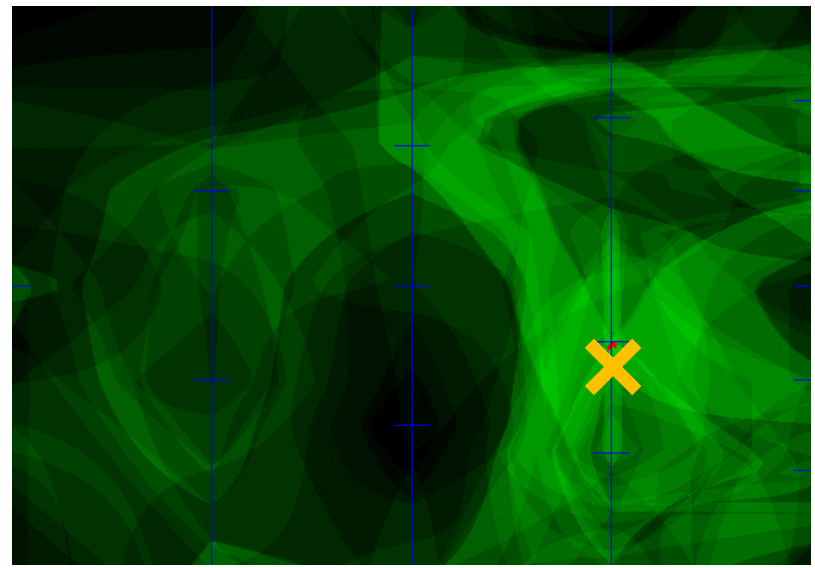
P%



CTh, mm

ε = 5%

P%



CTh, mm

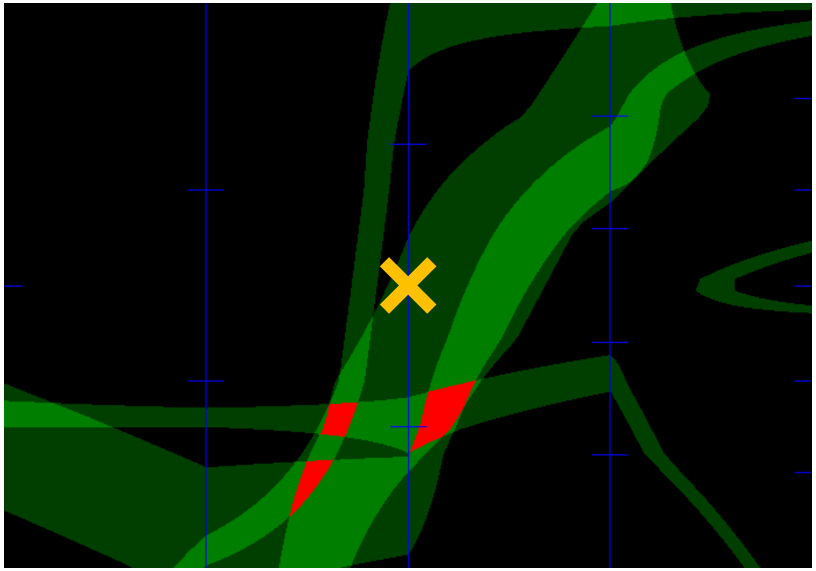
ε = 25%

4. Experimental results

Recognition physical criteria (velocities, attenuation): bilinear interpolation

Test object: CTh = 4 mm, P% = 50%, ST = 2 mm

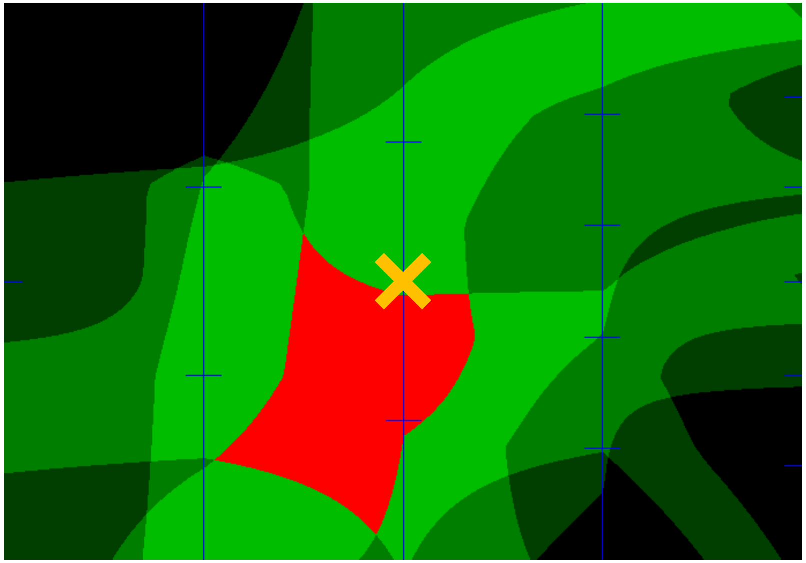
P%



CTh, mm

ε = 5%

P%

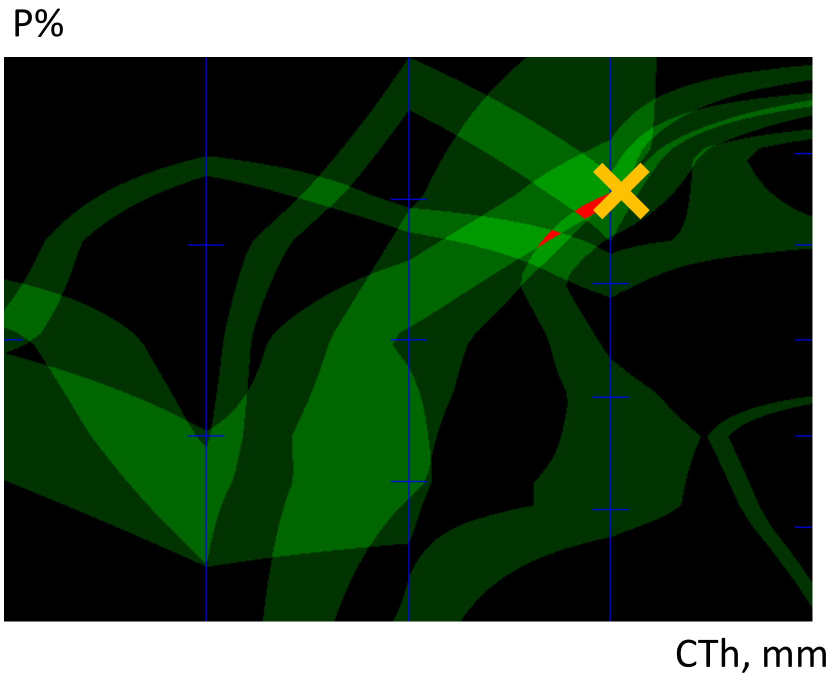


CTh, mm

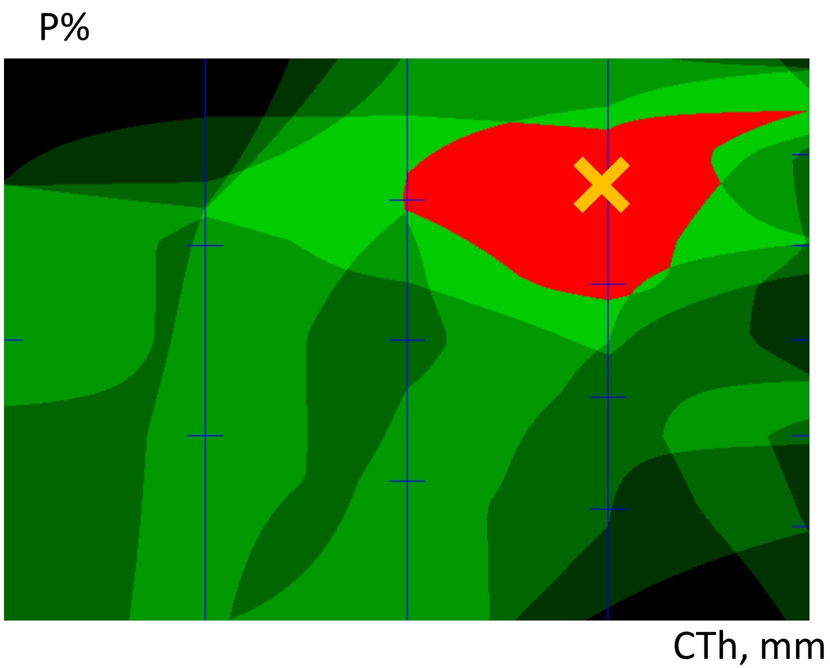
ε = 25%

Recognition physical criteria (velocities, attenuation): bilinear interpolation

Test object: CTh = 5 mm, P% = 80%, ST = 2 mm



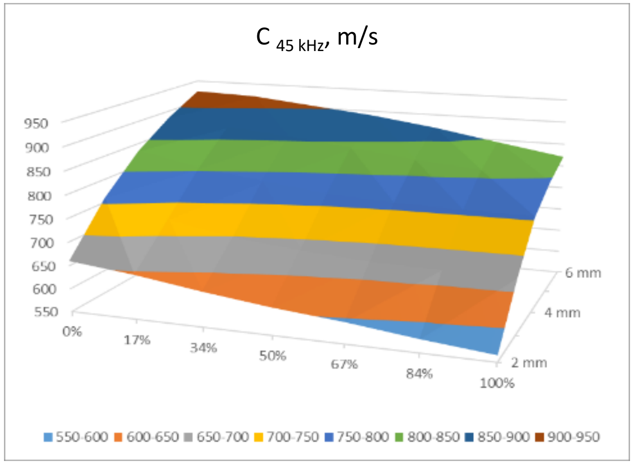
ε = 5%

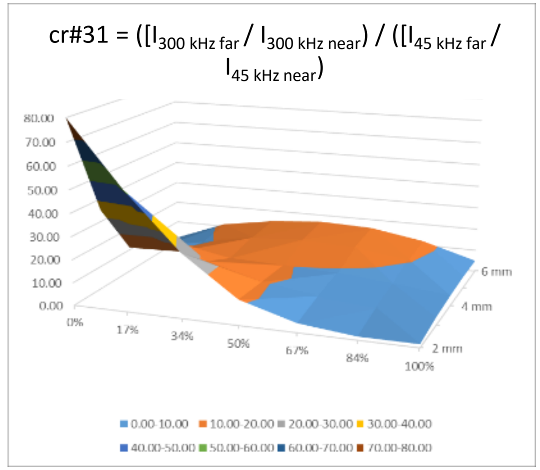


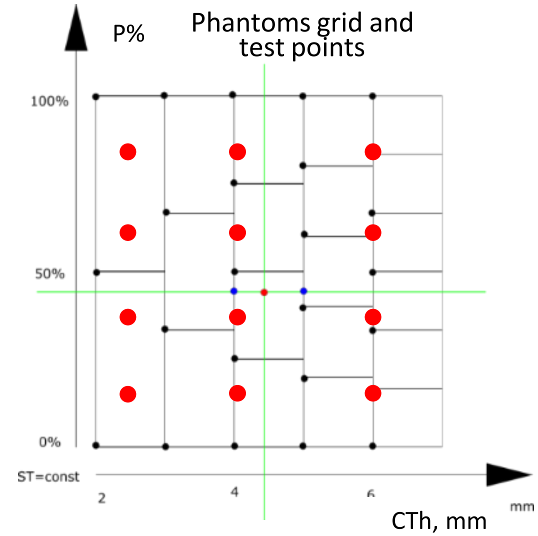
ε = 25%

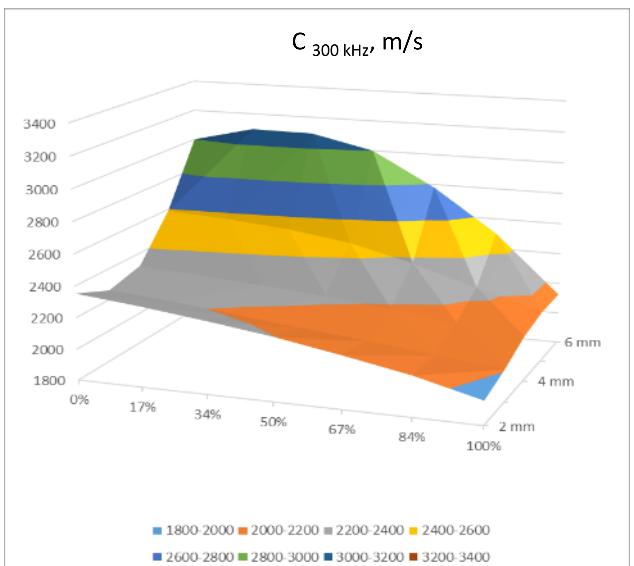
4. Experimental results

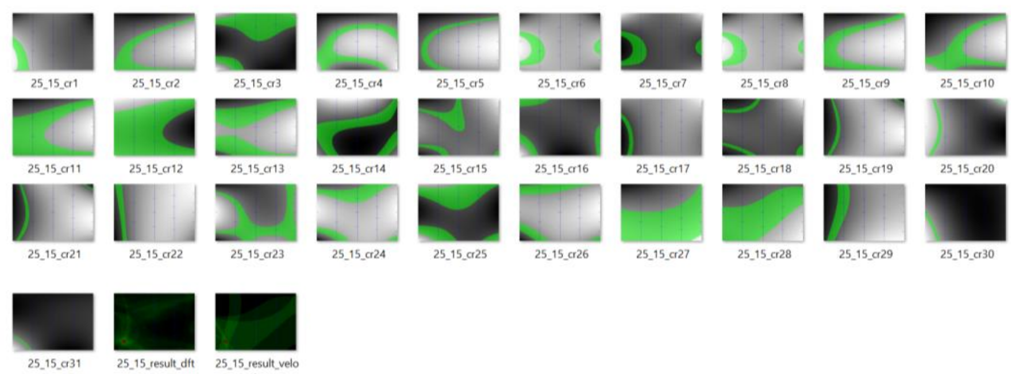
Evaluation of criteria and decision rules: biquadratic approximation











Evaluation of physical criteria and decision rules: biquadratic approximation

cr#27 = $C_{300\ \mathrm{kHz}}$

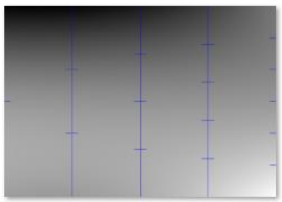
cr#28 = $C_{100\ \mathrm{kHz}}$

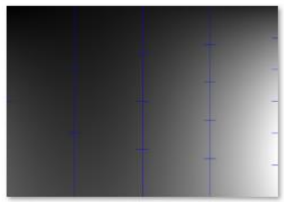
cr#29 = $C_{45\ \mathrm{kHz}}$

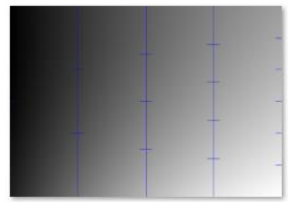
cr#30 = $I_{300\ \mathrm{kHz}} / I_{45\ \mathrm{kHz}}$

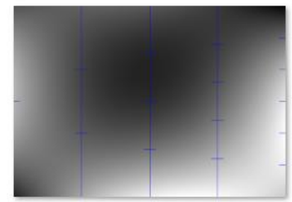
cr#31 = $([I_{300\ \mathrm{kHz\ far}} / I_{300\ \mathrm{kHz\ near}}) / ([I_{45\ \mathrm{kHz\ far}} / I_{45\ \mathrm{kHz\ near}})$

ST = 0 mm


st 0 mm_cr#27


st 0 mm_cr#28


st 0 mm_cr#29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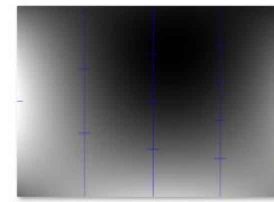
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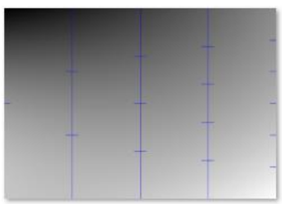
ST = 2 mm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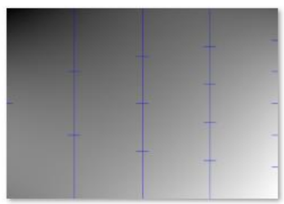
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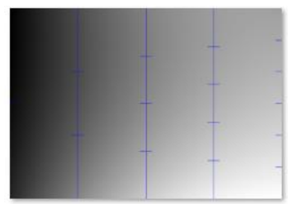
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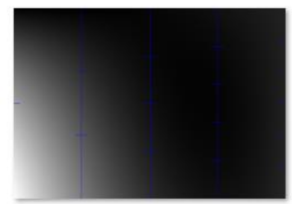
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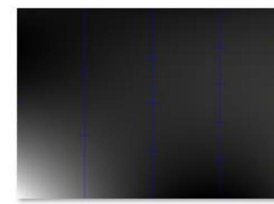
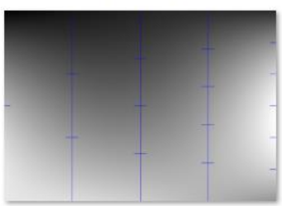

st 2 mm_cr#31

ST = 4 mm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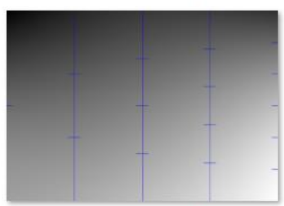
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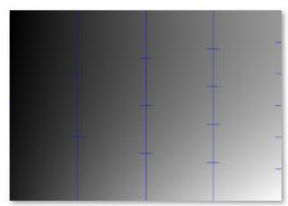
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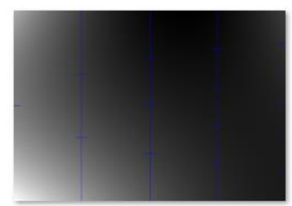
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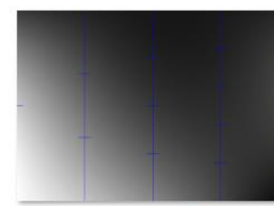
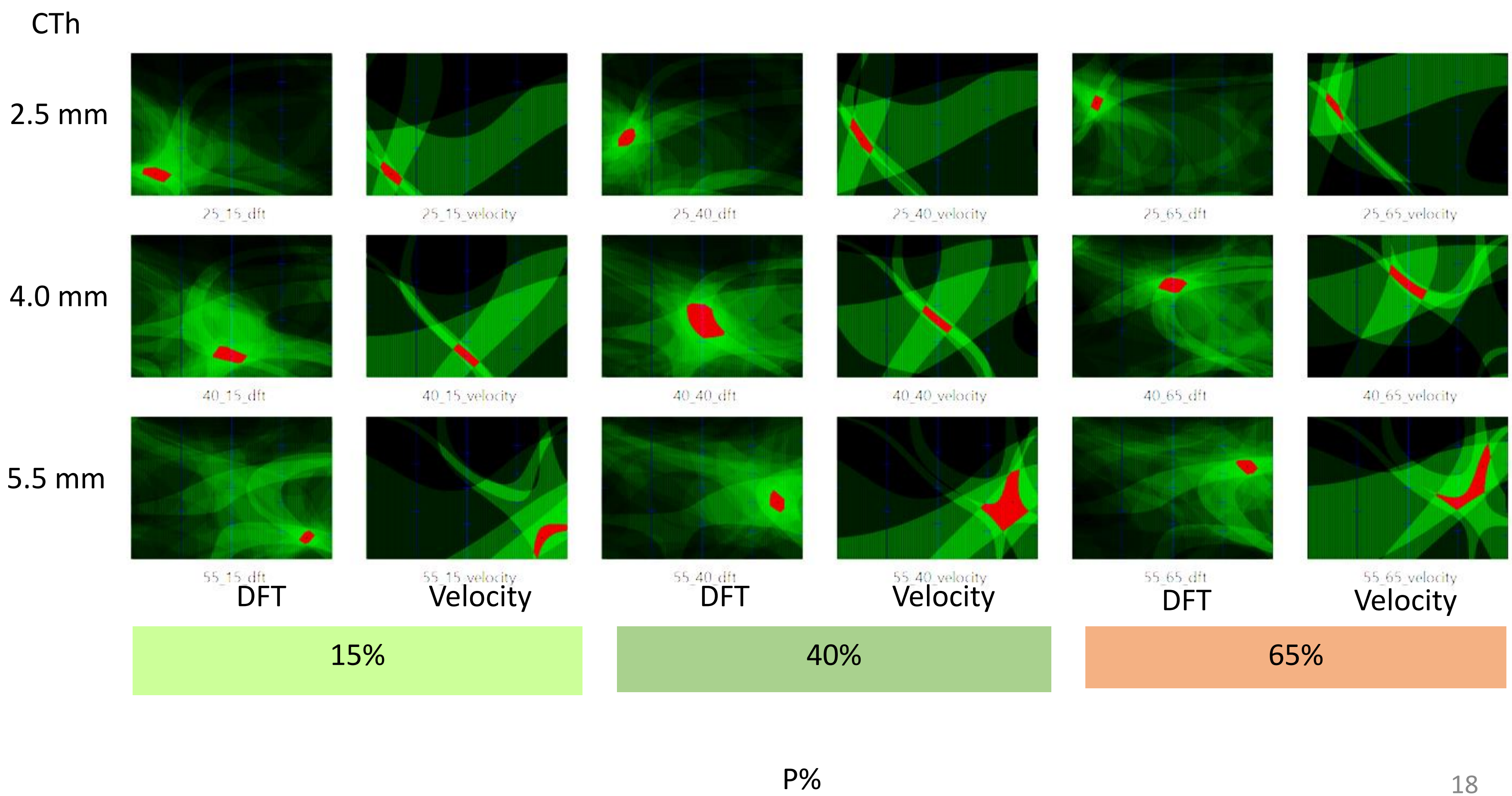

st 4 mm_cr#31

Evaluation of decision rules: biquadratic approximation

Intersection of decision rules for 9 points within the approximation area for the case of soft tissues 4 mm

$\varepsilon = 10\%$



Conclusions:

- GW: potential to discriminate cortical thickness and intracortical porosity
- Pattern recognition can be effective tool. Optimization of decision rules
- Soft tissues should be accounted. Direct measurements or 3-factor model
- Better detection relates to a thinner cortical bone. Metaphyses
- Mathematical simulations: prediction changes of ultrasonic waveforms and diagnostic features

Acknowledgement:

The study was supported by the research project of the Latvian Council of Science lzp-2021/1-0290 “Comprehensive assessment of the condition of bone and muscle tissues using quantitative ultrasound” (BoMUS)

Thank you for your attention !