Analysis of Energy Relations between Noise and Vibration Signals in the Scanning Area of an Open-Air MRI Device

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Motivation of Our Work

MR imaging is accompanied with vibration due to rapidly changing Lorenz forces in gradient coils producing significant mechanical pulses during execution of a scan sequence.

Mechanical vibration causing image blurring of thin layer samples produces also acoustic noise degrading the recorded speech signal during MR scan of the human vocal tract.

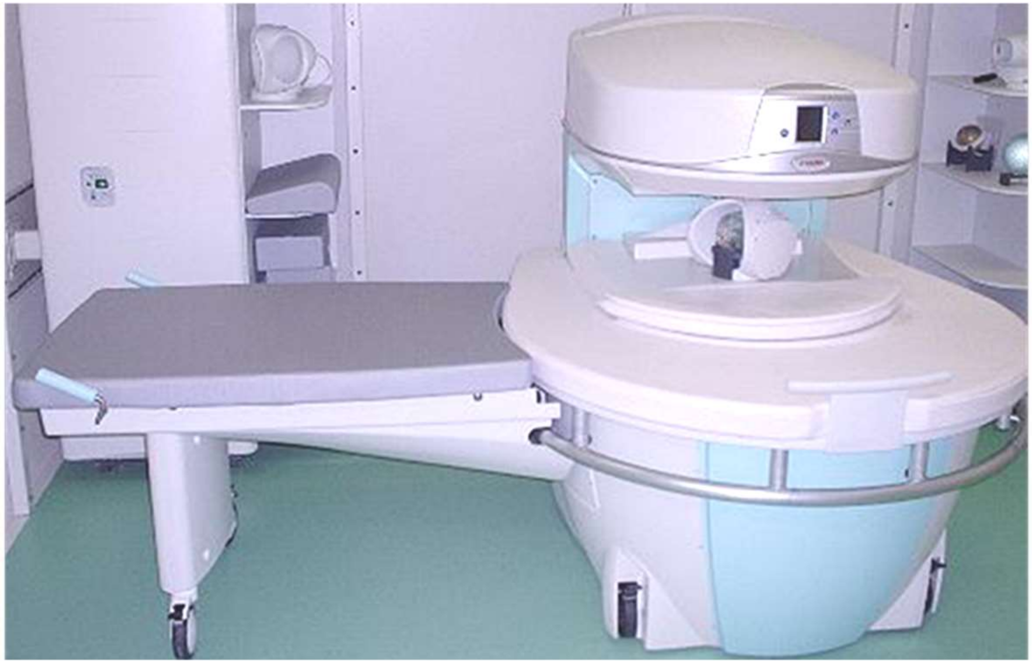
The acoustic noise has also negative physiological and psychical effects on the exposed person depending on the noise intensity and time duration of noise exposure.

In order to minimize these negative factors, this work is focused on mapping of the energy relationship between vibration and noise signals measured in the MRI scanning area and its vicinity.

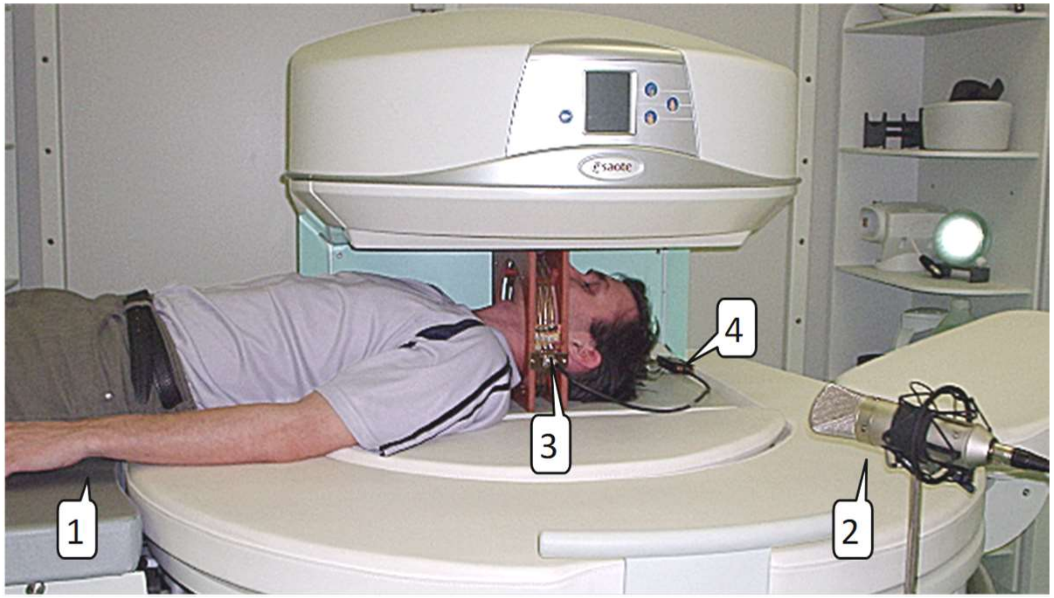
Basic Description of the Investigated MRI Device

Open-air MRI equipment Esaote Opera:

- stationary magnetic field with $B_0 = 0.178$ T is produced by a pair of permanent magnets,
- gradient system consists of 2 x 3 planar coils situated between the magnets and an RF receiving/transmitting coil with a tested object/subject.

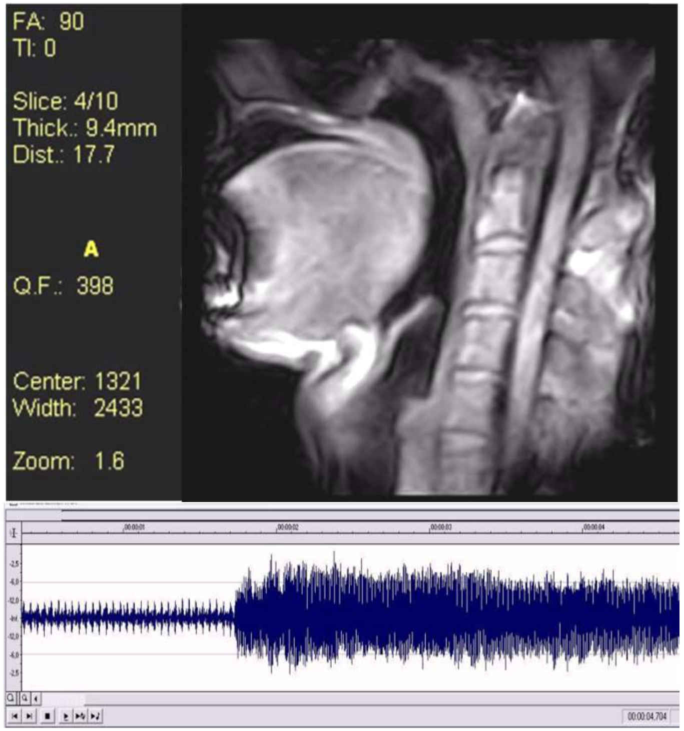


Example of MR Scan of the Human Vocal Tract



An examined person in the MRI device during scanning of the vocal tract:

(1) a patient's bed with the tested person,
(2) a pick-up microphone,
(3) a head RF coil,
(4) an external RF pre-amplifier.



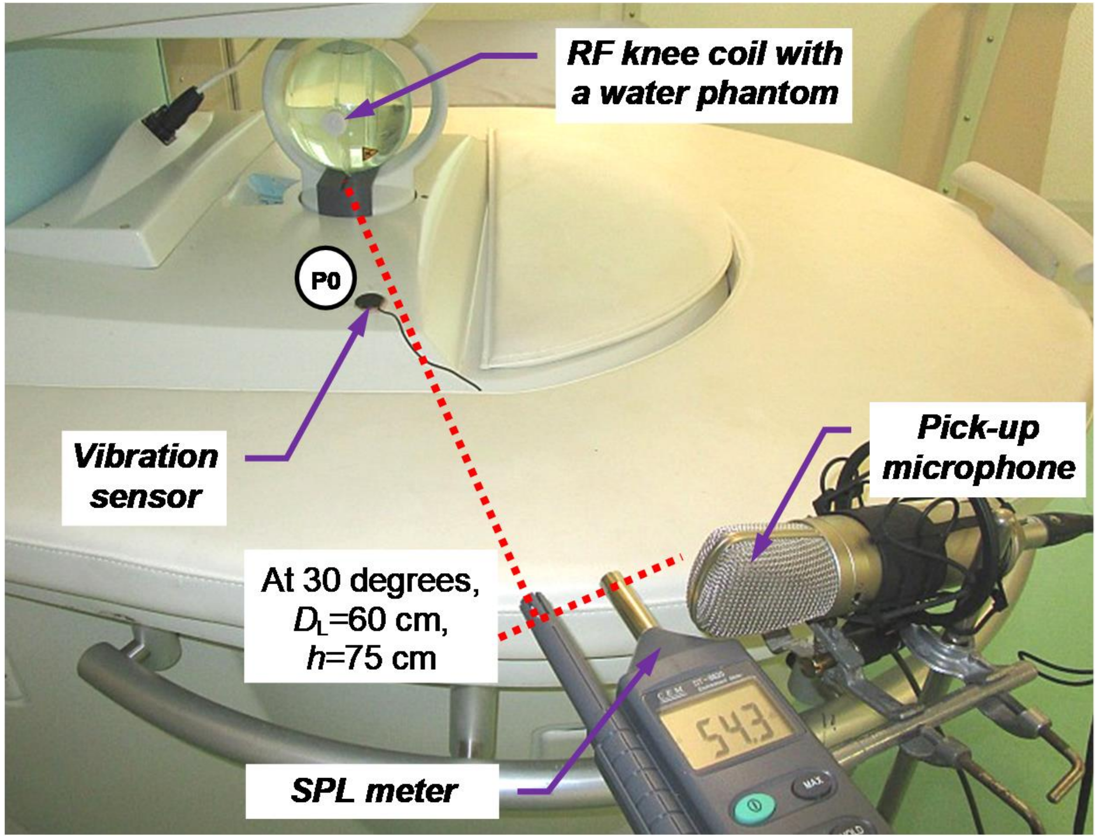
MR image of the vocal tract in a sagittal plane using the SSF-3D scan sequence (above); parallel recorded speech signal with an acoustic noise (below).

Description of Performed Experiments

Practical realization of experiments consists of 3 phases:

1) **Preliminary mapping of the acoustic noise SPL distribution in the MRI device vicinity at distances D_X = <*45 ~ 90*> cm.**
2) **Real-time recording of vibration and noise signals during execution of a scan MR sequence and manual measurement of noise SPL for:**
   - **different MR scan sequences of *Hi-Res* and *3-D* type,**
   - ***{Coronal, Sagittal,* and *Transversal}* orientation of scan slices,**
   - **times TE={*18, 22, 26*} ms, and TR={*60, 100, 200, 300, 400, 500*} ms,**
   - **different of object/subject masses inserted in the MRI scanning area *(testing phantom with a weight of 0.75 kg and male / female person with a weight of 85 kg / 55 kg)*.**
3) **Off-line processing of vibration and noise signals:**
   - **calculation of the signal energy parameters based on RMS, Teager–Kaiser energy operator, cepstrum, and autocorrelation; histogram building, statistical analysis, visualization.**

Arrangement of Measurement and Signal Recording in the Open-Air MRI Device



Placement of sensors in the open-air MRI device for recording of vibration, noise, and SPL measurement; the water phantom inside the knee RF coil.

Conditions of Measurement and Signal Recording

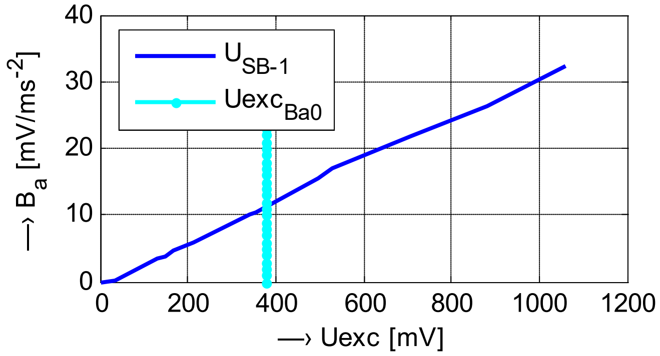
Real-time parallel recording of the vibration and noise signals in the scanning area of the MRI device was using:

- the multi-function environment meter *Lafayette DT 8820* – placed at the distance D_X = 60 cm from the central point of the scanning area, at the height of 75 cm from the floor – for noise SPL measurement,
- the vibration *sensor SB-1* mounted on the surface of the plastic holder of the bottom gradient coils,
- the 1" Behringer dual diaphragm *condenser microphone B-2 PRO* with a cardioid pickup pattern for noise signal recording,
- the *mixer device* Behringer XENYX 502, as a part of the Behringer PODCAST STUDIO equipment for pre-amplifying and processing of input analog signals,
- *manual synchronization* of signal recording and the MR scan process by the console operator,
- the *sampling frequency* of 32 kHz (resampled to 16 kHz) – signals were next processed by the sound editor program Sound Forge 9.0a.

The Vibration Sensor Usable for Measurement in the Low Magnetic Field Environment

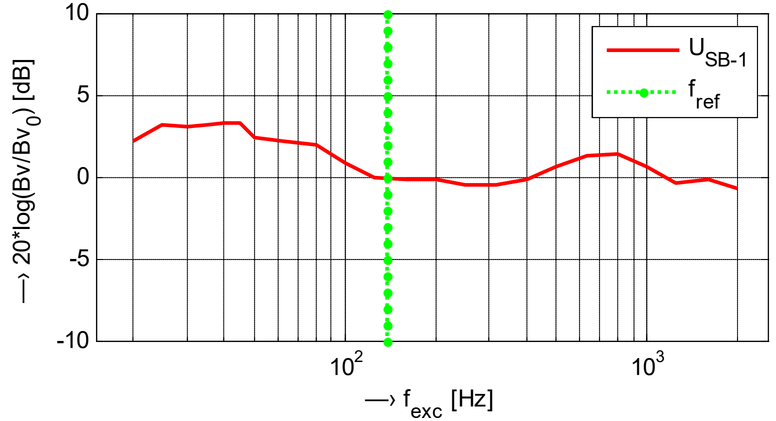
The vibration sensor constructed primarily for acoustic pickup in musical instruments:

- ✓ contains a piezoelectric element on a brass circular target,
- ✓ can be used in the stationary magnetic field with low B_0.



Our frequency range of interest corresponds to the frequency range of a voiced speech <*10 Hz ÷ 3.5 kHz*> and bass instruments:

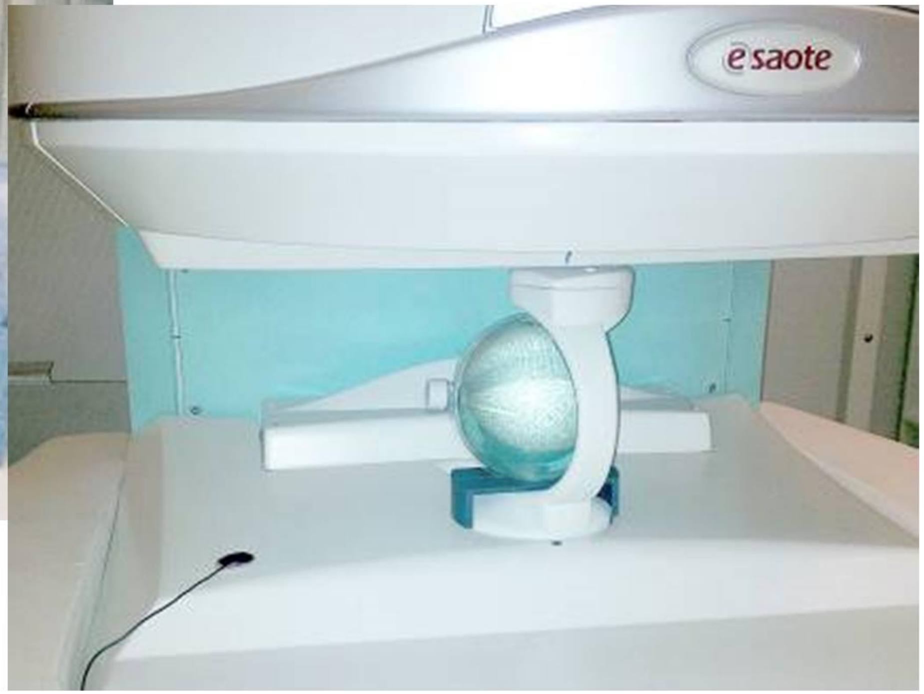
- ⇒ the sensor SB-1 with a 1″ brass disc was finally used,
- ⇒ designed primarily for contrabass pickup.



Recording of Vibration in the MRI Opera

Two working arrangements for vibration signal recording:

b) with a spherical water phantom



a) with a lying testing person

The vibration sensor SB-1 is mounted in the left corner on the bottom plastic cover in both cases.

MR Scan Sequences Used in Experiments

Description of used MR sequences and their basic scan settings.

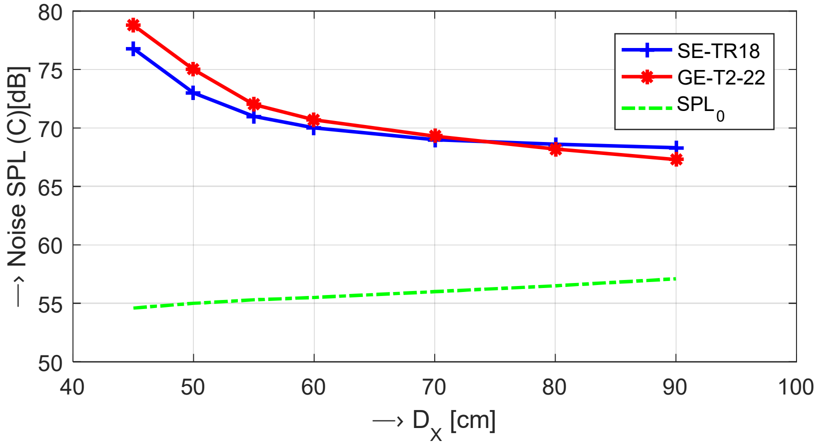
Type	Name of sequence	TE [ms]	TR [ms]	FOV [1]	Matrix size
Hi-Res	SE 18 HF	18	500	250x250x200	256x256
Hi-Res	SE 26 HF	26	500	250x250x200	256x256
Hi-Res	GE T2	22	60	250x250x200	256x256
3-D	SS 3D balanced	5	10	200x200x192	200x200
3-D	3D-CE	30	40	150x150x192	192x192

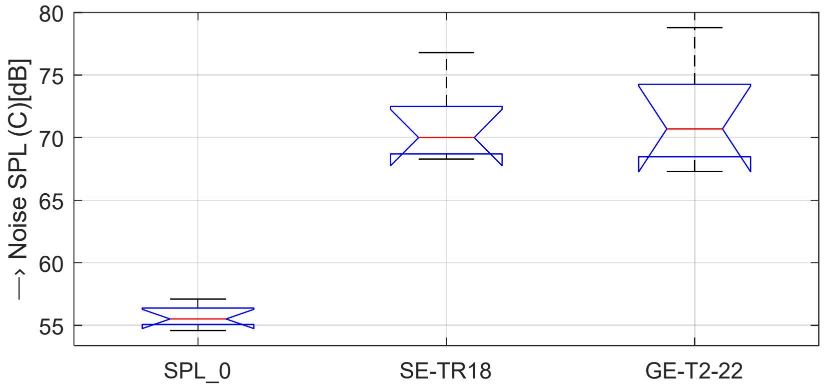
[1] **In all cases the sagittal slice orientation and the slice thickness of 4.7 mm were pre-defined**.

- ✓ **The TE and TR parameters were set manually, according to basic values introduced in this table to perform measurement and comparison in the range enabled by the current sequence.**

Obtained Results of Noise SPL Measurement

Mapping of acoustic noise SPL at distances D_X of {45, 50, 55, 60, 70, 80, and 90} cm for SE and GE types of Hi-Res scan sequences:





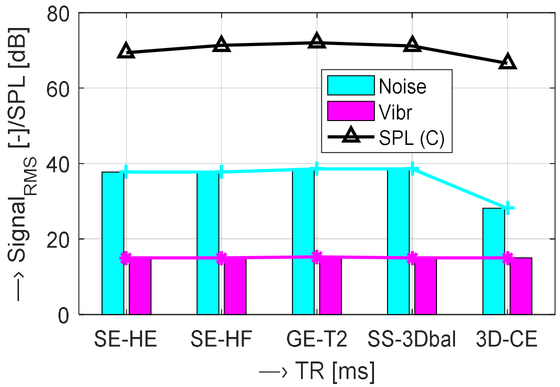
SPL values with background SPL_0 (left), basic statistical parameters (right).

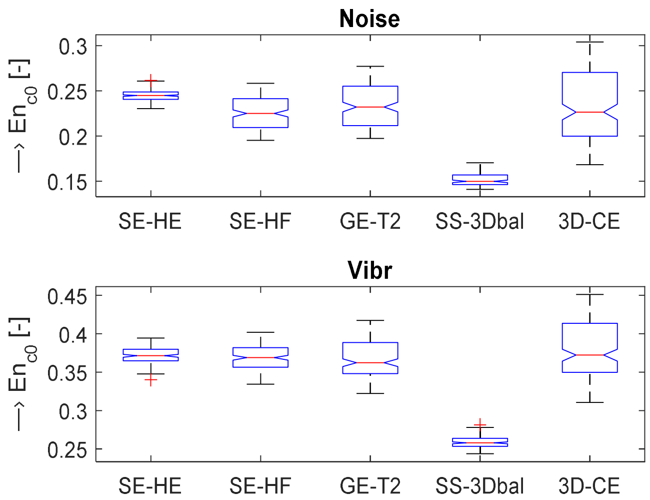
Measurement conditions and limitations:

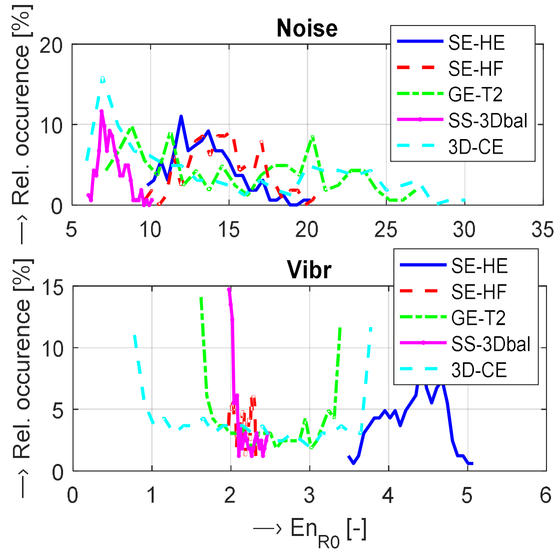
- *The SPL meter at the height of 75 cm from the floor (level of the bottom gradient coils), and at 30 degrees from the MRI left corner.*
- *The minimum D_X = 45 cm was set to eliminate interaction of metal parts of the SPL meter with static magnetic field of the MRI device.*
- *The maximum distance D_X = 90 cm was chosen with respect to the fact that the SPLs measured at this position are close to the background noise SPL_0*

Visualization of Energetic Relations of Recorded Vibration and Noise Signals

1) For different sequence types:







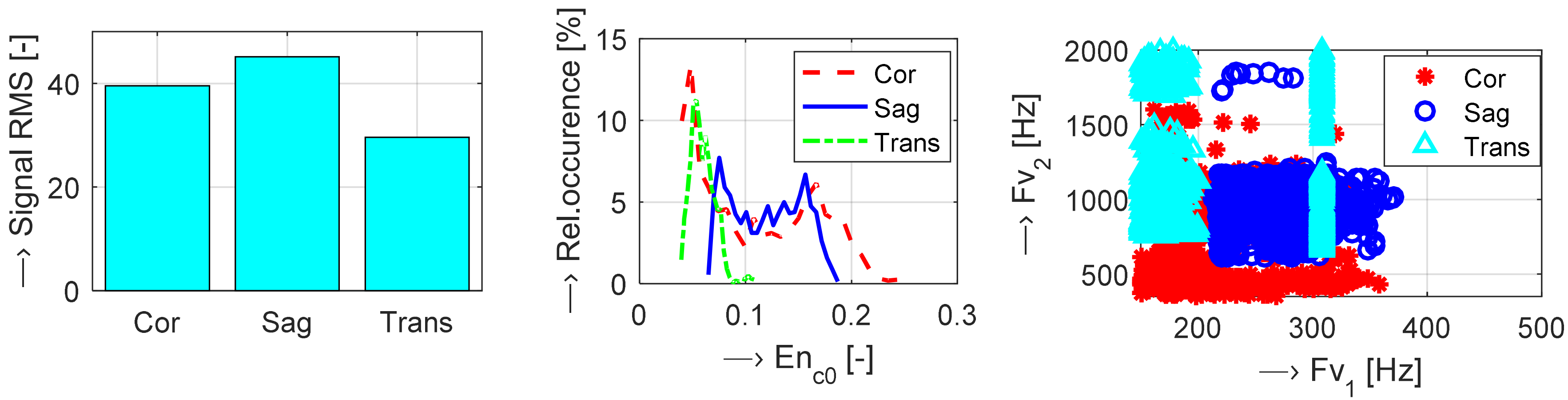
From left to right:

– signal RMS together with SPL values,
– bar-graphs of basic statistical parameters of En_{c0} values,
– corresponding histograms for En_{c0} parameter.

Used sequences of {Hi-Res SE-HE, Hi-Res SE-HF, Hi-Res GE-T2, SS-3Dbal, 3D-CE}, in all cases with a sagittal slice orientation.

Visualization of Energetic Relations of Recorded Vibration and Noise Signals

2) For different slice orientations of {*coronal, sagittal, transversal*}:



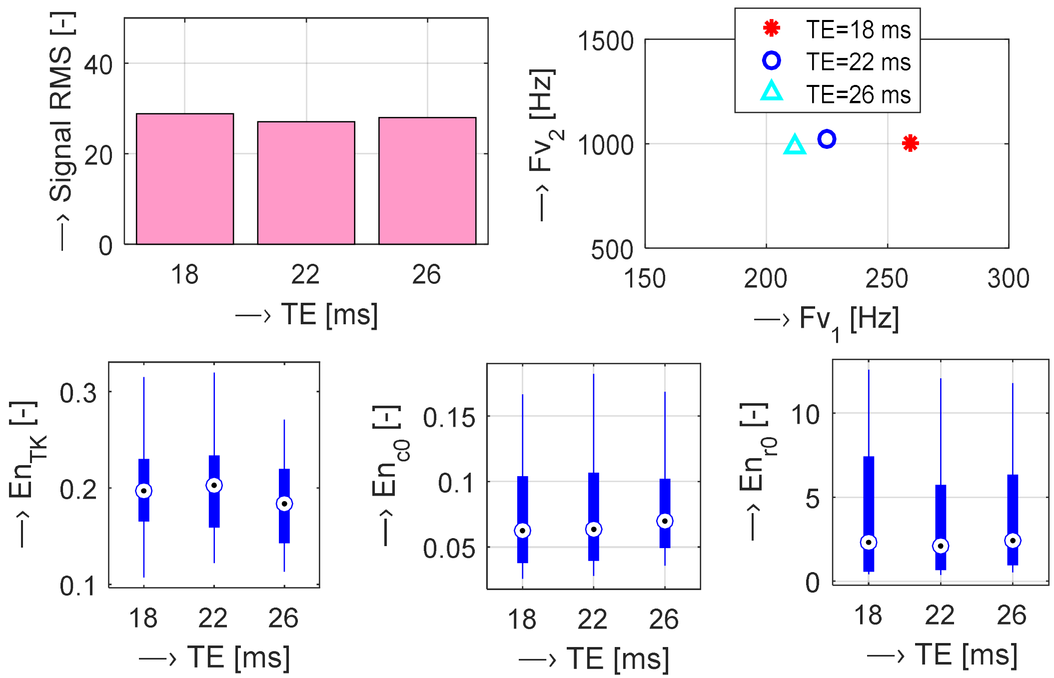
From left to right:

- **bar-graph of signal RMS values,**
- **histograms of En_{c0},**
- **mutual F_{v1} / F_{v2} positions.**

Used Hi-Res SE scan sequences (TE=18 ms, TR=500 ms).

Visualization of Energetic Relations of Recorded Vibration and Noise Signals

3) For different TE times of {*18, 22, 26*} ms:



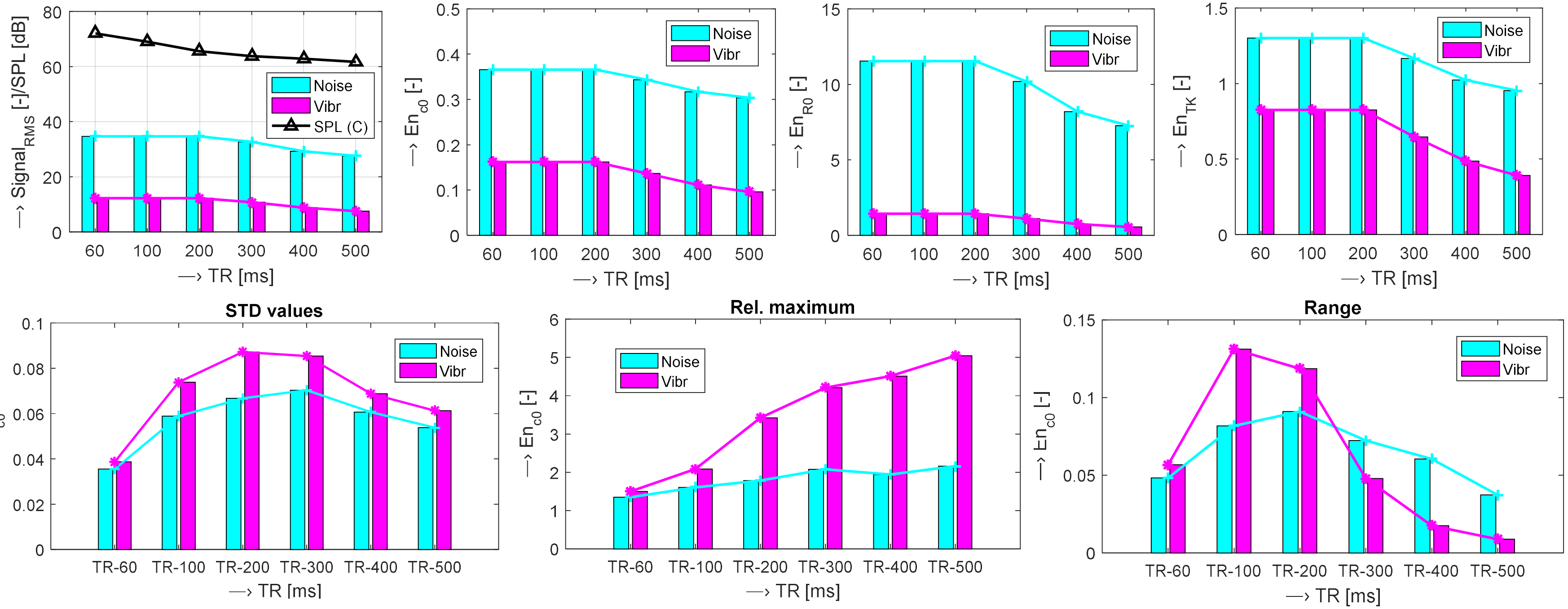
From left to right:

- **bar-graph of signal RMS values, mean mutual F_{v1} / F_{v2} positions;**
- **bar-graphs of basic statistical parameters of: En_{TK}, En_{c0}, En_{r0}.**

Used Hi-Res SE-HF sequences (TR=500 ms, sagittal orientation).

Visualization of Energetic Relations of Recorded Vibration and Noise Signals

4) For different TR times of {*60, 100, 200, 300, 400, 500*} ms:



From left to right:

a) signal RMS together with noise SPL values, mean En_{c0}, mean En_{r0}, mean En_{TK};

b) statistical parameters of En_{r0} values: standard deviation, relative maximum, range.

Used Hi-Res GE-T2 sequences with TE=22 ms, and sagittal orientation.

Obtained Results for Different Subjects in the Scanning Area of the MRI Device

5) For different object/subject masses in the MRI scanning area:

Subject type [1]	Vibrations (SB-1)			
	RMS	En_{TK}	En_{c0}	En_{r0}
Water phantom	34.6	4.69	0.0380	24.0
Male	26.8	4.96	0.0404	14.4
Female	28.7	4.93	0.0402	16.6

Subject type [1]	Noise (Mic. B2-Pro)			
	RMS	En_{TK}	En_{c0}	En_{r0}
Water phantom	20.1	4.05	0.0255	8.5
Male	25.5	4.51	0.0328	15.9
Female	23.2	4.19	0.0286	10.6

[1] Used Hi-Res SE-HF scan sequences with TE=18 ms, TR=400 ms, sagittal orientation.

Discussion of Obtained Results I.

From analysis of setting of the MR scan parameters follows:

1. **Influence of the choice of slice orientation on the energy of the produced vibration and noise signals is significant:**
   - → the maximum can be found in the sagittal plane and the minimum in the transversal plane.
2. **Experiments confirm influence of TR and TE times on the vibration and acoustic noise properties:**
   - → the TR parameter determines the fundamental frequency F_{V0} and its stretching causes energy fall of the final signal,
   - → TE time affects higher frequencies (the first two dominant frequencies $F_{V1,2}$) but the signal energy is unaffected.
3. **Spectral differences between two mostly used MR scan sequences (SE/GE types) show that:**
   - → the GE sequence has more structured noise,
   - → the SE sequence generates more compact vibration with higher energy in the final effect.

Discussion of Obtained Results II.

Further investigations show that:

4. **Energetic relations of vibration and noise signals for different sequence types manifest small differences:**
   → the 3-D SE sequence produces the noise with minimal intensity, maximum can be found for the SS-3Dbal (TE=5 ms, TR=10 ms).
5. **Performed experiments confirm that the produced vibration and acoustic noise are principally influenced by a load of a person lying in the scanning area of the MRI machine:**
   → the energy of the vibration signal is significantly higher for the male/female persons lying inside the MRI scan area in both types of analyzed MRI devices than using phantoms only,
   → the situation is opposite for noise signals – the maximum corresponds to the scanned male person (the greatest volume).
   → vibration signals with a testing person have smaller dispersion of spectral decrease, but higher frequency of the spectral centroid and higher F_{V1} to F_{V2} mutual positions.

Summary & Conclusion

1) **The maximum of acoustic noise SPL of about 78 dB(C) was achieved at the distance of 45 cm from the central point of the MRI scanning area for the GE scan sequence with short TE and TR times and sagittal slices orientation:**
   - **no special hearing protection aids (ear plugs or ear muffs) are necessary for the examined persons lying in the scanning area of the investigated MRI device Esaote Opera.**
   - **Due to low scanning times for mostly used 3D or Hi-res sequences (less than 15 minutes), exposition of the human organism and its ear by the noise and vibration is not great.**

2) **The obtained results will serve to create databases of initial parameters (such as the bank of noise signal pre-processing filters) for acoustic noise suppression in parallel with speech recording applied for 3-D modeling of the human vocal tract.**

Future plans:

- **measurement of the vibration signal on the surface of both plastic holders** ***for knowledge about the contribution of the upper gradient coil to the resulting produced noise,***
- **additional measurement and experiments** ***for better description of the acoustic noise conditions in the scanning area and in the vicinity of the MRI device.***

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