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INFLUENCE OF PERSON WEIGHT ON SPECTRAL PROPERTIES OF ACOUSTIC NOISE IN THE OPEN-AIR MRI

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Abstract **–** The paper analyses the change in spectral properties of an acoustical noise when the examined person lies in the scanning area of the open-air magnetic resonance imager (MRI) so that the holder of the lower gradient coils is loaded with his/her weight. Obtained results of spectral analysis will be used for design of a correction filter to suppress the noise in simultaneously recorded speech signal for 3D modelling of the human vocal tract.

Keywords: acoustic noise, noise reduction, signal processing, spectral analysis, statistical evaluation

1. INTRODUCTION

The magnetic resonance imaging (MRI) device usually consists of three gradient coils that produce three orthogonal linear fields for spatial encoding of a scanned object. From the physical principle follows that the rapid changes of Lorentz forces during fast switching inside the weak static field B_0 environment [1] result in a significant mechanical vibration of these gradient coils. This process subsequently propagates in the air a progressive sound wave received by the human auditory system as a noise [2]. Due to its harmonic nature and the audio frequency range, the produced acoustic noise of this device can generally be treated as a voiced speech signal, and thus it can be recorded by a microphone and processed in the spectral domain using similar methods as those used for speech signal analysis.

MRI technique enables analysis of the human vocal tract structure and its dynamic shaping during speech production while simultaneous recording of a speech signal [3] is performed. The primary volume models of the human acoustic supra-glottal spaces created from the MR images can then be transformed into the three-dimensional (3D) finite element (FE) models [4]. To obtain the 3D vocal tract model with good quality the synchronicity between image and audio acquisition must be ensured as well as a good signal-to-noise ratio must be achieved [5]. Several approaches to reduce the noise in the MRI equipment [6-8] are used in practice. One group of these enhancement methods is based on spectral subtraction of the estimated background noise. The noise estimation techniques based on statistical approaches are not able to track real noise variations; thereby they result in an artificial residual fluctuation noise and a distorted speech. In all cases the spectral properties of the acoustic noise generated by the gradient system of the MRI device must be analysed first.

To investigate the transmission of vibration through the plastic holder of the MRI device scanning area, the measurement arrangement consisting of the tested water phantom inserted in the scanning RF coil can be used [9]. The situation changes when the examined person lies in the scanning area of the open-air MRI and the holder of the lower gradient coils is loaded with his/her weight. Then the change in spectral properties of the generated acoustic noise is expected, too. To verify this working hypothesis, the noise signal recording and its spectral analysis were performed for different person weights and with the water phantom only (for comparison). Obtained results will be used to devise an improvement of the developed cepstral-based noise reduction method [10] in speech recorded during MRI scanning.

2. ANALYSIS OF SPECTRAL PROPERTIES OF THE ACOUSTIC NOISE SIGNAL

The basic as well as the supplementary spectral properties are usually determined from the frames (after segmentation and widowing). To obtain the smoothed spectral envelope, the mean periodogram can be computed by the Welch method [11]. For further detailed analysis the nearest region of interest (ROI) can be determined – see visualization in Fig. 1. The periodogram represents an estimate of the power spectral density (PSD) of the input signal. Using the N_{FFT}-point FFT to compute the PSD as $S(e^{j\omega})/f_s$ and the sampling frequency f_s in [Hz], we obtain the resulting spectral density in logarithmic scale expressed in [dB/Hz] – see an example in Fig. 2. The basic spectral properties include also the spectral decrease (tilt – S_{tilt}) representing the degree of fall of the magnitude or power spectrum. It can be calculated by a linear regression using a mean square method.

The supplementary spectral properties describe the shape of the magnitude of the power spectrum $|S(k)|^2$ of the noise signal and they can be determined with the help of the additional statistical parameters. The spectral centroid (S_{centr}) is defined as a centre of gravity of the spectrum, i. e. the average frequency weighted by the values of the normalized energy of each frequency component in the spectrum

$$S_{centr} = \sum_{k=1}^{N_{FFT}/2} k\left|S(k)\right|^2 \Big/ \sum_{k=1}^{N_{FFT}/2} \left|S(k)\right|^2. \qquad (1)$$

The spectral spread (S_{spread}) parameter represents the dispersion of the power spectrum around its mean value

$$S_{spread} = E(x-\mu)^2 = \sigma^2, \qquad (2)$$

where μ is the first central moment and σ is the standard deviation of the spectrum values. The spectral skewness (S_{skew}) is a measure of the asymmetry of the data around the sample mean and can be determined as the third moment

$$S_{skew} = \frac{\mu^3}{\sigma^3} = \gamma_1. \qquad (3)$$

The measure S_{gama2} is also used for describing the statistical properties of the spectrum. It is defined using the spectral kurtosis and the spectral spread as follows

$$S_{gama2} = S_{kurt} / S_{spread}^2, \qquad S_{kurt} = \left(\mu^4/\sigma^4\right) - 3, \qquad (4)$$

where the spectral kurtosis (S_{kurt}) expressed by the fourth central moment represents a measure of peakedness or flatness of the shape of the spectrum relative to the normal distribution for which it is 3 (or 0 after subtraction of 3).

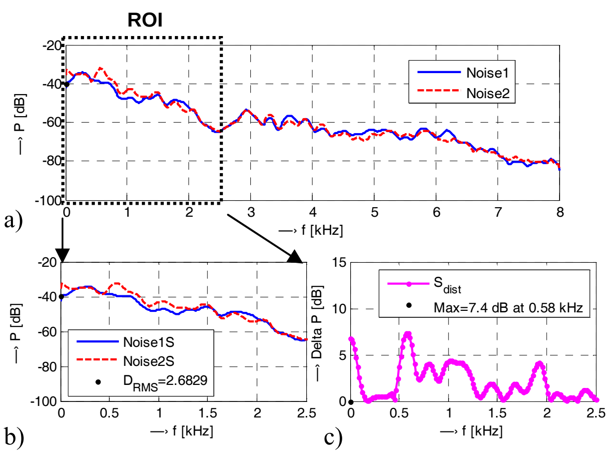

Fig. 1. The mean periodograms of two noise signals in the full frequency range $0 \div f_s / 2$ (a), ROI in the low-frequency band $0 \div 2.5$ kHz (b), spectral distance between the signals (c).

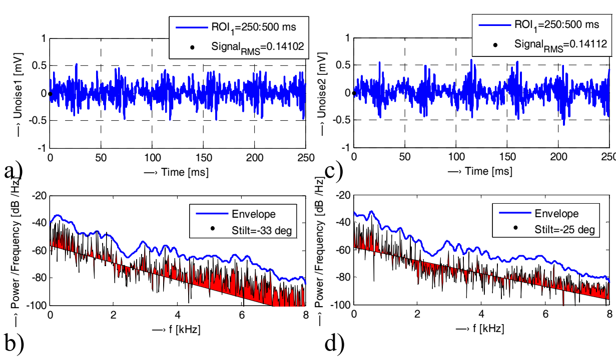

Fig. 2. Example of two noise signals and their spectral density: the original noise signal (a, c), PSD, its spectral envelope and spectral tilt (b, d).

3. SUBJECT AND PERFORMED EXPERIMENTS

The analysed open-air MRI equipment E-scan OPERA contains an adjustable bed which can be positioned in the range of 0÷180 degrees, where the 0 degree represents the left corner near the temperature stabilizer device [12] – see principal angle diagram of the MRI scanning area in Fig. 3c. This noise has almost constant sound pressure level (SPL) and consequently it can be easily subtracted as a background. Due to the low basic magnetic field B_0 (up to 0.2 T) in the scanning area of this MRI machine, any interaction with the recoding microphone must be eliminated. As the noise properties depend on the microphone position, the optimal recording parameters (the distance between the central point of the MRI scanning area and the microphone membrane, the direction angle, the working height, and the type of the microphone pickup pattern) must be found. The chosen type of the sequence together with the basic scan parameters – repetition time (TR) and echo time (TE) – have significant influence on the scanning time. Values of these parameters result primarily from the chosen type of the scanning sequence. They can also be slightly changed manually, but their final values depend on the setting of the other scan parameters – field of view (FOV), number of slices, slice thickness, etc.

The realization of the experiment with measurement of the acoustic noise produced by a gradient system of the MRI device consists of two phases. First, the noise signal was recorded by the pick-up microphone during execution of a scan MR sequence:

– with different testing persons lying in the scanning area of the MRI device (see Fig. 3a),
– using only the test phantom placed in the middle point of the scanning area – see Fig. 3b.

Then, the noise signals were processed as follows:

1. Calculation of the basic and supplementary spectral properties of the recorded acoustic noise signals; determination the main differences between the signals with and without a lying person in the scanning area, and detailed analysis of the influence of different person weights on the spectral properties.
2. Visual comparison of spectral envelopes in the full frequency range of $0 \div f_s / 2$ (0-8k) and for the sub-ranges of 0÷2.5 kHz (0-2k), and 2÷6 kHz (2-6k); determination of the spectral distances D_{RMS} of these envelopes between individual persons or the phantom object, and localization of the position F_{max} of the maximum difference ΔP_{max} within the low-frequency band 0-2k.
3. Statistical processing of determined values of the basic and supplementary spectral properties; numerical matching of the obtained results.

The SSF-3D scanning sequence chosen for this comparison experiment can be used for the 3D MR scans of the human vocal tract [10], [13]. The auxiliary parameters were set as follows: TE=10 ms, TR= 45 ms, 10 slices, 4-mm thick, sagittal orientation. The spherical testing phantom filled with doped water inserted in the scanning RF knee coil was used when the noise signal was recorded without a lying testing person in the MRI scanning area.

The noise measurement was practically realized by real-time recoding of the signal by a microphone and transferring it to an external notebook during execution of a chosen scan MR sequence. The recording microphone was located in the distance of 60 cm, horizontally in the positions of 30, 90, and 150 degrees (the lying testing person at 180 degree in all cases) and vertically in the middle between both gradient coils. The 1" Behringer dual diaphragm condenser microphone B-2 PRO with setting of a cardioid pickup pattern was connected to the Behringer PODCAST STUDIO equipment for the noise signal recording. The input analogue signal was pre-amplified and processed by the mixer device Behringer XENYX 502 connected to the notebook by the USB audio interface U-CONTROL UCA202. The noise signal originally recorded at 32 kHz was resampled to 16 kHz and subsequently processed. The stationary signal parts with the time duration of 8 sec were selected and normalized to the level of – 16 dB using the sound editor program Sound Forge 8.0. The collected noise database originates from the records using the six testing persons lying in the MRI scanning area (3+3 male/female) with different approximate weights and the testing water phantom with a holder (WP) - see Table 1.

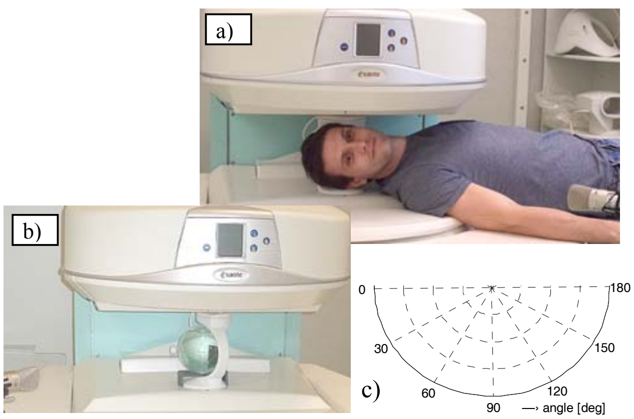

Fig. 3. An arrangement of noise recording in the MRI Opera: a lying person (a), a testing phantom (b), a principal angle diagram of the MRI scanning area (c).

Table 1. Approximate weights of tested persons / phantom used the experiment.

	$JP_{(M1)}$	$TD_{(M2)}$	$LV_{(M3)}$	$AP_{(F1)}$	$BB_{(F2)}$	$ZS_{(F3)}$	$XX_{(WP)}$
Weight [kg]	78	75	80	53	50	55	0.75

4. DISCUSSION OF OBTAINED RESULTS

Evaluation of obtained results comprises comparison of the basic spectral properties of noise signals comparing the values for the pairs: female/male, male/male, female/female, female/phantom, and male/phantom (shown in Table 2). Comparison of spectral envelopes in the low-frequency band up to 2.5 kHz for selected pairs can be seen in Fig. 4. The box-plot of the basic statistical parameters (minimum, maximum, mean value, and standard deviation) of the supplementary spectral properties is presented in Fig. 5, and their bar-graph comparison for different microphone locations is shown in Fig. 6. In both figures the groups "Male" and "Female" represent values of all three male (M1-M3) and female (F1-F3) persons.

The determined spectral differences of noise signals between persons with similar weights (male/male and/or female/female – see values in Table 1) are small in all three observed frequency ranges. For the male/female pairs the spectral differences are bigger and well visible on the spectral envelopes in the low-frequency band up to 2.5 kHz – see cases (a) and (b) in Fig. 4. For the female/phantom and male/phantom pairs the spectral differences are the biggest and they can be observed in the whole frequency range up to $f_s / 2$ – see subplots of (e - f) in Fig. 4. These results are in correlation with numerical matching which can be seen in Table 2.

From the performed comparison of the supplementary spectral properties for three tested locations of the recording microphone follows that no significant differences exist, however, the best results are obtained for the microphone position at 90 degree, i. e. directed at the face of a lying person. At the microphone position of 0 degree the influence of the MRI temperature stabilizer can be superimposed as an additive noise with normal distribution. The microphone position at 150 degree is unnatural from the point of the lying person – the distance between the speaker face and the recording microphone is the longest. It holds when the patient's bed is located at 180 degree – this configuration was chosen due to maximum elimination of the mentioned temperature stabilizer.

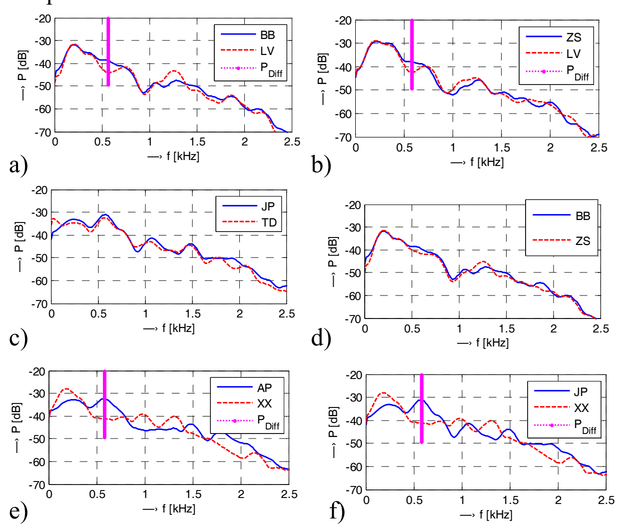

Fig. 4. Spectral envelopes in the band up to 2.5 kHz for the selected pairs: female/male (a-b), male/male (c), female/female (d), female/phantom (e), and male/phantom (f); microphone at 90 deg.

Table 2. Comparison of the basic spectral properties of the acoustic noise for the selected pairs.

Selected pairs of*)	ZS/LV	JP/TD	BB/ZS	AP/XX	JP/XX
S_{tilt} [deg]	-40/-44	-44/-42	-39/-40	-40/-15	-43/-15
F_{max} [kHz]	0.575	1.85	1.26	0.577	0.578
ΔP_{max} [dB]	5.49	3.65	3.27	8.85	10.1
$D_{RMS\ (0\text{-}2k)}$ [dB]	2.25	1.62	1.29	4.29	4.43
$D_{RMS\ (2\text{-}6k)}$ [dB]	3.98	1.72	1.69	2.87	3.15
$D_{RMS\ (0\text{-}8k)}$ [dB]	3.49	1.62	1.54	3.83	4.45

*) Noise signal recorded at 90 deg.

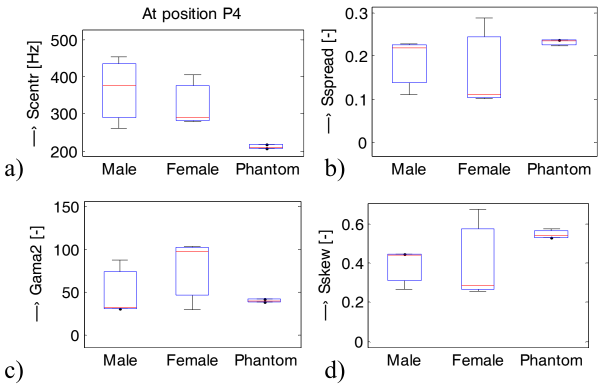

Fig. 5 Box-plot of basic statistical parameters of the supplementary spectral properties: spectral centroid (a), spread (b), gama2 (c), and skewness (d); the microphone located at 90 deg.

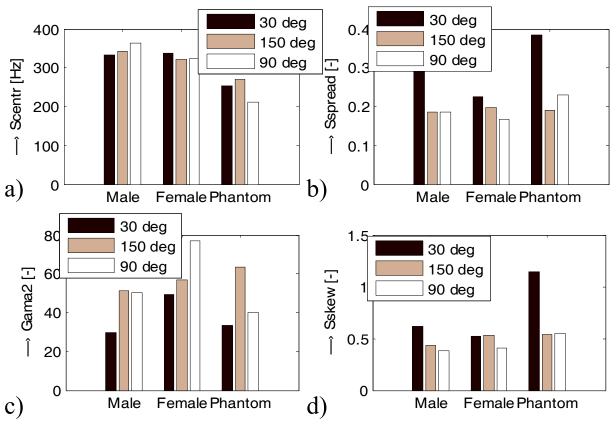

Fig. 6. Comparison of the supplementary spectral properties for different microphone locations: spectral centroid (a), spread (b), gama2 (c), and skewness (d).

4. CONCLUSIONS

The changes in the spectral properties of the noise signal generated by the gradient coils during the MRI scanning sequences were analysed while the examined person lay in the scanning area of the in the open-air MRI machine. The obtained results will serve to create databases of initial parameters (such as the bank of noise signal pre-processing filters) of a developed cepstrum-based algorithm for noise suppression in the recorded speech [10]. It will be useful in experimental practice, when it often occurs that the basic parameter setting of the used scanning sequence as well as the other scanning parameters must be changed depending on the currently tested person.

For better knowledge of the acoustic noise conditions in the scanning area and in the vicinity of the MRI device, accomplishment of additional measurement and experiments is necessary. To describe how the vibrations induce the acoustic noise and how they travel through the plastic holder of the MRI device, the time delay between the vibration impulses caused by the gradient coils and the noise signal must be analysed, too. In the future we will also try to analyse the influence of the metal shielding cage [12] on the reflected acoustic wave.

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