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STUDY OF EFFECTS OF SURGICAL TREATMENT IN THE LARYNX AREA ON THE SPEECH SIGNAL

Wiesław WSZOŁEK(1), Maciej KŁACZYŃSKI(1), Maciej MODRZEJEWSKI(2)

(1) AGH University of Science and Technology
Al. Mickiewicza 30, 30-059 Kraków, Poland
e-mail: {wwszolek, mklaczyn}@agh.edu.pl

(2) Jagiellonian University Collegium Medicum
Św. Anny 12, 31-008 Kraków, Poland

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The speech signal emitted by humans may be a source of useful diagnostic and prognostic information. The signal may become, indirectly by some selected parameters, an additional source of information concerning the condition of the patient's vocal tract anatomy, as well as physiology and pathology (deformation) of his/her other internal organs. The paper presents the next, consecutive stage of the authors' research, concerning the search for additional parameters, which could be used for objective detection and registration of pathological changes in the larynx and vocal tract area.

Keywords: speech processing, speech analysis, pathological speech, surgical treatment.

1. Introduction

At present in the practical larynx diagnosis, more and more frequently larynx pathologies are encountered, which in consequence lead to voice disorders. The general absence of voice organ care is considered to be the main factor lying at the origin of such illnesses. This fact is directly related to the civilization progress, as a result of which, more and more people use their voice organs, namely larynx, as a tool in their professional activity. As it has been shown by specialized studies, several other adverse external factors like nicotine, alcohol, harmful dietary habits, commonly found allergies and presence of synthetic chemical substances, cannot be neglected either. The statistical data concerning occupation-related diseases reveal that more than 20% of cases are the voice organ disorders. It is estimated that about half of the persons suffering from voice disorders are affected by the so-called benign hypertrophic changes in the vocal folds area – laryngeal polyps, Reinke's edema, vocal cord nodule, laryngeal papillomatosis, granuloma or decubitus ulcers. On the other hand, it should be noticed that almost 60% of all cancer-related diseases located in the head and neck area are identified as larynx cancer cases.

The recent development of professional methods for sound registration and processing enables an efficient search for acoustic speech signal parameters that could be useful in elaboration of objective diagnostic methods, aiding the evaluation of the patient's health condition. While in typical studies concerning analysis of normal speech the main attention is focused on revealing (by selected parameters) the semantic aspects of the uttered text, in the typical tasks of medical diagnosis, based on the analysis of pathologically deformed speech, the semantic contents of the uttered text is irrelevant, sometimes it can be even treated as an interference.

The most important and at the same time the most difficult element of the research activity preceding the practical employment of speech as a source of medically useful diagnostic and prognostic information, is the detection and description of such signal parameters, which are as independent as possible from both the language context and personal features of the voice being examined. Additionally the required signal features must be highly sensitive to even the smallest voice deformations in the layer related to the structure and functioning of the speech signal generators (larynx) and the structure of vocal tract, used during the articulation process.

In such a situation a nontrivial problem is the elaboration of such research methodology, which could reveal the existence of any surgical damages (and other, e.g. post-intubation damages) of larynx elements (in particular the vocal cords). Such studies could allow the evaluation of the produced damages, and enable monitoring of the rehabilitation process in the cases of surgical damages and possibly additional control of that process, when phoniatric intervention is necessary. The studies may also provide a basis for objective evaluation of the risk factors related to surgical procedures applied in the larynx area.

It seems necessary to introduce to the laryngological and phoniatrical practice objective, acoustic methods, aiding the multilateral medical evaluation of the patient's health condition, required for diagnosis, prevention and therapy of the voice organ (larynx). Acoustical diagnosis of the voice organ can be defined as unanimous recognition of the voice source parameters, based on the set of relevant acoustic features, contained in the acoustic speech signal. Such features, recognized and extracted from the speech signal, could allow with high probability (when appropriate classification methods are applied) the patient's attribution to one of several classes, predefined with respect to the illness stage.

Therefore in the present work the attention has been focused on the possibilities offered by properly oriented acoustic analysis of the speech signal, and contributing to the scope of presently considered problem.

2. Research material

The study, oriented towards determination of usefulness of selected methods of a typical speech signal parameterization in diagnosis of pathological speech, has been carried out using time domain samples of both the pathological and normal speech signals, the latter being treated as a separate, individually pre-adjusted reference set. The study has been carried out in cooperation with the Chair and Clinic of Otolaryngology Collegium Medicum of the Jagiellonian University in Kraków.

The selection of sounds and groups of words uttered by the examined persons has been based on morphological and functional analysis of the expected (for a given pathology type) dysfunction of speech organs. The phonetic material available for the study consisted of groups of words, selected according to their phonetic features, in order to provide maximum contribution of information concerning the examined pathology.

The registration of time-dependent acoustic speech signals has been carried out in the anechoic chamber, located in Chair of Mechanics and Vibroacoustics, AGH-UST Kraków. A professional PDR 100-digital recorder, by HHB, has been used for registration of time dependences of acoustic pressure $p(t)$ during the text utterance. The registration system, (together with type 40 AF measuring microphone and preamplifier, by G.R.A.S.) ensured signal registration in the 20 Hz to 20 kHz band, with dynamic range not less than 80 dB.

The research subject consisted of patients exhibiting pathological changes of vocal folds and other parts of larynx and glottis. A database has been created, containing samples of acoustic signal of deformed speech, collected from 60 patients being treated in the local clinical hospital. The research has been realized in three stages:

- pre-treatment – the first recording, dated ca. 14 to 7 days before the planned surgical procedure, or during the check-up visit in the hospital,
- early check-up – the second recording, dated between 14 and 30 days after the surgical treatment,
- late check-up – the third recording, realized 90 days after the surgical treatment.

Additionally 36 patients have been registered only in the pre-treatment mode, before their stay in the hospital. In parallel a group of 128 persons, both males and females, have been registered as reference samples of Polish speech, for which no pathology has been detected, which could affect the quality of their voice. In the study the clinical acoustic database has been also used, containing speech recording of patients suffering from speech disorders [12]. The database contains parameterized data for 659 persons uttering the /***a***/ vowel with prolonged phonation.

3. Methods used in the study

The registered research material has been used for creation of a database, containing acoustic signal samples, recorded in the “wave” format. The created database also contains the information concerning the patient’s illness, and respective identifier accompanied by the therapy stage number. Such a database can be used for applying an arbitrary parameterization or any other processing of each database record. The subject literature search shows that majority of authors [1, 3, 5–8, 13, 15] agree, that the features allowing recognition of acoustic speech patterns, including pathological speech, are contained in the amplitude vs. frequency spectra of the acoustic signal. The changes in the human vocal tract itself (geometrical, weight) can be seen by extracting from the acoustic signal the formant parameters, spectral moments, relative spectral power coefficients[1] and melcepstral coefficients [2, 3, 16, 17]. The research methodology applied in the present work has been directed towards detection in the speech certain signal traces of deformations related to the effects of surgical procedures carried out in the larynx area. The changes in glottis area, resulting from the surgical procedures, strongly affect the primary tone F_0 function of the acoustic speech signal.

The evaluation of surgical treatment effects in the glottis area has been based on parameters resulting from changes of the primary tone function. The respective parameters have been divided into the following groups with respect to [9]:

- base frequency (F_0, F_{hi}, F_{lo}, T_0, PFR, STD),
- fluctuation of the base frequency (Jitta, Jitt, PPQ, RAP, sPPQ, vF_0),
- fluctuation of signal amplitude (ShdB, Shimm, APQ, sAPQ, vAm),
- variation of the signal's time sections (NSH, NUV, NVB, DSH, DUV, DVB),
- noise present in the signal (VTI, SPI, NHR),
- tremble (Fatr, Fftr, ATRI, FTRI).

Having ready the set of acoustic signals, represented by some parameterization, it is possible to find out, in an objective way, to what extent are the signals (objects) different from one another. One possible realization of such a study is by comparing the recordings of deformed speech in consecutive therapy stages, e.g. patient's utterances registered before and after the surgical treatment (so-called "internal standards") or by comparing the recordings of deformed speech with registered utterances of the reference group, consisting of normal people (speaking correctly, without extra voice training – so-called "external standards"). In most cases such an analysis is carried out using articulated vowels of prolonged phonation like /***a***/ or /***i***/, which to some extent reduce the emotional attitude of the examined people to the text being uttered and set steady working conditions for the glottal apparatus.

4. Analysis of the results

The main purpose of this acoustic signal analysis of pathological speech was to find out objectively, whether the speech signal of patients treated surgically has been deformed and which of the signal parameters might be the most affected (thus the most useful).

The acoustic signal parameters selected for the analysis are available in the MDVP software package, offered by KAY ELEMETRICS [9]. From these selected parameters, a 33-dimensional feature vector has been created in the following form:

$$X_n = \langle F_0, T_0, F_{\mathrm{hi}}, F_{\mathrm{lo}}, \mathrm{STD, PFR, Fftr, Fatr, Tsam, Jita, Jitt, RAP, PPQ, sPPQ, vF_0}, \\ \mathrm{ShdB, Shim, APQ, sAPQ, vAm, NHR, VTI, SPI, FTRI, ATRI, DVB, DSH}, \\ \mathrm{DUV, NVB, NSH, NUV, SEG, PER}\rangle.$$

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[1] Coefficient defined as a ratio of signal power in the selected frequency band to the total signal power in the whole frequency range.

In Table 1 typical parameterized data are presented for pathological speech signals and the respective averaged standard (reference) values for both female and male speech samples.

Table 1. Parameterized feature vector for correct and pathological speech.

Name	Unit	P_001a	P_002a	P_003a	P_004a	Standard Female	St. Dev.	Standard Male	St. Dev.
F_0	Hz	233.90	224.50	224.57	234.31	243.97	27.46	145.22	23.41
T_0	ms	4.31	4.45	4.45	4.27	4.15	0.43	7.06	1.05
F_{hi}	Hz	317.77	276.28	263.97	249.18	252.72	26.57	150.08	24.36
F_{lo}	Hz	153.02	192.90	186.18	176.25	234.86	28.97	140.42	23.73
STD	Hz	23.28	4.84	7.44	7.89	2.72	2.12	1.35	0.68
PFR		14.00	7.00	7.00	7.00	2.25	1.06	2.10	1.06
Fftr	Hz	–	3.12	–	–	3.08	1.96	3.66	3.73
Fatr	Hz	2.04	–	–	–	2.38	1.74	2.73	1.76
Tsam	s	1.07	1.72	0.61	0.68	3.00	0.00	3.00	0.00
Jita		77.54	45.65	95.12	57.29	26.93	16.65	41.66	36.48
Jitt	%	1.79	1.02	2.13	1.34	0.63	0.35	0.59	0.54
RAP	%	0.96	0.57	1.24	0.81	0.38	0.21	0.35	0.33
PPQ	%	1.10	0.53	1.37	0.84	0.37	0.21	0.34	0.29
sPPQ	%	1.27	0.81	0.74	0.55	0.53	0.22	0.56	0.30
vF_0	%	9.95	2.15	3.31	3.36	1.15	1.01	0.94	0.43
ShdB	dB	0.38	0.33	0.47	0.30	0.18	0.07	0.22	0.09
Shim	%	3.97	3.55	5.10	2.87	2.00	0.79	2.52	1.00
APQ	%	2.98	2.62	3.93	2.16	1.40	0.53	1.99	0.81
sAPQ	%	5.33	4.99	9.24	3.53	2.37	0.91	3.06	1.34
vAm	%	26.86	19.17	39.41	41.81	10.74	5.70	7.71	3.93
NHR		0.20	0.10	0.09	0.11	0.11	0.01	0.12	0.01
VTI		0.04	0.04	0.03	0.04	0.05	0.01	0.05	0.02
SPI		8.04	9.52	22.33	18.72	7.53	4.13	6.77	3.78
FTRI	%	–	0.49	–	–	0.30	0.16	0.31	0.14
ATRI	%	4.52	–	–	–	2.66	1.93	2.13	1.36
DVB	%	0.00	0.00	0.00	0.00	0.20	0.10	0.20	0.10
DSH	%	0.00	0.00	0.00	0.00	0.20	0.10	0.20	0.10
DUV	%	0.00	5.26	10.00	9.09	0.20	0.10	0.20	0.10
NVB		0.00	0.00	0.00	0.00	0.20	0.10	0.20	0.10
NSH		0.00	0.00	0.00	0.00	0.20	0.10	0.20	0.10
NUV		0.00	3.00	2.00	2.00	0.20	0.10	0.20	0.10
SEG		35.00	57.00	20.00	22.00	92.59	0.00	95.00	0.00
PER		246.00	363.00	125.00	144.00	713.19	0.00	433.14	0.00

The database created in such a way (as shown in Table 1) has been used for evaluation of effects of surgical procedures in the larynx area on changes of estimated parameters of the acoustic speech signal, by applying the Fisher (Least Significant Differences) test[(2)] [10]. Figure 1 graphically presents results of the Fisher test for the variance analysis carried out for various recognition classes – larynx cancer, vocal cord polyps, chronic laryngitis, vocal cord paralysis, leukoplakia, dysphonia, in various stages of therapy.

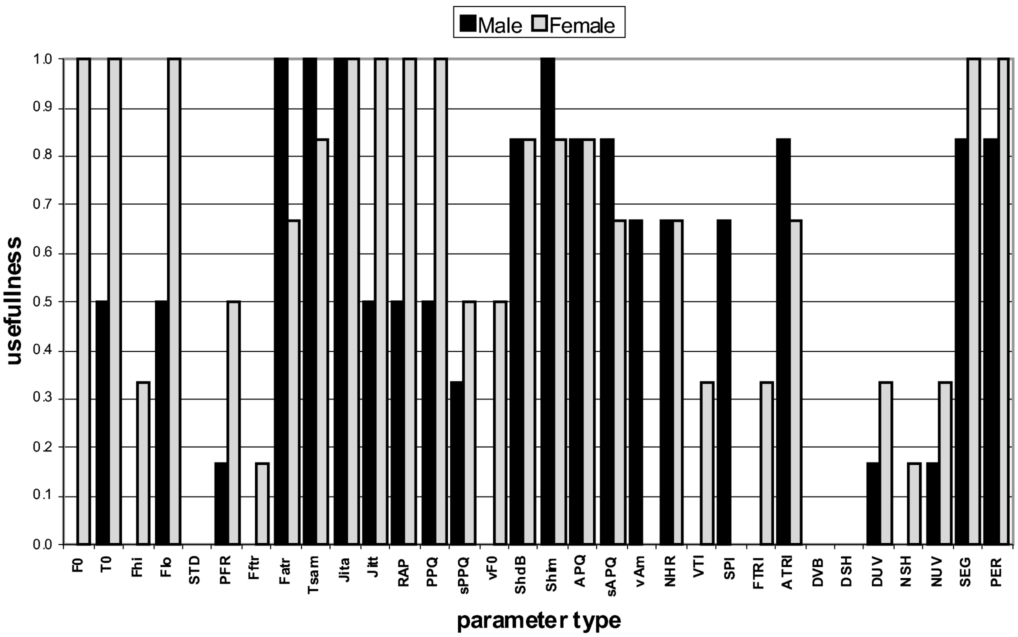

Fig. 1. Usefulness of acoustic parameters with respect to recognition of larynx disorder types (prevention, diagnosis, monitoring).

From the calculation results it follows that for the confidence level $p \leq 0.05$, the same parameter may exhibit different effectiveness in the disorder-type determination, depending on the sex of the patient. The completed research leads to a conclusion that the best usefulness can be achieved for the following parameters:

- Jita (Absolute Jitter) [ms] – evaluating the variability of F_0 within the analyzed time period,

$$\text{Jita} = \frac{1}{N-1} \sum_{i=1}^{N-1} \left| F_0^{(i)} - F_0^{(i+1)} \right|. \tag{1}$$

[(2)] This test, also known as multiple comparisons test, determines the significance of differences between group averages in the variance analysis system.

- Jitt (Jitter) [%] – evaluating the relative irregularity (variability) of the primary tone frequency in consecutive cycles, in relation to the average frequency value,

$$\mathrm{Jitt} = \frac{\frac{1}{N-1}\sum_{i=1}^{N-1}\left|F_0^{(i)} - F_0^{(i+1)}\right|}{\frac{1}{N}\sum_{i=1}^{N} F_0^{(i)}}. \tag{2}$$

- Fatr (Amplitude Tremor Frequency) [Hz] – the frequency ($F_{\text{atr}} = 1/T_{\text{atr}}$) of the most intensive low-frequency amplitude-modulating component in the analysis speech signal divided into window. It is given by the (3) formula.

$$f(i + T_{\text{atr}}) = f(i) = \frac{\frac{1}{N-|k|}\sum_{n=1}^{N-|k|} x_n^i \cdot x_{n-k}^{*i}}{\sum_{n=1}^{N} x_n^{2i}} \cdot 100\%, \qquad -N+1 \leq k \leq N-1, \tag{3}$$

where i-th window of speech signal, n-th sample of speech signal in i-th widow.

- ShdB (Shimmer) [dB] – evaluating amplitude variability (peak to peak) from cycle to cycle,

$$\mathrm{ShdB} = \frac{1}{N-1}\sum_{i=1}^{N-1}\left|20\log(A^{(i+1)}/A^{(i)})\right|. \tag{4}$$

- Shim – (Shimmer) [%] - determines relative amplitude irregularity (variability) for the primary tone in consecutive cycles with respect to its average amplitude,

$$\mathrm{Shim} = \frac{\frac{1}{N-1}\sum_{i=1}^{N-1}\left|A^{(i)} - A^{(i+1)}\right|}{\frac{1}{N}\sum_{i=1}^{N} A^{(i)}}. \tag{5}$$

- APQ (Amplitude Perturbation Quotient) [%] – relative evaluation of short-term amplitude variability, calculated cycle to cycle within the analyzed time period, with smoothing over 5 consecutive cycles,

$$\mathrm{APQ} = \frac{\frac{1}{N-4}\sum_{i=1}^{N-4}\left|\frac{1}{5}\sum_{r=0}^{4} A^{(i+r)} - A^{(i+2)}\right|}{\frac{1}{N}\sum_{i=1}^{N} A^{(i)}}. \tag{6}$$

- PPQ (Pitch Perturbation Quotient) [%] – relative evaluation of F_0 variability, within the analyzed time period, with smoothing factor equal to 5 consecutive cycles,

$$\mathrm{PPQ} = \frac{\dfrac{1}{N-4}\sum\limits_{i=1}^{N-4}\left|\dfrac{1}{5}\sum\limits_{r=0}^{4}F_0^{(i+r)} - F_0^{(i+2)}\right|}{\dfrac{1}{N}\sum\limits_{i=1}^{N}F_0^{(i)}}. \tag{7}$$

Satisfactory results are also obtained for the so-called descriptive parameters – namely Tsam, PER and SEG. However, their sensitivity in the feature vector is strictly related to the length of the analyzed time period and the number of detected signal segments of various properties. These parameters do not carry any diagnostic information. It is interesting that three of the analyzed parameters (STD – standard deviation of the base frequency, DVB – fraction of silent periods in the voice emission, DSH – ratio of the number of subharmonic tones to the number of periods of the primary tone F_0) seem to be useless for solution of the considered problem. As a result of the performed analysis several other features have been also extracted, which seem to be sensitive to the changes in the acoustic speech signal, and which are related to the larynx deformations. The next problem that has been taken under consideration was the possibility of objective evaluation, whether speech signal of the patients after clinical operative treatment has:

- *improved* – i.e. the value of metric (distance) of the pathological signal before the operation from the external standard of speech signal is greater than the respective value in the post-treatment and final evaluations and simultaneously – a subjective improvement of the patient's speech is found by a team of physicians. The following relations must be true:

$$\underset{n}{\exists}\,\underset{i}{\forall}\left[d(X^w,X^p)_{i,I}^n > d(X^w,X^p)_{i,II}^n > d(X^w,X^p)_{i,III}^n\right], \tag{8}$$

  where n – total number of patients, i – number of all metrics included, $d(X^w,X^p)_{i,I}^n$ – pathological signal distance (calculated according to i-th metric) from the external standard of speech signal, calculated for the n-th patient in the I-st evaluation (before the surgical treatment) [4, 11, 14],

- *deteriorated* – i.e. the value of metric (distance) of the pathological signal before the operation from the external standard of speech signal is less than the respective value found during the post-treatment and final evaluations and simultaneously, a subjective deterioration of the patient's speech is found by a team of physicians. The following relations must be true:

$$\underset{n}{\exists}\,\underset{i}{\forall}\left[d(X^w,X^p)_{i,I}^n < d(X^w,X^p)_{i,II}^n < d(X^w,X^p)_{i,III}^n\right]. \tag{9}$$

The criteria of qualitative and quantitative evaluation have been based on application of scalar measures of similarity for acoustic signals, i.e. the distance of these objects in the properly constructed topological space. Therefore calculations have been carried out for six most frequently applied metrics – Hamming (Manhattan), Euclidean, Camberra, Bray and Curtis, Clark, Jeffreys–Matusist [4]. It has been assumed that the bigger the value of scalar metric (signal distance from the reference signal), the bigger is the measure of dissimilarity between these signals. For the case of distance between examined signals close to zero, their similarity is considered to be full. Practical applications of studying the distance of pathological speech signal from internal standard (speech signal of the same person before the treatment) allow the evaluation of effectiveness of the therapy (surgical or conservative treatment), and the trend monitoring, i.e. evaluation whether the positive changes are permanent or transient. On the other hand, the studies with respect to the external standard (reference group of patients, correct speech) provide an objective criterion determining the level of deformation of pathological speech. Figures 2 and 3 graphically present typical results, obtained by calculation of distance

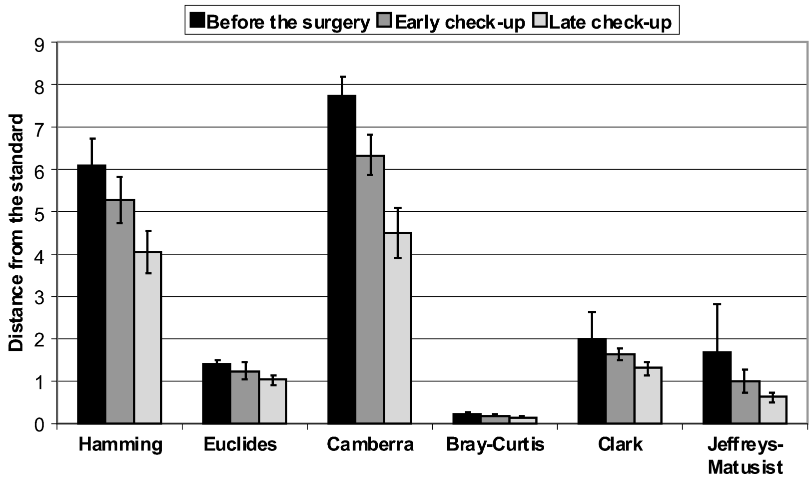

Fig. 2. Average distance from the external standard for the deformed speech signal for vowels of prolonged phonation – /a/, /e/, /i/, /u/, male, diagnosis: Reinke's edema.

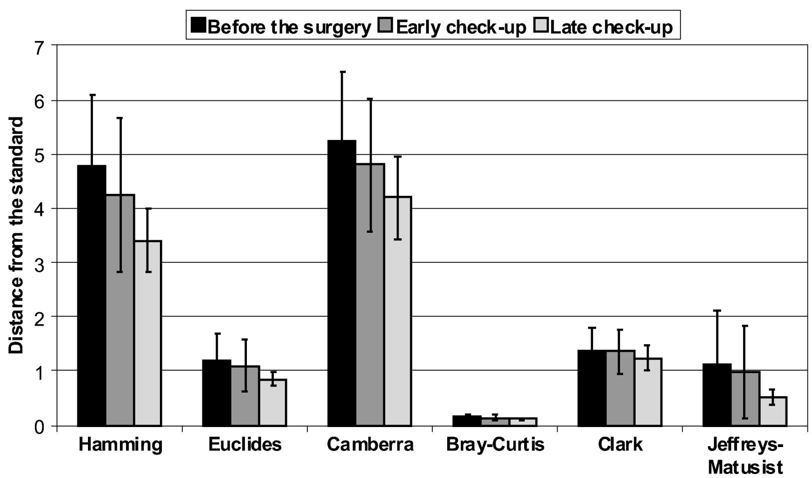

Fig. 3. Average distance from the external standard for the pathological speech signal, for vowels of prolonged phonation – /a/, /e/, /i/, /u/, male, diagnosis: larynx polyp.

between the pathological speech and the reference speech in three different stages of the therapy. In both cases the team of physicians has found a subjective improvement of their speech quality.

In the presented figures it can be seen, that the value of speech signal distance from the standard before the operation is considerably greater than the respective speech signal distance value during the early and late examinations. Figure 4 presents the results of statistical analysis (average value and standard deviation for the distance from external standard) in the group of six vocal tract irregularities most frequently encountered in the database – vocal fold edema (42 patients), ventricular compression (64 patients), paralysis (36 patients), leukoplakia (25 patients), hyperfunction (160 patients), A-P squeezing (100 patients). The calculations have been carried out for a set of samples registered before the surgical treatment.

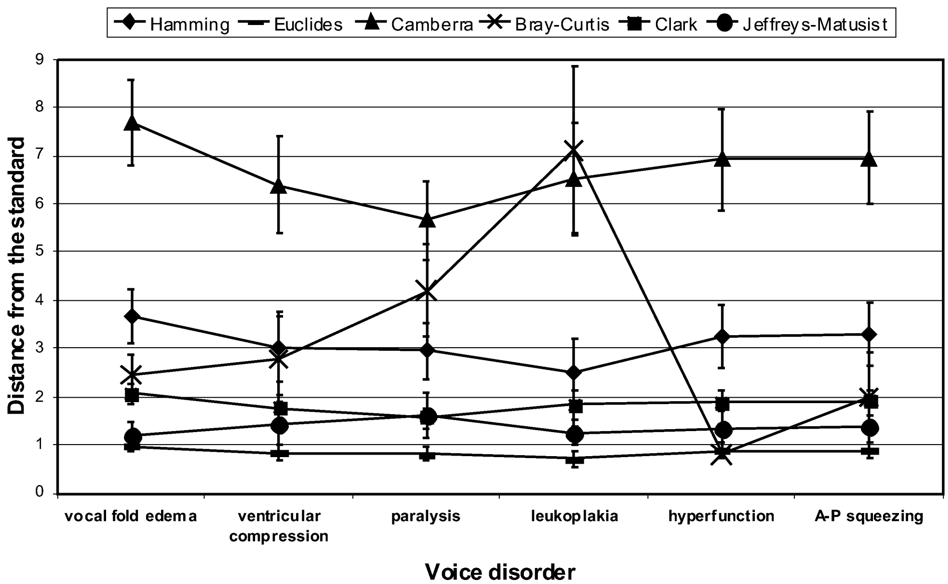

Fig. 4. Average distance from the external standard for deformed speech signal for the /a/ vowel with prolonged phonation.

The required goal is to find such measures, which exhibit respectively high span of values for the distance from external standard, with simultaneous presentation of essential difference with respect to the other diagnosed disorders. On the basis of the obtained results it can be noticed that the Bray-Curtis metric exhibits high sensitivity to the type of diagnosed disorder. We can clearly distinguish between various disorders related to malfunctions of vocal folds (vocal fold edema, ventricular compression, paralysis, hyperfunction) and the ones related to the illnesses of oral cavity (leukoplakia) and esophagus (A-P squeezing). The Camberra and Hamming metrics are also sensitive to the considered deformations and exhibit satisfactory span of values for the distance from the external standard.

5. Conclusions

Further stage of the study included an attempt to evaluate the usefulness of various similarity measures (metrics) for the task of recognition of various vocal tract dysfunction states. On the basis of completed analyses and the obtained results it has been shown that it is possible to evaluate by an objective acoustic method, the level of speech signal deformation, caused by the pathological changes (before the treatment) and the relative deformation changes introduced by the surgical treatment. The Bray-Curtis metric turned out to be the best for metricizing (measuring distances) the space of selected feature vectors. The authors have also determined (at the confidence level of 0.05%) the usefulness of the estimated speech signal parameters with respect to the information significance for recognition of a specific disorder. The set of such parameters includes mainly the ones that are based on evaluation of primary tone frequency and amplitude fluctuations.

The information acquired by such means may be useful in the context of objective evaluation of the speech signal deformation level. The presented results may be used as practical premises during construction of computer systems employing the speech signal for medical diagnosis and therapy. Such systems (implemented in mobile computers) may be used the therapeutic teams (laryngologists, phoniatrists, speech therapists). Further studies should be directed towards the application of effective recognition processes to the medical imaging (e.g. artificial intelligence algorithms – artificial neural networks, multidimensional analysis – support vectors machine).

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