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Comparison of multichannel electrogastrograms obtained with the use of three different electrode types*

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Abstract

The goal of the study was to establish if the conductive area size of recording electrodes affects the quality of a multichannel electrogastrogram. In twelve volunteers (9F, 3M, median age 24 years, range 22–28) on three separate days fasted and postprandial four-channel electrogastrograms were registered in randomized order with Red Dot class Ag/AgCl electrodes of a type: '2222' (conductive area/total area: 2.00/10.24 cm^2, '2271' 2.54/29.64 cm^2, or '2660' 11.64/11.64 cm^2 (total surface conductive!), and subsequently analyzed with a dedicated software. In the case of type 2271 and 2660 the between-electrode electrical conductivity improved at the end of the recording relative to the basal measurement, whereas type 2222 yielded a stable between-electrode electrical conductivity throughout the examination. Despite the differences in either the conductive area size or its construction, the analysis of variance on parameters describing quantitatively the multichannel electrogastrogram did not reveal a superiority of any from among the electrodes tested. Type 2271 was, however, rated the less handy among the three electrodes. Multichannel surface electrogastrography seems to be technically feasible with any type of high quality electrodes, therefore small dimensions and easy handling may favor the choice of a particular type for this examination.

Key words: electrodes, gastric myoelectrical activity, multichannel electrogastrography

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Introduction

During the past decade electrogastrography - a method enabling a non-invasive registration and subsequent analysis of the gastric myoelectrical activity (GMA) - has been drawing an increased attention of researchers and clinicians. A proof thereof is obtained by the analysis of the publications devoted to electrogastrography: two thirds of the world total bibliography on this method was published after the year 2000 (Jonderko *et al.*, 2005a). Coincidentally or not, it was just in the year 2000 that the Federal Drug Administration approved electrogastrography as a test for patient evaluation (Parkman *et al.*, 2003). Undoubtedly that decision may be considered a recognition of the technological maturity of the method, the other specific proof of which consists in availability on the market of a number of commercially offered electrogastrographic recording and analysis systems. Electrogastrography evolves, however, still further. Introduction and validation of the methodology of recording and analysing a multichannel electrogastrogram (Chen *et al.*, 1999; Liang, 2005; Lin and Chen, 2001; McNearney *et al.*, 2002; Wang *et al.*, 2003) was followed soon by a proposal of normal ranges of electrogastrographic parameters designed as quantitative descriptors of the spread of slow waves throughout the stomach, such as: the (A)PSWC = *(average) percentage of slow-wave coupling*, the MDFD = *maximum dominant frequency difference*, the SDPD = *spatial dominant power difference* (Medtronic A/S, 2002; Simonian *et al.*, 2004a, 2004b). The multichannel variety of electrogastrography remains, however, a novelty and huge research work still has to be done until its potential advantages over the 'classical' single channel approach will have ultimately and unequivocally been proven. Also there seems to be space for searching on any possible technical refinements of the method. In the current study we tested if a choice of a particular electrode type may affect the parameters of a multichannel electrogastrogram.

Methods

Subjects

Twelve subjects volunteered to participate in the study, among them were 3 men and 9 women, their median age was 24 years, (range 22–28) and the average body mass index amounted to 20.66 kgm^{-2} (range 17.44 to 25.14). No one among the subjects was a cigarette smoker. During a screening interview ten participants declared themselves as being in full health according to the World Health Organisation criteria, whereas two subjects reported complaints suggestive of functional disorders of the digestive tract which were diagnosed with the use of the *Rome II Integrative Questionnaire* (Drossman *et al.*, 2000) as functional dyspepsia in one of them and irritable bowel syndrome in the other one. A standard ^{13}C-urea breath (Gomolon *et al.*, 2003) test fell positive in four subjects (one of them having also functional dyspepsia), whereas eight volunteers were free from *Helicobacter pylori* infection. Exclusion criteria comprised a history of an abdominal surgery affecting the anatomical integrity of the digestive tract, except for appendectomy, current use of any drugs which might affect gastrointestinal motility, pregnancy. The study was conducted in accordance with the Helsinki Declaration, and every volunteer gave a written consent to participate after having been made

Fig. 1. Placement of electrodes for registration of a multichannel electrogastrogram on the abdominal surface: A1–A4 = active electrodes, R = reference electrode, G = grounding electrode. The photo shows also a routine quality control procedure - a checkup of the electrical resistance between every of the active electrodes and either the reference or the grounding electrode (cf. the text of the respective chapter "*The electrodes and study protocol*".

familiar with the aim, protocol and methodology of the study. The research project was approved by the Bioethics Committee of the Silesian Medical University.

Preparatory procedures

The research was performed on patients reporting to the laboratory in the morning, after a 12-h overnight fast. After completion of a standard preparatory procedure, involving shaving of the skin, if necessary, and a careful abrasion until pink with the use of Every paste (Sorimex, Toruń, Poland), a set of six electrodes was positioned on the abdomen. As illustrated in Fig. 1, four of them were active electrodes: the third active (A3) electrode was fixed in the midline half way between the xyphoid process and the umbiculus (which is a standard position for a single-channel electrogastrography), the fourth (A4) electrode was attached 4–6 cm to the right - in line horizontally with A3 electrode, whereas the second (A2) and the first (A1) electrode were placed with an interval of 4–6 cm on a line leading up from A3 at a 45 degree angle towards the left costal margin. The reference electrode (R) was fixed at the interception of a horizontal line passing through A1 and a vertical line stretching from A3. The grounding electrode (G) was put on the left costal margin on a horizontal line starting from A3. In every subject the exact positions of the electrodes, as well as of the anatomical landmarks such as the costal margins and the umbiculus, were marked on a transparent foil so that they could be exactly reproduced on repeat examination sessions. Finally a motion sensor was taped to the abdominal skin (Medtronic A/S, 2002).

The electrodes and study protocol

Every subject attended three examination sessions on separate days. The median interval

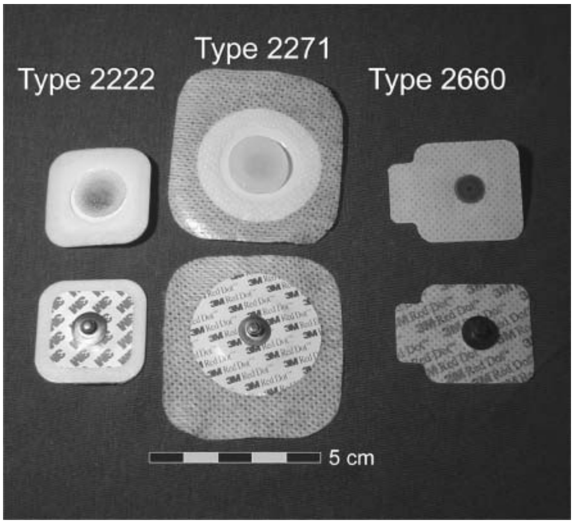

Fig. 2. Electrode types used in the study for registration of a multichannel electrogastrogram: the 2 cm^2 conductive area of type *2222* consists of a sponge soaked with a liquid conductive medium, type *2271* has a 3 mm high cylinder made of a firm conductive gel with a 2.54 cm^2 circular conductive basis, whereas the whole 11.64 cm^2 area of type *2660* is layered with a sticky conductive gel.

between two consecutive examinations amounted to 5.5 days (range 2–12 days). Care was taken to assure that in a given subject the registration on the three examinations days started possibly at the same time, with a maximum accepted deviation of ±15 min. On every session a six-piece set of one of the three tested Red Dot class Ag/AgCl electrode types (3M Canada, London, Ontario, Canada), designed primarily for long-term electrocardiographic monitoring: type *2222* (conductive area/total area: 2.00/10.24 cm^2, type *2271* 2.54/29.64 cm^2, type *2660* 11.64/11.64 cm^2 (total surface conductive!), was applied in random order for the registration of the multichannel electrogastrogram (Fig. 2). In the case of the type *2222*, a drop of a high conductive gel for electroencephalographic recordings (MediGel, Sorimex, Toruń, Poland) was applied directly to the conductive surface of each electrode just before fixing it to the skin. The other two types were fixed on the prepared skin without any additional conditioning. The electrical resistance between every active electrode and either the reference electrode (pairs: A1-R, A2-R, A3-R, A4-R) or the grounding electrode (pairs: A1-G, A2-G, A3-G, A4-G) electrode was checked with the use of a digital ohmmeter (type M3850D, Metex, Seoul, Korea) (Fig. 1), and in case it exceeded 5 KΩ, the respective electrodes were removed and the whole preparatory procedure was started from the beginning (Jonderko *et al.*, 2004; Jonderko *et al.*, 2005b). The measurement of the electrical resistance between the electrode pairs specified was taken again at the end of the registration session.

The examination commenced always with a 30-min basal fasted registration performed with a subject lying comfortably on a couch. Then, at a time point designated '0', the subjects assumed a sitting position and were offered a solid test meal - a pancake made of two eggs, 30 g wheat flour and 0.1 g baking powder, which before serving was smeared with 50 g of strawberry jam; the total energy content of the meal was 1,574 kJ (378 kcal) and it contained 15.5 g proteins, 16.8 g fat, and 43.0 g carbohydrates; 200 ml still mineral water was taken along the meal. Up to ten minutes were allowed to the subjects for the ingestion of the test meal. Thereafter, the recline position was resumed and the postprandial multichannel electrogastrogram was recorded for 90 min after completion of the meal.

Multichannel electrogastrogram registration and analysis

The electrodes were connected to a Medtronic Polygram Net™ EGG 311224 system (Medtronic S/A, Skovlunde, Denmark). The primary signal was sampled at 105 Hz, filtered through a 15 cpm low pass and 1.8 cpm high pass filter, and subsequently down-sampled to 1 Hz and stored in a database on a laptop computer.

The obtained electrogastrograms were analyzed off-line with the use of a dedicated software (Polygram Net. EGG 311224, Medtronic A/S, Skovlunde, Denmark) by a researcher blinded to the experimental conditions linked to a particular data set. At first a visual inspection of the tracings was performed in order to identify and remove any fragments containing motion artefacts. Three algorithms were applied then for the analysis of the multichannel electrogastrograms:

(i) A *running spectrum analysis* involved an autoregressive moving average approach executed on consecutive 60-sec data sets. Frequency ranges were defined as 0.5–2.0 cpm for bradygastria, 2.0–4.0 cpm for normogastria, 4.0–9.0 for tachygastria. A default value of 2.5 dB for the classification threshold was assumed. This stage of analysis yielded the following parameters for each of the four registration channels within a given period:
   - the relative time share of normo-, brady-, tachygastria and arrhythmia,
   - the share of the power within the normogastria-range, the bradygastria-range, and the tachygastria-range relative to the total power of the whole considered frequency band,
   - the instability coefficients of the dominant frequency (DFIC) and the dominant power (DPIC).

(ii) For the *overall spectrum analysis* a fast Fourier transform using a Hamming window was run on consecutive 256-sec data sets with a 128-sec overlap. The analysis yielded the overall dominant frequency (DF) and the power at the dominant frequency (DP). Subsequently the meal-induced change in DP relative to the fasted situation, termed ΔDP, was derived by computation of a net difference in dB between the relevant DPs. Those parameters were derived by default from the third channel tracing.

(iii) A *cross-channel analysis* was accomplished with the use of the VAIVA Propalyzer module (Medtronic A/S, 2002) in order to derive:
   - the percentage of slow wave coupling defined as the relative time within a given period during which the difference in DF between two channels is less than 0.2 cpm; averaging the results pertaining to six possible channels pairs yielded the averaged percentage of slow wave coupling, APSWC.

The analysis outlined was performed for the 30-min interdigestive period and the 90-min postprandial epoch considered as a whole, and additionally for three sub-periods, such as: 1–30 min, 31–60 min, and 61–90 min after completion of the test meal.

Statistical analysis

Statistical analysis of the results involved the repeated measures analysis of variance (R_ANOVA). Significance of differences between means was checked *post hoc* with the Tukey's honest significant difference (HSD) test (Armitage, 1971). Statistical significance was set at the $P<0.05$ level, two-tailed. If not otherwise stated the results are presented as means ± SE. All statistical analyses were performed with the use of the Statistica 6.1 software, license # abdb409a903816ar (StatSoft, Inc., 2004).

Results

Electrical resistance between electrodes

Four factors were included in the R_ANOVA: the reference point for the measurement of between-electrode resistances (two levels: the grounding or the reference electrode), the electrode type (three levels), the moment of taking the measurement (two levels: before or after the recording session), the position of an active electrode (four levels: A1–A4). Since the choice of the reference point did not affect significantly the result of the measurement, this factor was omitted from the further analysis. R_ANOVA disclosed that the electrode type ($F_{2;46}=87.604$, $P=2.056\cdot10^{-16}$) and the moment of taking the measurement ($F_{1;23}=125.32$, $P=8.727\cdot10^{-11}$) exerted both a highly statistically significant influence on the results of the measurement. Moreover, a statistically significant interaction between those two factors was found ($F_{2;46}=58.829$, $P=2.103\cdot10^{-13}$). A respective *post hoc* analysis revealed that type *2660* electrode yielded a consistently higher between-electrode resistance (3.60 KΩ) when compared to the other two types (1.56 KΩ - type *2222* and 1.84 KΩ = type *2271*; $P=0.000128$ in either case of comparison *vs* the *2660* type). In the case of the electrode type *2222* there was no statistically significant difference in the between-electrode conductivity before and after the registration of the electrogastrogram (Fig. 3). Whereas either in the case of type *2271* or type *2660*, the between-electrode conductivity statistically significantly improved throughout the examination, as judged from the lower electrical resistance found at the end of the recording session when compared to the starting value (Fig. 3). Finally, also the position of an active electrode determined significantly the between-electrode resistance ($F_{3;69}=14.450$, $P=2.109\cdot10^{-7}$). According to the *post hoc* analysis, the A2 electrode yielded consistently higher between-electrode electrical resistance than any other of the remaining active electrodes did (detailed data are not shown for the reason of space saving).

Parameters of multichannel electrogastrograms obtained with different electrode types

Dominant frequency classification

According to the R_ANOVA, the electrode type did not affect significantly the relative time share of normogastria, either pre- or postprandially, at any of the four channels considered (Fig. 4). The same result was found for the relative time share of other rhythm classes: bradygastria, tachygastria and arrhythmia.

At no one of the four channels studied was there any significant effect of the electrode type on the dominant frequency instability coefficient detected, either pre- or postprandially.

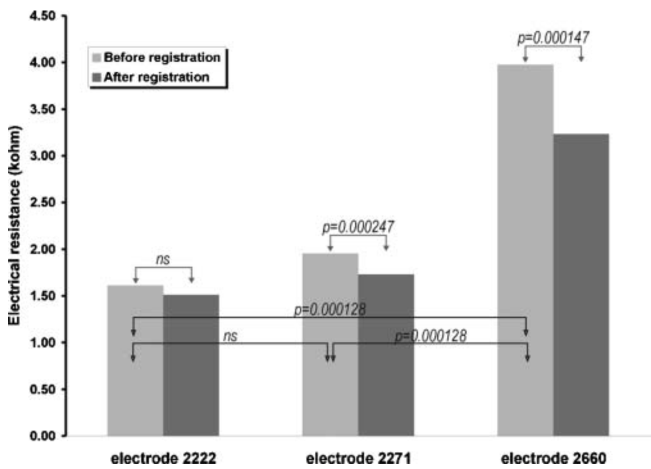

Fig. 3. Graphical presentation of the results of a *post hoc* analysis of the effect of the electrode type and the moment of taking the measurement (before or after the recording session of a multichannel electrogastrography) with regard to the effect on the between-electrode electrical resistance. Type *2660* electrode yielded a consistently higher between-electrode resistance when compared to the other two types. Either in the case of type *2271* or type *2660* the between-electrode resistance was significantly lower at the end of the examination; ns = difference statistically not significant.

Power share relative to rhythm classification

Neither in the fasted nor in the fed state did the electrode type affect the share of the power within the limits of the normogastria frequency range relative to the total power of the whole frequency band considered (Fig. 5). The same was stated with regard to the relative shares of power within the brady- and the tachygastria frequency ranges relative to the total power of the entire frequency band. The dominant power instability coefficient was not affected significantly by the electrode type at any of the four channels studied, either in the fasted or in the fed state.

Slow wave coupling

The electrode type did not exert any statistically significant influence on the average percentage of slow wave coupling either in the fasted period or during any of the sub-periods analyzed after meal stimulation of the stomach (Fig. 6).

Parameters derived from a single channel analysis of the electrogastrograms obtained with different electrode types

Meal-induced evolution of the dominant frequency and the dominant power

Following ingestion of the test meal, a trend towards an increase in the dominant frequency was observed - a phenomenon discernible by means of visual analysis of a respective graph (Fig. 7, upper panel) which did not, however, get a statistical corroboration by means of the R_ANOVA. As theoretically expected with the kind of the test meal used in this study, the postprandial DP increased statistically significantly when compared to the fasted situation (Fig. 7, lower panel). For the effect mentioned R_ANOVA revealed an $F_{3;33}$=13.399, P=0.000007; *post*

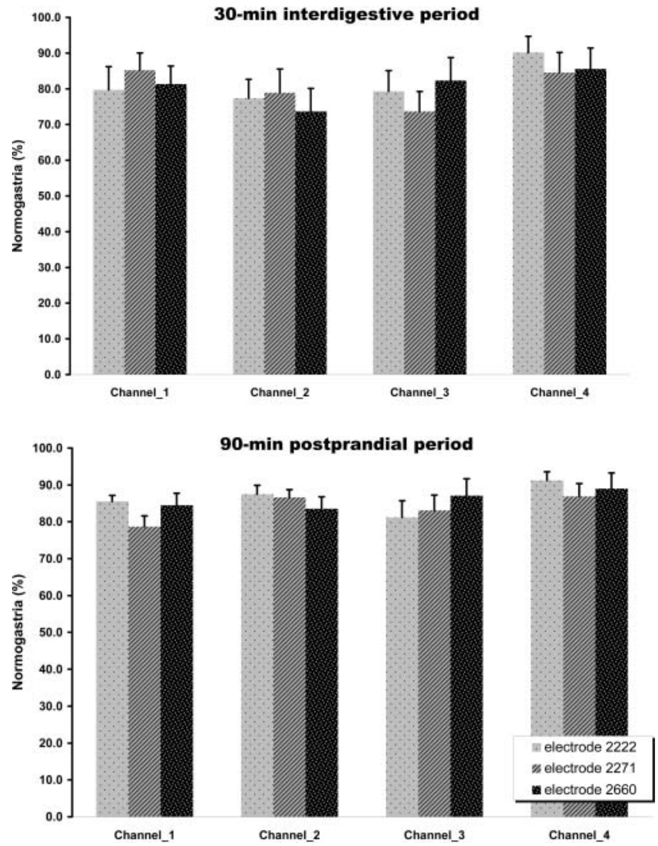

Fig. 4. Relative time share of normogastria in multichannel electrogastrograms registered with three different electrode types.

hoc: the DP increased from a pre-meal value of 41.60 dB to 48.29 dB (P=0.00017), 46.97 dB (P=0.00035), and 46.38 dB (P=0.0107) during the first, the second and the third 30-min postprandial sub-period, respectively. There was no statistically significant difference among the three electrode types tested with respect to their ability to convey correctly the meal-induced evolution of the dominant frequency and the dominant power (Fig. 7).

Discussion

A known limitation of the 'classical' single channel electrogastrography consists in its inability to provide information about regional electrical activity of the stomach. Whereas data confirming the place of origin of the gastric slow waves, and describing the characteristics of their migration from the pacesetter area towards the distal antrum have been successfully derived by means of direct recordings of the electrical events from electrodes placed surgically onto the serosal surface of the stomach, such an approach cannot be considered applicable in a clinical gastroenterology setting. Therefore the idea of developing an effective multichannel electrogastrographic system has been quite a tough challenge for a long time.

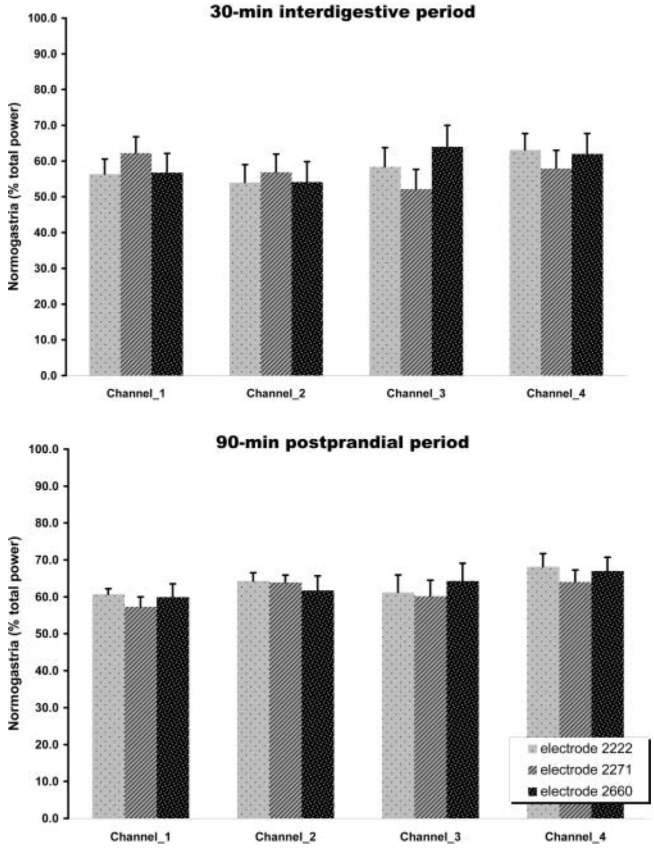

Fig. 5. Share of the power within the limits of the normogastric frequency range (2.0–4.0 cpm) relative to the total power within the whole frequency range considered (0.5–9.0 cpm) in multichannel electrogastrograms registered with three different electrode types.

Ten years ago a discouraging report was published, according to which a fiveelectrode recording system, configured to provide 8 differential channels of registration of the GMA along the longitudinal stomach axis, failed to yield meaningful time shifts even between the most distant electrode pairs separated by 10 cm (Mintchev and Bowes, 1996). A breakthrough came in 1999 - with the use of an originally developed cross-covariance analysis Chen *et al.* were able to detect time lags between the voltage signals recorded from the abdominal surface with a system comprising four differential channels (Chen *et al.*, 1999). Soon thereafter, another analytical approach - the cross running spectrum - was validated in an animal experiment as being able to provide information about the percentage of slow wave coupling between any pair of the multichannel electrogastrographic system (Wang *et al.*, 2003).

A remark on the importance of electrodes for derivation of a good quality recording of the GMA can be found in the ingenious paper of the inventor of electrogastrography - in the year 1922 Walter C. Alvarez wrote: "(…) *I first proved to my satisfaction that good quality electrogastrograms could be obtained by applying nonpolarizable electrodes to the shaved abdominal walls of rabbits.* (…)" (Alvarez, 1922). Fifty three years later the problem was still serious, as

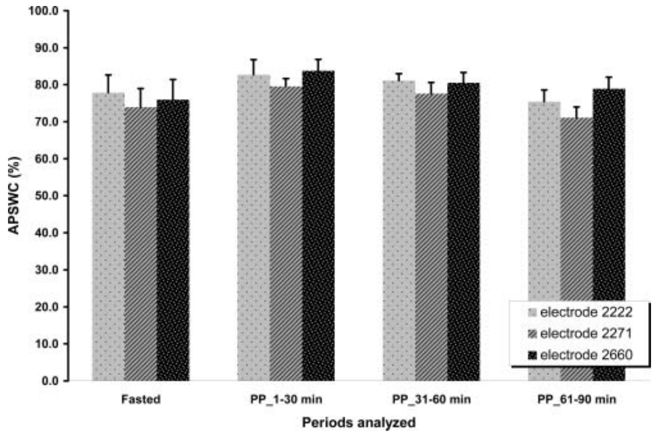

Fig. 6. Average percentage of slow wave coupling (APSWC) determined in multichannel electrogastrograms registered with three different electrode types; PP=postprandial period.

judged from the statement found in the paper by Brown BH *et al.*: "(...) *If recording was started within an hour of attaching electrodes there was often a large amount of electrode 'noise' and respiratory artefact* (...)" (Brown *et al.*, 1975). To a large extent the "electrode problem" was soon overcome with the invention of a proper skin preconditioning procedure (Burbank and Webster, 1978) and of application of a conductive gel to the conductive surface of electrodes (Myers *et al.*, 1984), as well as the elaboration of an optimum configuration of electrode positioning on the abdomen (Mirizzi and Scafoglieri, 1983; Hamilton *et al.*, 1988). But still at the end of the twentieth century the issue of how external factors, such as: the inter-electrode distance, abdominal thickness, *i.e.* how far are the surface electrodes from the source of the GMA, as well as the geometry of electrodes affect the electrogastrogram, remained a problem intensely examined by researchers active in the field of electrogastrography (Mintchev and Bowes, 1996; Mintchev *et al.*, 1997; Mintchev and Bowes, 1998).

Three items gave a direct boost to undertake the research described in this paper: a former report published by Mintchev *et al.* on the impact of different electrode surface areas on electrogastrograms (Mintchev *et al.*, 1997), stringent requirements of a superior quality equipment, as accentuated in the first description of the multichannel electrogastrographic system given by Chen *et al.* (1999), and finally introduction to the market of a new Red Dot class Ag/AgCl electrode - the type *2660*. The *2660* electrode offers two unique features: it is fully repositionable without any deterioration of the quality of registration of bioelectric signals, and its entire surface of 11.64 cm^2 is conductive.

The latter feature attracted our particular attention, because according to the results obtained by the Mintchev's group, too small an electrode conductive area would bring about a weakening of the electrical signal received from the abdominal surface (Mintchev *et al.*, 1997). In the study quoted, the performance within an 8-channel electrogastrographic recording system of a "small electrode" of a conductive area of 0.78 cm^2 was compared against a "large" electrode the conductive surface of which amounted to 5.31 cm^2 (ratio 1:6.81). Especially during the postprandial recording period the "large" electrode yielded a stability of the dominant

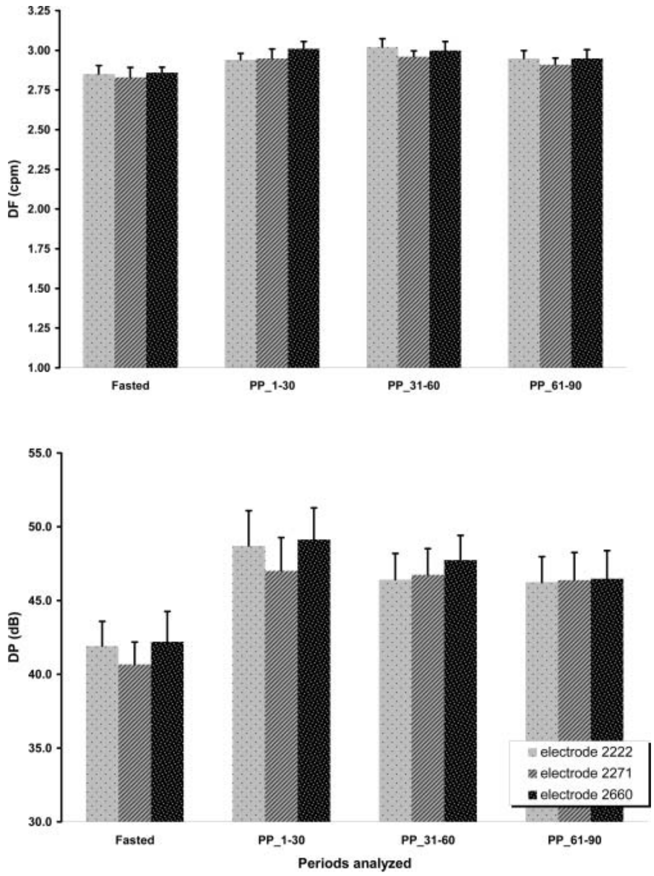

Fig. 7. Meal-induced changes in the dominant frequency (DF) - upper panel, and the dominant power (DP) - lower panel captured with three different electrode types; PP=postprandial period.

frequency superior to the "small" one. Moreover, with the smaller electrode a marked worsening of the signal quality was noted (Mintchev *et al.*, 1997).

In our study the conductive surfaces amounted to 2.00, 2.54, and 11.64 cm^2 in the case of the type *2222*, *2271* and *2660*, respectively. Thus the ratio between the conductive surfaces was 1:5.82 in the case of type *2222* contrasted with *2660*, and 1:4.58 when type *2671* was compared to *2660*. Despite the differences in either the size of the conductive area or its construction (in type *2222* it consists of a sponge soaked with a liquid conductive medium, type *2271* has a 3 mm protruding cylinder made of a firm conductive gel with a circular conductive basis, whereas the whole surface of type *2660* is layered with a sticky conductive gel), all the three types tested offered a good between-electrode conductivity. It is worth of noting, however, that in the case of types *2271* and *2660* the low between-electrode resistance was obtained without application of any additional conductive gel. The between-electrode conductivity remained stable throughout the recording time with type *2222*, whereas with the other two types - *2271* and *2660* - even a slight but statistically significant improvement of conductivity was observed, as confirmed by the comparison of the between-electrode resistance measured before the commencement and after the end of the electrogastrographic session.

We scrutinized the three electrode types for their performance of registration of a multichannel electrogastrogram. A vast panel of parameters currently recommended for a quantitative description of a multichannel electrogastrogram was taken into consideration. It comprised the dominant frequency classification, the power share relative to rhythm classification, the slow wave coupling, as well as the meal-induced evolution of the dominant frequency and the dominant power (Medtronic A/S, 2002). According to the results of the statistical analysis of the results obtained, in no instance a superiority of any from among the electrodes tested was discernible. One may therefore infer that: (i) even the 2–2.5 cm^2 conductive area is sufficient to obtain an accurate multichannel electrogastrogram, provided that the recording electrodes are of a good quality and the procedures of proper skin preparation are observed carefully, and/or (ii) that the present day systems of bioelectrical signals acquisition, conditioning, and analysis are elaborated near to perfection so as to cope efficiently with a noisy source of a weak electrical signal which is the case of voltages transmitted across the abdominal wall from the stomach to the abdominal surface. Therefore just a practical aspect may be decisive for the choice of a particular electrode type, namely an easy handling. According to our experience, type *2271* with its width of 52 mm appeared to be simply inconvenient for use with the multichannel electrogastrography because a correct positioning of 6 pieces thereof onto an abdomen of a slim subject appeared to be a tough task. Taking into account the results obtained, type *2660* electrode is worth of recommendation because it offers a flawless performance of a multichannel electrogastrogram, and it does not require any supplementation with a conductive gel.

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