Polish Journal of Medical Physics and Engineering 2017;23(2):37-42 June 2017
doi: 10.1515/pjmpe-2017-0007
ISSN 1898-0309

Scientific Paper

Effect of electrode contact area on the information content of the recorded electrogastrograms: An analysis based on Rényi entropy and Teager-Kaiser Energy

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(received 2 March 2017; revised 18 April 2017; accepted 2 May 2017)

Abstract

Electrogastrograms (EGG) are electrical signals originating from the digestive system, which are closely correlated with its mechanical activity. Electrogastrography is an efficient non-invasive method for examining the physiological and pathological states of the human digestive system. There are several factors such as fat conductivity, abdominal thickness, change in electrode surface area etc, which affects the quality of the recorded EGG signals. In this work, the effect of variations in the contact area of surface electrodes on the information content of the measured electrogastrograms is analyzed using Rényi entropy and Teager-Kaiser Energy (TKE). Two different circular cutaneous electrodes with approximate contact areas of 201.14 mm^2 and 283.64 mm^2, have been adopted and EGG signals were acquired using the standard three electrode protocol. Further, the information content of the measured EGG signals were analyzed using the computed values of entropy and energy. Results demonstrate that the information content of the measured EGG signals increases by 6.72% for an increase in the contact area of the surface electrode by 29.09%. Further, it was observed that the average energy increases with increase in the contact surface area. This work appears to be of high clinical significance since the accurate measurement of EGG signals without loss in its information content, is highly useful for the design of diagnostic assistance tools for automated diagnosis and mass screening of digestive disorders.

Key words: electrogastrography; biopotentials; cutaneous electrodes; Rényi entropy; Teager-Kaiser energy operator; information content.

Introduction

The gastrointestinal (GI) tract is a tubular system that begins with the mouth starting from oropharynx, esophagus, stomach, small and large intestines and terminating at the anus. Process of digestion has several stages in which food is broken down and absorbed [1]. Additionally, the gastrointestinal tract is a route for drug administration, absorption, biotransformation, detoxification, and excretion [2]. The electrophysiology of the digestive system is highly complex and the electrical activity of the digestive system is closely correlated with the mechanical process of digestion [3].

Electrogastrography is the measurement and recording of the electrical activity associated with the process of digestion. In this technique, the electrical signals originating from the abdomen over the stomach are recorded using cutaneous electrodes placed on the abdominal skin [4]. The recorded signal is called an electrogastrogram and is clinically useful for diagnosis of various digestive disorders such as Gastroesophageal reflux diesaese, functional dyspepsia, stomach ulcer, etc. Further, the non-invasive nature of this method makes it a simple, cost effective and efficient technique for classification of the pathological and physiological states of the digestive system [5].

The complexity of the physiological system and the associated information content can be quantified using a number of techniques derived from the fields of nonlinear dynamics, thermodynamics and statistical mechanics [6]. The entropy associated with the system is derived from the second law of thermodynamics and has found its application in biomedical signals and time series analysis. The entropy of a system is a measure of the disorder associated with the system and hence is used to quantify the information content of a signal. In recent years, several researchers have used entropy measures for solving significant problems in the field of biomedical engineering [7-10]. Bromiley *et al.* (2004) [11]

have presented the utility of entropy measures such as Shannon entropy and Rényi entropy. Further, the authors have derived the correlation between Rényi entropy and information content. Also, the authors have concluded that Rényi entropy is a monotonic function of the information content and can be interchangeably used.

Energy of the system is defined as the capacity of a system to do work. Biological systems are natural energy transformers. The activity of biological systems produces associated electric signals which are closely related with the system dynamics [12]. Teager-Kaiser Energy operator is an efficient tool for analyzing the energy of biosignals in both continuous and discrete domains. The Teager-Kaiser Energy is a measure of the energy required by the physiological system to produce the associated biosignal [13].

The change in electrode conductive area affects the quality of the electrophysiological measurements. Several biomedical researchers have presented the effects of different electrode surface area for analysis of biosignals [14-16]. Mintchev *et al.* (1997) [16] have experimentally concluded that the quality of the EGG signals depends on the electrode surface area used. Further, the authors have experimentally demonstrated that the specificity of the EGG test significantly varies with changes in the contact area of the surface electrodes used for measurement. Additionally, there are several other factors such as fat conductivity, abdominal thickness etc. affects the EGG signal recordings. Mintchev et al. (1998) [17] have presented the effect of different abdominal thickness on non invasive recordings of Electrogastrograms. Kim *et al.* (2012) [18] have experimented two complementary methods such as Magnetogastrograms and Electrogastrograms for measurement of gastric electric potentials. Further, the authors have quantified the effects of fat conductivity and thickness parameters on both electric and magnetic fields. Also, the authors have concluded that the increase in thickness of fat layer merely affects the amplitude of the EGG signal.

The objective of this work is to analyze the effect of electrode surface area on the information content of the measured electrogastrograms.

Methodology

EGG Signal Acquisition

In this work, a three electrode EGG measurement system was adopted for noninvasive measurement of EGG signals. According to the standard electrode placement protocol, the first and second electrodes positioned below the left costal margin and, between the xyphoid process and the umbilicus, respectively. The third cutaneous electrode is placed away from the stomach region for isolation purpose [19, 20]. Two different conductive solid gel Ag/AgCl surface electrodes with contact areas of 201.14 mm_2 and 283.64 mm_2 were used to record EGG signals from ten normal individuals in consecutive sessions. The recordings were used to analyze the effect of the change in electrode contact areas on the information content of EGG signals. Further, the acquired EGG signals were amplified using an instrumentation amplifier designed using IC AD624. The amplified EGG signals were acquired using LABVIEW data acquisition card (NI USB-6009) and recorded using LABVIEW (V 14.0.1) software. The EGG signals of ten normal male adults were recorded with their consent, for a period of 10 minutes using the two different electrodes with varied contact surface area. A sampling time of 0.01 seconds was used for recording the EGG signals. Further, the EGG signals were de-trended and were further analyzed.

Rényi entropy

The statistical concept of order and disorder was revealed by the investigations of Boltzmann and Gibbs in statistical physics. The quantitative connection is expressed by [21]:

$$entropy = k \log D \qquad \text{Eq. 1}$$

where, k is the Boltzmann constant, and D is a quantitative measure of the system disorder. In natural system, entropy appears to be a positive function of time and tends to reach a state of maximum entropy [21].

The concept of entropy was introduced by Rudolph Clausius in connection with the second law of thermodynamics [6]. Entropy is a measure of disorder associated with a system and hence is a measure of information content, uncertainty and complexity of the system [22]. The concept of entropy is utilized in various fields of science and engineering such as statistical mechanics, information theory, biomedical signal processing, chaos theory, neural networks, mathematical linguistics, and taxonomy [6]. Alfred Rényi proposed the most general definition of information measure that would preserve the additivity for independent events and was compatible with probability axioms [23].

For a given a sample of probabilities p_i:

$$\sum_{i=1}^{N} p_i = 1 \qquad \text{Eq. 2}$$

Rényi entropy of the sample $H(\alpha)$ is given by [22]:

$$H(\alpha) = \frac{1}{1-\propto} \ln\left(\sum_{i=1}^{n} p_i^{\alpha}\right) \qquad \text{Eq. 3}$$

where p_i is the probability that a random variable takes a given value out of n values, and α is the order of the entropy measure. As α increases, the entropy values become more sensitive to higher probabilities and less sensitive to lower probabilities. The Rényi entropy is a monotonic function of the information which implies that the Rényi entropy and information content can be used interchangeably in any practical applications [11]. The information content of the recorded EGG signals for variations in the contact surface area of the measuring electrodes was quantified using the Rényi entropy.

Teager-Kaiser Energy operator

The energy of a simple oscillation is proportional to both the square of the amplitude and the square of the frequency of the oscillation. Teager-Kaiser energy (TKE) operator is an efficient tool for analyzing both continuous and discrete signals from the energy point of view [24].

The discrete Teager-Kaiser energy operator Ψ is defined as [24]:

$$\Psi[x(n)] = x^2(n) - x(n+1) \cdot x(n-1) \qquad \text{Eq. 4}$$

where, x is the measured EGG value and n is the sample number [25]. In recent years, the Teager-Kaiser energy operator is used to calculate the overall change in energy of the signal on biological systems [26]. Further, the Teager-Kaiser Energy operator tries to model the energy of the source of the signal, and not the energy of the signal which is actually measured [13]. In this work, the energy associated with the measured EGG signals was quantified using the TKE operator.

Results and Discussion

Figures 1a and **1b** show a typical EGG signal measured using the surface electrode with a contact area of 201.14 mm^2, for a period of 10 minutes and the single sided amplitude spectrum of the signal, respectively. It is observed that the frequency range of 0.01 to 0.1 Hz is prominent in the FFT of the EGG signals acquired using the surface electrode with a contact area of 201.14 mm^2.

Figures 2a and **2b** show a typical EGG signal measured using the surface electrode with a contact area of 283.64 mm^2, for a period of 10 minutes and the single sided amplitude spectrum of the signal, respectively. It is observed that the frequency range of 0.01 to 0.06 Hz is prominent in the FFT of the EGG signals acquired using the surface electrode with a contact area of 283.64 mm^2. While comparing the single sided amplitude-frequency spectrum of the EGG signals acquired from two different electrodes, it is clearly observed that the contact surface area affects both the amplitude and frequency of the EGG signal.

Figures 3a-e show the average Rényi entropy of normalized EGG signals for two different contact area of measuring electrodes, for five different α values (α = 0.2, α = 0.4, α = 0.6, α = 0.8 and α = 0.9) respectively. It is seen that the average Rényi entropy increases with increase in contact surface area. This phenomenon may relate to the increased signal collecting ability of the electrode with larger surface area. Further, it is observed that the Rényi entropy increases with increase in α. Hence at higher orders, the relation between the Rényi Entropy and Surface area is more prominent. Since, Rényi entropy is a measure of the information content in the measured EGG signals, it is demonstrated that the information content of the EGG signals increases with increase in the contact area of the surface electrodes used for acquiring the signals. Also, the difference in the Renyi entropy values of EGG signals acquired from electrodes with different contact areas, was found to be statistically significant ($P < 0.006$).

While comparing the percentage change in the information content (with = 0.9) with a change in the contact area of the measuring surface electrode, it is found that an increase of 29.1% in electrode surface area leads to an increase in the information content of the measured EGG signals by 6.72%.

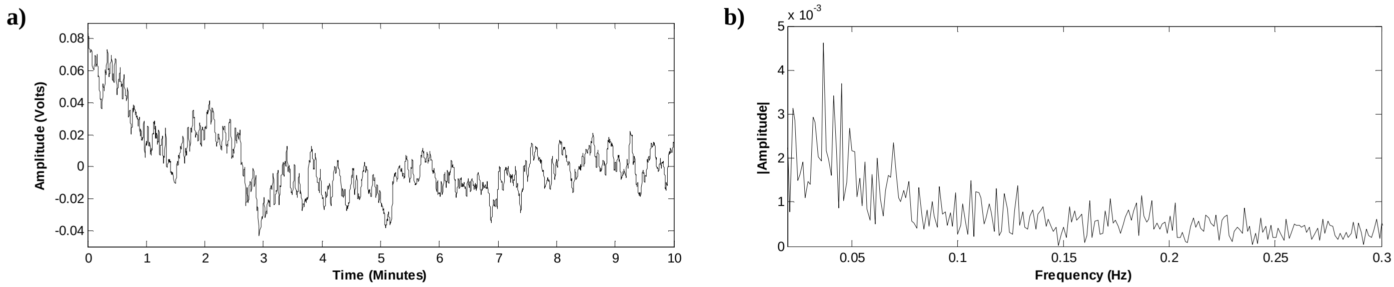

Figure 1. (a) A typical EGG signal measured using the surface electrode with a contact area of 201.14 mm^2, (b) the single sided amplitude spectrum of the EGG signal.

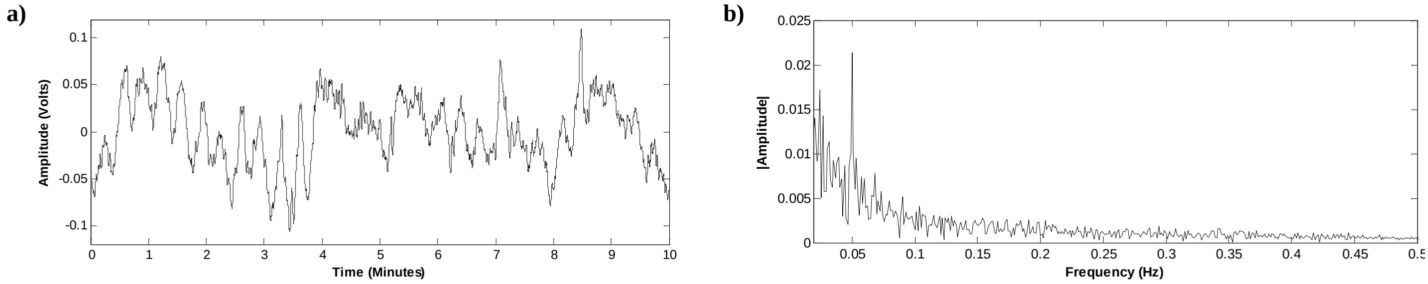

Figure 2. (a) A typical EGG signal measured using the surface electrode with a contact area of 283.64 mm^2, (b) the single sided amplitude spectrum of the EGG signal.

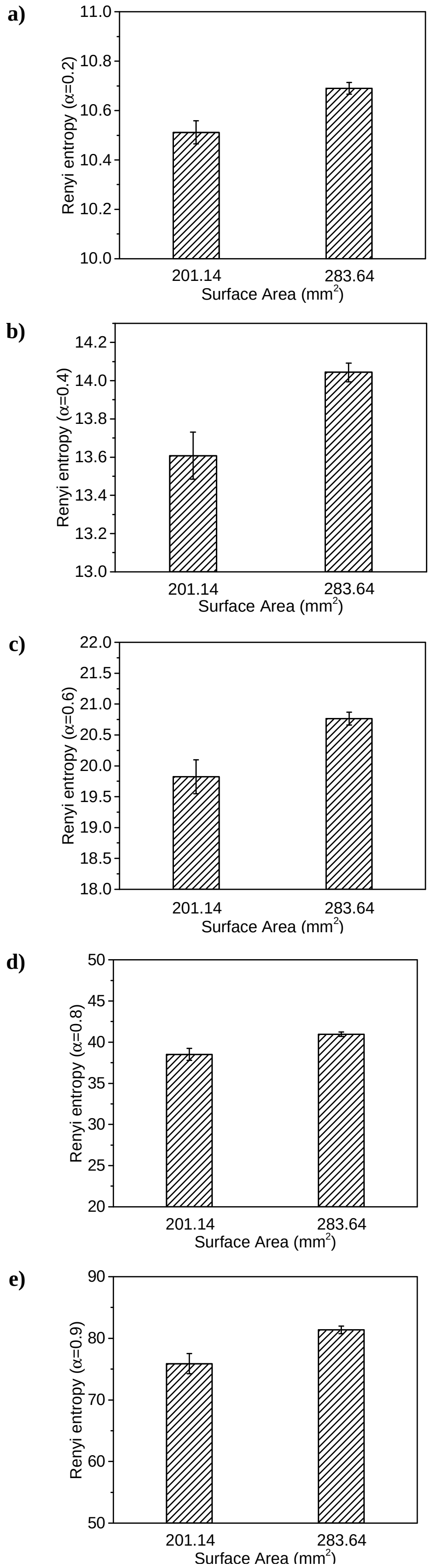

Figure 3. The Rényi entropy (Mean ± Standard Error) of EGG signals collected from electrodes with different contact area for five different α values (a) α = 0.2 (b) α = 0.4 (c) α = 0.6 (d) α = 0.8 and (e) α = 0.9.

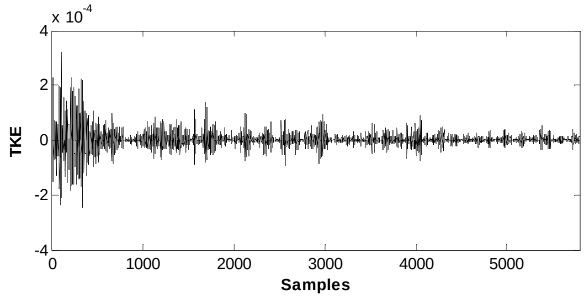

Figure 4. Teager-Kaiser Energy of the EGG signal acquired using surface electrode with 201.14 mm^2 contact area as a function of sample number.

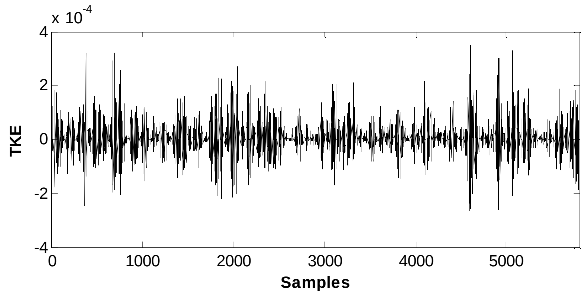

Figure 5. Teager-Kaiser Energy of the EGG signal acquired using surface electrode with 283.64 mm^2 contact area as a function of sample number.

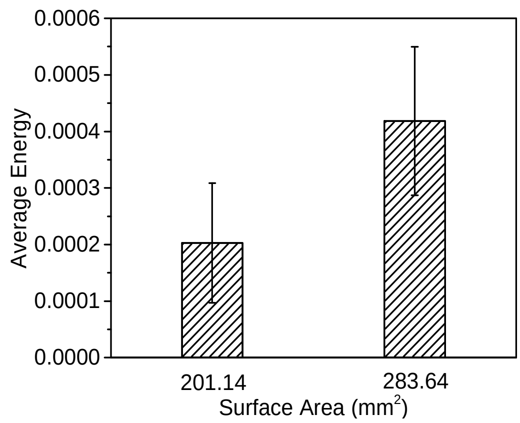

Figure 6. The Teager-Kaiser Energy (Mean ± Standard Error) of EGG signals for different electrode contact areas.

Figure 4 and **Figure 5** show the Teager-Kaiser Energy of the EGG signal acquired using the surface electrode with contact areas of 201.14 mm^2 and 283.64 mm^2, respectively as a function of sample number. It is observed that the Teager-Kaiser Energy of the measured EGG signals assumes both positive and negative values. This phenomenon appears due to the fact that the Teager-Kaiser Energy operator tries to model the energy of the source of the signal rather than the energy of the signal itself [13]. This result demonstrates that the EGG signal is generated by multiple sources in the digestive system.

Hence, it is seen that the EGG signal consists of information about several subsystems of the human digestive system and using proper analysis, the EGG signals acquired using the adopted protocol can be used for assessment of various parts of the human digestive system. **Figure 6** shows the average Teager-Kaiser Energy of normalized EGG signals, acquired from electrodes with different contact area of 201.14 mm^2 and 283.64 mm^2 electrode. It is seen that the average energy increases with increase in contact surface area.

Conclusion

The electrical signals originating from the digestive system are collectively called as Electrogastrograms. Electrogastrography is a cutaneous measurement and recording technique of the gastric electrical activity associated with the process of digestion [22]. Further, the non-invasive nature of this method and the mechano-electric correlations makes it a simple and efficient technique for classification of various disorders associated with the digestive system. The change in electrode surface area impacts the quality of the EGG recordings. In this work, the effect of variations in the contact area of surface electrodes on the information content of the measured electrogastrograms is analyzed using Rényi entropy and Teager-Kaiser Energy. The three electrode system and the standard recording protocol were adopted for recording the EGG signals. Two different circular cutaneous electrodes with approximate contact areas of 201.14 mm^2 and 283.64 mm^2 have been adopted. Further, the information content of the measured EGG signals was analyzed using the computed values of entropy and energy. Results demonstrate that the information content of the measured EGG signals increases by a factor of 6.72% for an increase in the contact area of the surface electrode by 29.1%. Further, it was observed that the average energy increases with increase in the contact surface area and the contact surface area affects both the amplitude and frequency of the EGG signal. This work appears to be clinically significant since the measurement of EGG signals without loss in its information content is required for assessing the electromechanical associations and for the design of systems for diagnosis of digestive disorders.

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