Digestive Diseases and Sciences, Vol. 45, No. 11 (November 2000), pp. 2137–2144

Misinterpretation of Human Electrogastrograms Related to Inappropriate Data Conditioning and Acquisition Using Digital Computers

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Despite the fact that digital techniques for data acquisition and processing were widely used in electrogastrographic (EGG) research during the last decade, inappropriate signal conditioning and digitization are still potential pitfalls threatening the reliability of the experiments. The aim of this paper was to review: (1) the importance of the antialiasing low-pass filtering for reducing recording artifacts and interferences, (2) the advantages brought by the proper choice of filter cutoff frequency and the slope for the decrement of the minimal required sampling frequency, (3) the impact of incorrectly selected sampling frequency on data interpretations, with particular attention to the percent distribution ranges, and (4) the "leakage effect" related to the finite number of samples processed simultaneously in frequency domain representation of the recordings. A model of electrogastrographic (EGG) recording was mixed with a model of electrocardiographic (ECG) artifact. The resulting finite-duration signal was low-pass filtered and then digitized with a sampling frequency of 1 Hz. The cutoff frequency of the first-order low-pass filter was altered from 0.5 to 0.1 Hz. Amplitude frequency spectra of the digitized recordings were investigated. An example with a real human electrogastrogram in which an ECG artifact was present confirmed the simulation results. When a first-order anti-aliasing filter is utilized at least a fivefold difference between the filter cutoff frequency and the sampling frequency is recommended for compliance with the Nyquist theorem of digitization. Leakage effects associated with the finite-time duration of the recordings and the use of the discrete Fourier transform should be considered when frequency domain analysis is performed. Misinterpretation of the "bradygastric" and "tachygastric" ranges in the percent distribution of EGG frequency components is possible if inappropriate signal conditioning and digitization are employed.

KEY WORDS: gastric recordings; data acquisition; digital signal processing; aliasing; filtering; Fourier transform; Nyquist theorem.

In the last two decades development of digital computers significantly influenced electrogastrographic (EGG) research (1). Recordings of gastric electrical activity (GEA) and electrogastrography are presently routinely performed using digital data acquisition and analysis systems. However, in many

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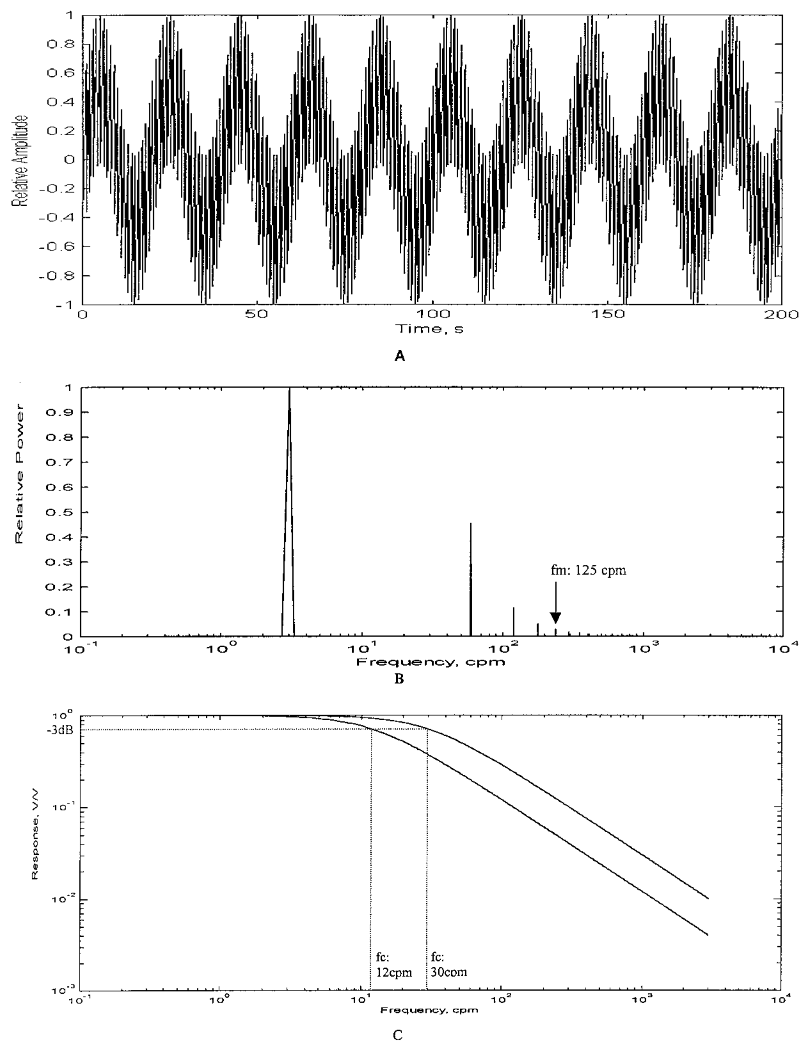


Fig 1. A model of electrogastrographic signal (frequency of 3 cpm) mixed with 60-cpm sawtooth noise in time (A) and frequency domain (B). This model is subjected to two different antialiasing filters, one with a cutoff frequency of 30 cpm and another with a cutoff frequency of 12 cpm (C).

instances these systems are utilized without any preliminary evaluation of their suitability for gastric applications (2–5). One of the typical examples of technological misuse of digital data acquisition systems is the lack of compliance with the Nyquist theorem of discretization (6). The purpose of the present work is to explain and discuss some of the most common problems related to digitization of gastric electrical signals using as an illustration modeled and real electrogastrographic signals.

MATERIALS AND METHODS

Modeling of Possible Pitfalls in Digitization Process. The infralow frequency nature of GEA and its spectral characteristics as functions of the electrode recording technique have been well documented (1, 7, 8). For the purpose of this discussion we have synthesized a continuous sine wave signal with a frequency of repetition of 3 cpm (0.05 Hz), which can be considered a model of the human EGG exhibiting, after an appropriate amplification and conditioning (8), an amplitude in the range of 2 V (peak-to-peak). The recording environment for GEA is not ideal, and a variety of artifacts and external influences contaminate the recordings (1, 7, 8). In our example we have modeled an electrocardiographic (ECG) artifact as a bipolar sawtooth signal with frequency of repetition of 60 cpm (1 Hz) and peak-to-peak amplitude of 2 V, ie, the artifact was of comparable power to the modeled EGG signal. The normalized resulting signal mixture in the time domain and its relative spectral power distribution in the frequency domain are shown on Figure 1. Typically, EGG signals are

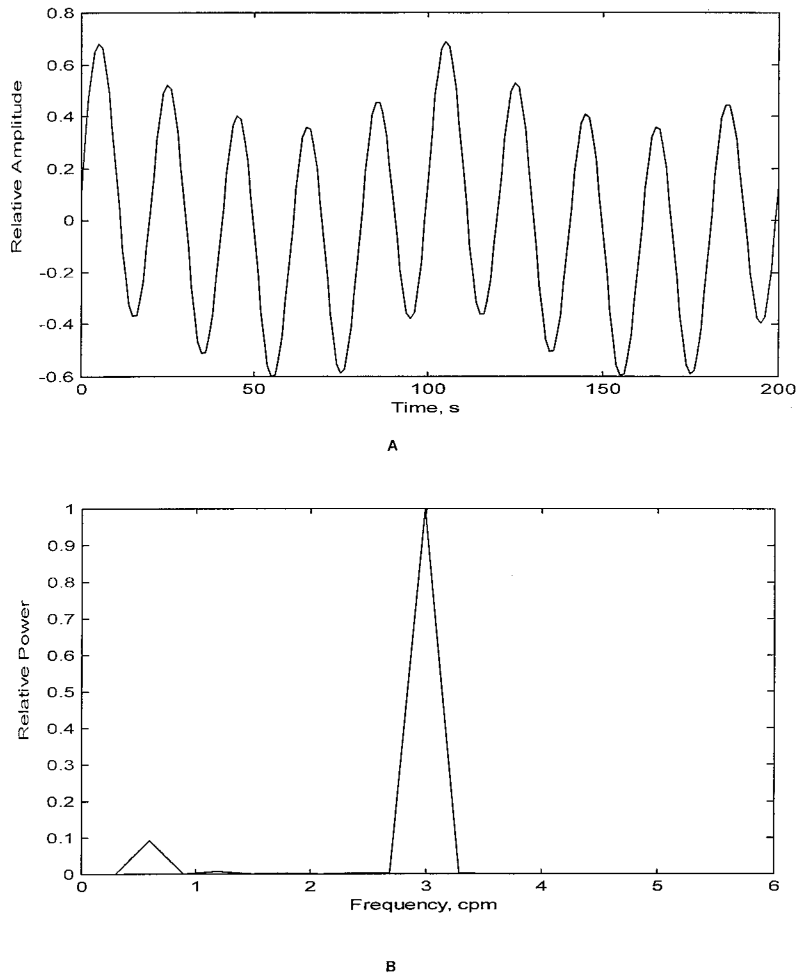


Fig 2. Time (A) and frequency (B) domain representations of the digitized signal (sampling frequency of 60 cpm) after a first-order antialiasing low-pass filter with a cutoff frequency of 30 cpm. The parasitic signal at 0.6 cpm is clearly evident as floating of the zero line in the time domain and spectral elevation at 0.6 cpm in the frequency domain.

analyzed in the frequency domain using Fourier methodology (9).

The first noticeable nonideality in the frequency domain is the frequency distribution around the peaks, a phenomenon related to the fact that the integral of Fourier with which the actual conversion from time to frequency domain is performed has limited boundaries because of the limited time interval of conversion (in our case 200 sec), while the theory stipulates that the integration should be in an infinite interval (6). This phenomenon is known as the "leakage effect." Because of its very nature, it can result in the presence of spectral components outside a predetermined "normogastric" range of frequencies, thus leading to misinterpreting the phenomenon as "bradygastrias" or "tachygastrias."

Suppose now that the signal from Figure 1 is to be digitized. The digitization should be performed according to the Nyquist theorem, which governs the relationship between the frequency components represented in the spectrum of the signal that is to be digitized and the sampling frequency. This relationship is described as follows (6):

$$Fs > 2fm \tag{1}$$

where fm is the frequency of the rightmost last significant spectral component (see Figure 1B). The determination of the significance of this component can be made objective if one considers the resolution of the analog-to-digital converter utilized by the data acquisition system and its range. The error of digitization can be expressed as (6):

$$E = \pm\frac{1}{2}LSB = \pm\frac{1}{2}(AR/2^n) \tag{2}$$

where AR represents the analog resolution (eg, 10 V for monopolar range of 0–10 V, or bipolar range of ±5 V), n denotes the number of bits of the digital conversion (eg, 12), and LSB is the volt weight of the least significant bit in

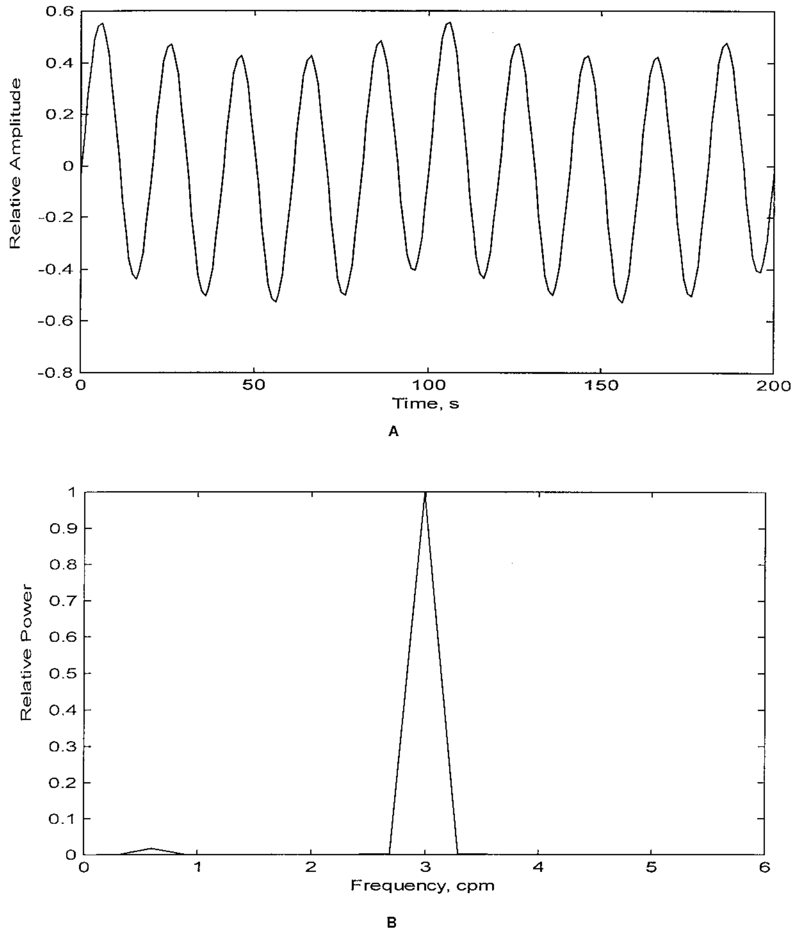


Fig 3. Time (A) and frequency (B) domain representations of the digitized signal (sampling frequency of 60 cpm) after a first-order antialiasing low-pass filter with a cutoff frequency of 12 cpm. The parasitic signal at 0.6 cpm is significantly diminished.

the conversion process. Returning to the amplitude of the frequency component at fm, it can be estimated that its significance would be lost after it becomes lower than the error E. In other words, the level of E can be used to determine fm. To define precisely the position of fm on the spectral scale, fm can be considered the frequency of the first rightmost frequency component, the amplitude of which is comparable to the digitization error E.

Let us now consider a conditioning low-pass filter, which is traditionally utilized in the data acquisition systems to prepare the continuous signal for digitization (6). Suppose the cutoff frequency fc (also denoted in some sources as f_H or -3 dB frequency) of this filter is 30 cpm (0.5 Hz) and the slope is 6 dB/oct (Figure 1C). The physical meaning of this slope should be interpreted as an amplitude decay of two times with a two times increment of the frequency. The relationship between the logarithmic scale and traditional input–output ratio can be described as:

$$V_o/V_{in}[\mathrm{dB}] = 20\log(V_o/V_{in}) \tag{3}$$

Clearly, after a substitution and taking into consideration the definition of a base $-$ 10 logarithm:

$$-6[\mathrm{dB}] = 20\log(1/2), \tag{4}$$

it should be noted also, that a slope of 6 dB/oct is associated with a first-order filter usually containing a single filtering capacitor in its analog electronics realization. Suppose that after passing the mixed EGG–ECG signal through this filter a digitization is to be performed with a sampling frequency of 60 cpm (1 Hz). This sampling frequency is a direct violation of the Nyquist theorem since the filter cutoff frequency is significantly lower than the frequency of the rightmost last significant spectral component. Therefore, the time domain representation of the digitized signal differs from the continuous sinusoidal EGG signal in terms of amplitude, which becomes time variant and "floats" at low frequency (Figure 2A). Moreover, the spectral representation of this new digital signal now contains a component with a frequency of 0.6 cpm (0.01 Hz), which was not present in the original continuous signal prior to the digitization (Figure 2B, see also Figure 1B). This parasitic signal created because of the lack of compliance with the Nyquist theorem can easily be labeled "bradygastria" if the misleading EGG terminology utilized by some research

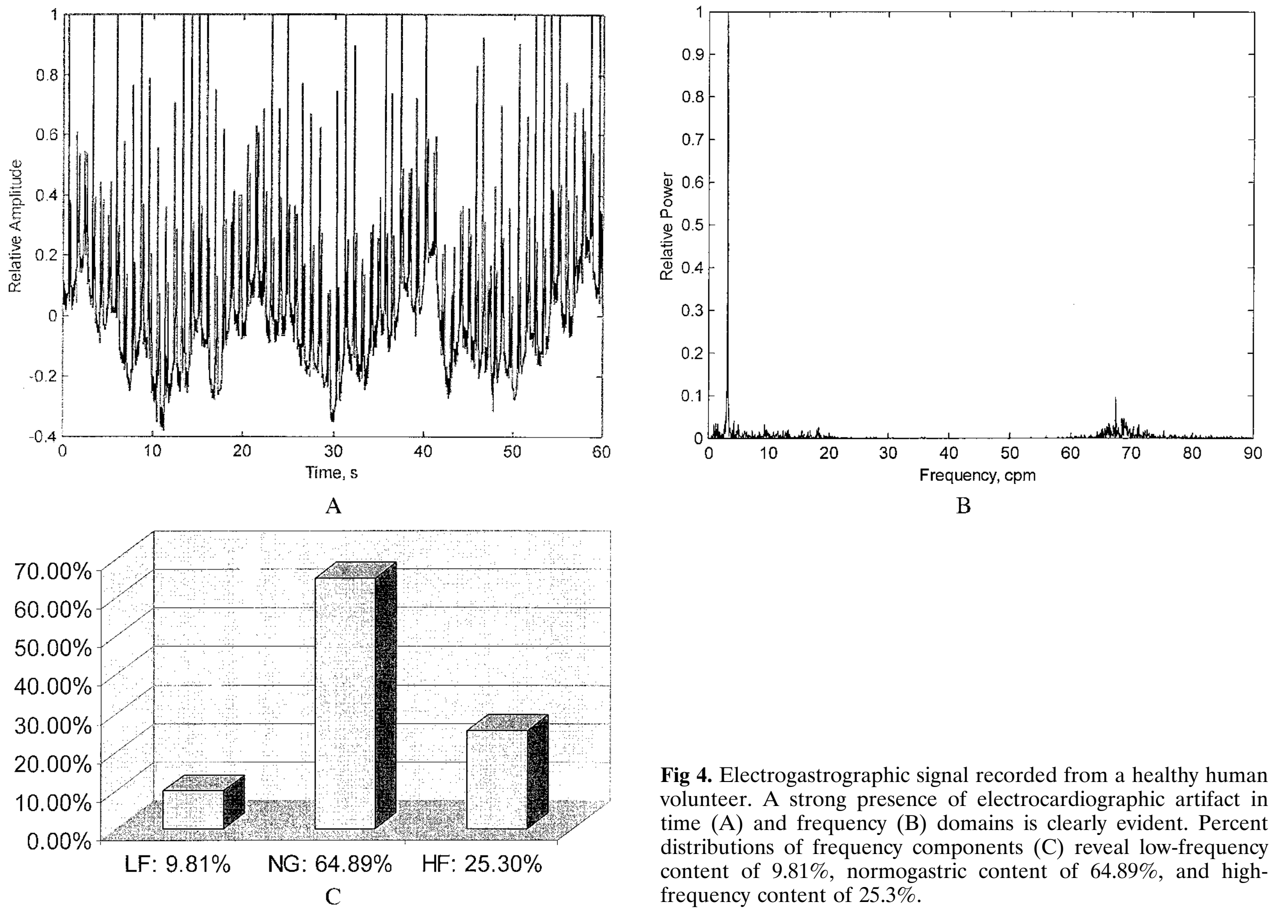


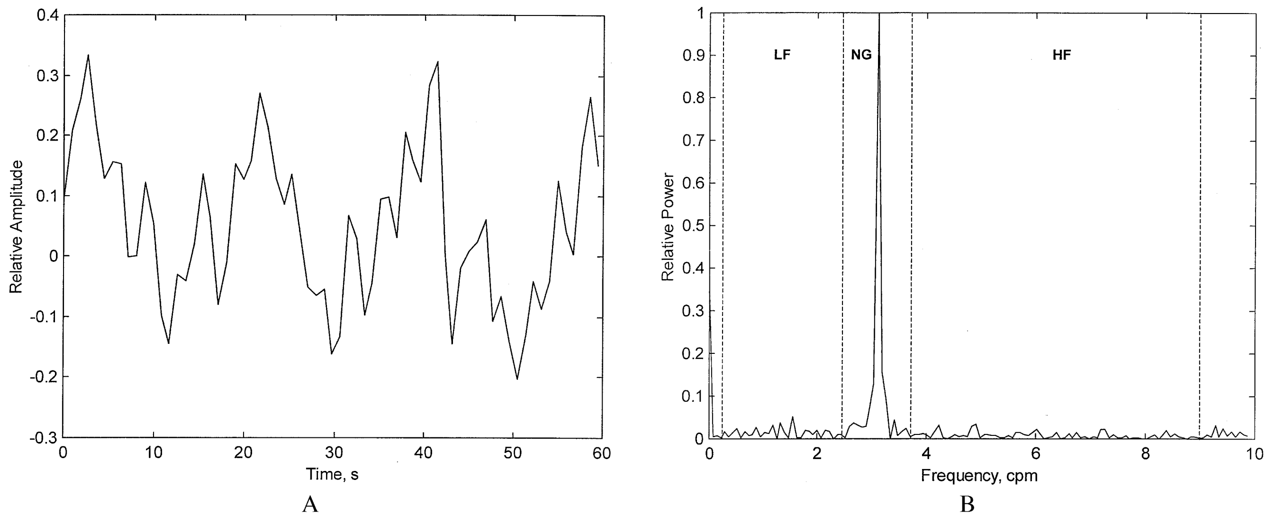
Fig 4. Electrogastrographic signal recorded from a healthy human volunteer. A strong presence of electrocardiographic artifact in time (A) and frequency (B) domains is clearly evident. Percent distributions of frequency components (C) reveal low-frequency content of 9.81%, normogastric content of 64.89%, and high-frequency content of 25.3%.

groups is to be used (10, 11). In fact, this artificially created entity is entirely due to the effect of aliasing and represents one frequently seen error in the interpretation of the Nyquist theorem, the replacement of *fm* (the frequency of the rightmost last significant spectral component) with *fc* (the cutoff frequency of the antialiasing filter) in Equation 1.

Realizing that the choice of cutoff frequency for the antialiasing low-pass filter was not appropriate, we can now suggest a new cutoff frequency of 12 cpm (0.2 Hz), keeping the order of the filter (ie, the slope) at 6 dB/oct (Figure 1C) and the sampling frequency at 60 cpm. This approach delivers a sine wave with diminished floating of the amplitude in time domain (Figure 3A) and a frequency domain representation of a single peak with an insignificant aliasing elevation at 0.6 cpm (Figure 3B).

Along with the effect of aliasing, the digitization process underlined even more the leakage effect, which manifested itself in widening of the frequency distribution around the dominant peak at 3 cpm (see Figures 2B and 3B). This phenomenon is related to the finite frequency resolution in the digitized spectral domain and can be partially compensated by introducing various nonrectangular windows in frequency domain (eg, Hamming, Hanning, etc.) (6). Although these techniques can reduce the leakage effect in the frequency domain, they should be used with a great caution if subsequent inverse Fourier transform is to be performed, because the obtained time-domain signal would contain unquantifiable nonlinear distortions.

Electrogastrographic Illustration of Percent Distribution Changes Due to Erroneous Signal Conditioning. A typical continuous electrogastrographic recording in time and frequency domains from a healthy human volunteer with an average body mass index as well as the percent distribution of frequency components (10) are shown on Figure 4. The conditions of the recording and the experimental setup were published before (12). Since the volunteer had never had any gastrointestinal complaints, it was assumed that his/her gastric electrical activity was normal and coupled, thus expecting insignificant presence of frequency components outside the normogastric range (2.4–3.6 cpm, 10) due to external factors. The acquired signal was low-pass filtered with a cutoff frequency of 30 cpm and slope of 6 dB/oct and was subsequently digitized with a sampling frequency of 60 cpm (1 Hz), repeating the first part of the modeling example from the previous section (Figure 5A). Spectral representation of the actual signal (Figure 4B) reveals certain percent distribution of frequency components in the so-called bradygastric (0.6–2.4 cpm), normogastric (2.4–3.6 cpm), and tachygastric (3.6–9.9 cpm) frequency ranges (Figure 4C) (10), with the substantial presence of elec-



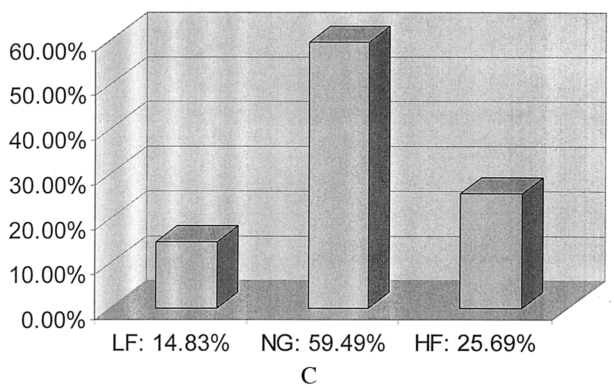


Fig 5. Time (A) and frequency (B) domain representation of the signal from Figure 4 after digitization with 60-cpm sampling frequency and low-pass filtering by a single-order antialiasing filter with a cutoff frequency of 30 cpm. Percent distributions of frequency components (C) reveal a substantial (more than 50%) increment in the low-frequency ("bradygastric") range and a significant (about 10%) decrement in the normogastric range.

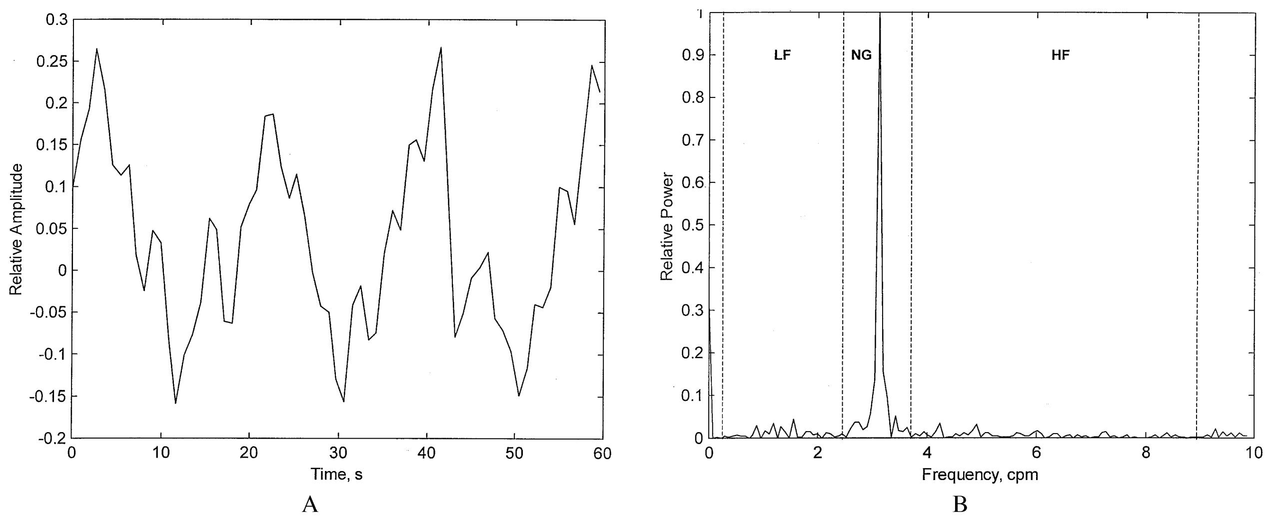
trocardiographic artifact in the range of 65–70 cpm. Because of the erroneous antialiasing filter employed in the digitization process using the inappropriate cutoff frequency of 30 cpm (0.5 Hz) (see Figure 5), digitized signal representation in the frequency domain (Figure 5B) as well as the respective percent distribution of frequency components (Figure 5C) differ substantially from the real ones (shown on Figure 4C), with about 50% increase in the "bradygastric" range, and 10% decrease in the "normogastric" range.

The replacement of the cutoff frequency of the antialiasing filter with 12 cpm does not introduce a clearly noticeable change in the time-domain representation of the signal (Figure 6A), but delivers important changes in the spectral power distribution of the signal (Figure 6B) and, thus, in percent distributions in the frequency domain (Figure 6C), bringing the bradygastric and the normogastric ranges closer to the actual percent distribution (see Figure 4C), and reducing the tachygastric range in which the presence of non-GEA signals was clearly evident.

All this shows that the percent distributions obtained with the 30-cpm cutoff frequency (see Figure 5C) were in fact erroneous and would be misleading when interpreting the ranges outside the normogastric range as "bradygastrias" or "tachygastrias" in a clinical setup, since the frequency components in these ranges were not necessarily electrophysiologically related to the electrogastrographic signal itself.

RESULTS AND DISCUSSION

The introduction of digital computers and digital signal processing techniques in the assessment of gastric electrical activity (GEA) and the electrogastrograms (EGG) significantly enhanced the opportunities for quantitative evaluation of gastric electrophysiology, but also created the possibility for misinterpretations of the signals related to inappropriate sampling, inadequate use of antialiasing filters, and lack of understanding of the limitations of the digitization process. In the present study we used a model of an EGG signal, as well as a real human EGG, to illustrate one such misinterpretation using the percent distribution of EGG frequency components (10), which has been suggested as a major avenue for interpreting the cutaneous recordings of GEA.



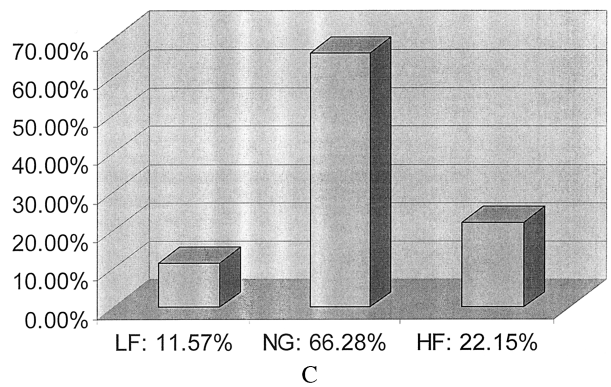


Fig 6. Time (A) and frequency (B) domain representation of the signal from Figure 4 after digitization with 60-cpm sampling frequency and low-pass filtering by a single-order antialiasing filter with a cutoff frequency of 12 cpm. Percent distributions of frequency components (C) are improved underlining better the normogastric range.

In this work we demonstrate: (1) the effects of aliasing and leakage on a modeled EGG signal; (2) the effect of aliasing on the percent distribution of the frequency components recorded from a healthy human volunteer; and (3) the impact of a strong electrocardiographic artifact on the EGG signal in a setup with minimized impact of respiratory and motion artifacts.

The fact that the so-called tachygastric range (10) was reduced after applying a simple, single-pole antialiasing filter with a cutoff frequency at 12 cpm (0.2 Hz) demonstrates that the ranges outside the "normogastric" range are influenced by a variety of external factors that are generally not related to the electrophysiological phenomena in the stomach and overemphasizing the importance of these ranges in electrogastrography can be misleading. In fact, the presence of significant percent distribution of frequency components in the "bradygastric" and the "tachygastric" ranges in signals recorded by completely healthy volunteers underlines the above statement even more and calls for abandoning the use of these terms altogether, replacing them with the more appropriate "lower frequency range," and "higher frequency range."

CONCLUSION

Digitization of gastric electrical signals should be performed with caution in order to avoid introducing artificially created nonexistent parasitic artifacts associated with the effect of aliasing. The interpretation of the digital signals should take into the account also the increased leakage effect associated not only with the limited rectangular boundaries when solving the integral of Fourier but also with the replacement of the latter by the discrete Fourier transform, introducing finite resolution between the spectral samples in the frequency domain when processing digitized recordings.

When a first-order antialiasing low-pass filter is utilized, at least a fivefold difference between the cutoff frequency of the filter and the sampling frequency is needed to avoid significant aliasing in environments in which the signal and the noise are of comparable power. With an increment of the slope of the filter, this number can be proportionally reduced, but the stability of the filter system can be jeopardized.

In order to comply fully with the Nyquist theorem, the frequency of the maximal frequency component *fm* can be determined taking into account the error of digitization associated with the analog-to-digital conversion.

The interpretation of erroneously digitized gastric electrical signals can lead to misleading conclusions regarding the percent distribution of the frequency components.

ACKNOWLEDGMENTS

This research was sponsored in part by Natural Sciences and Engineering Research Council of Canada, Canada Foundation for Innovation and the Whitaker Foundation (USA).

REFERENCES

1. Verhagen MAM, VanSchelven LJ, Samsom M, Smout AJPM: Pitfalls in the analysis of electrogastrographic recordings. Gastroenterology 117:453–460, 1999
2. Liang J, Cheung JY, Chen JDZ: Detection and deletion of motion artifacts in electrogastrogram using feature analysis and neural networks. Ann Biomed Eng 25:850–857, 1997
3. McCallum RW, Chen JDZ, Lin Z, Schirmer BD, Williams RD, Ross RA. Gastric pacing improves emptying in patients with gastroparesis. Gastroenterology 114:456–461, 1998
4. Chen JDZ, Lin Z, Pan J, McCallum RW: Abnormal gastric myoelectrical activity and delayed gastric emptying in patients with symptoms suggestive of gastroparesis. Dig Dis Sci 41(8):1538–1545, 1996
5. Eagon JC, Kelly KA: Effect of electrical stimulation on gastric electrical activity, motility and emptying. Neurogastroenterol Motil 7:39–45, 1995
6. Proakis JG, Manolakis DG: Digital Signal Processing. Englewood Cliffs, New Jersey, Prentice-Hall, 1996
7. Mintchev MP, Kingma YJ, Bowes KL: Accuracy of cutaneous recordings of gastric electrical activity. Gastroenterology 104:1273–1280, 1993
8. Mintchev MP, Bowes KL: A new look at the amplification of gastric electrical signals. *In* Proceedings of the 17th International Conference of IEEE–EMBS, Montreal, Canada, September 1995
9. Van der Schee EJ, Grashuis JL: Running spectrum analysis as an aid in the representation and interpretation of electrogastrographic signals. Med Biol Eng Comput 25:57–62, 1987
10. Koch KL, Stern RM: Electrogastrographic data acquisition and analysis—the Penn State experience. *In* Electrogastrography: Principles and Applications. JZ Chen, RW McCallum (eds). New York, Raven Press, 1994, pp 31–44
11. Chen J, McCallum R: Electrogastrographic parameters and their clinical significance. *In* Electrogastrography: Principles and Applications. JZ Chen, RW McCallum (eds). New York, Raven Press, 1994, pp 45–73
12. Mintchev MP, Bowes KL: Extracting quantitative information from digital electrogastrograms. Med Biol Eng Comp 34:244–248, 1996