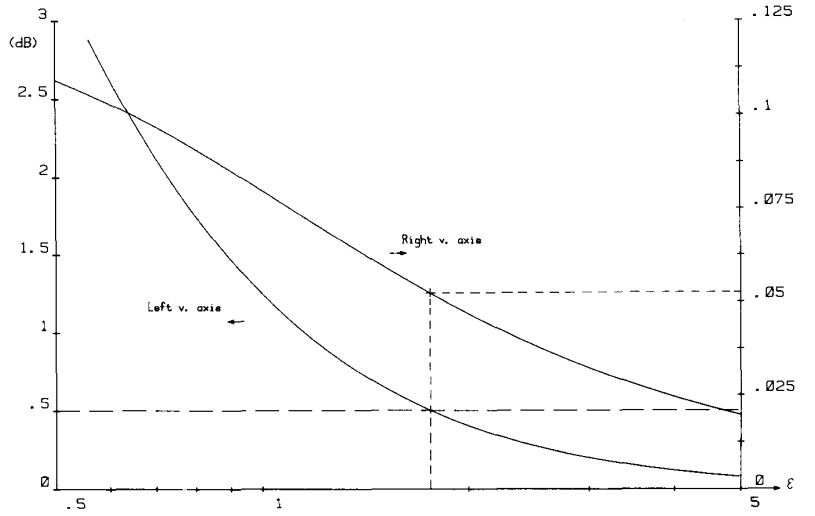

Fig. 5. Horizontal axis: damping factor ϵ. Left vertical axis: overshooting of the transfer function of the buffer see (15). Right vertical axis: frequency where the gain is -3 dB [ω_m, (16)] when the frequency, where gain is 0 dB (ω_0), has been chosen to be 0.14 Hz.

used for the circuit because gain limitations of the operational amplifier do not have any noticeable effect at these low frequencies.

The fact that the impedance at 124 Hz is 11.5 times that at 50 Hz, instead of 2.5 times as predicted by an inductive-looking impedance, suggests that there is some resonance effect. Assuming this, if an input capacitance C paralleling the equivalent input inductor L is considered, then from the value of the impedance at 50 and 124 Hz, it is deduced that $C \approx 3$ pF and $L \approx 0.4$ MH. At 50 Hz, this inductance has an impedance of 120 MΩ. The frequency of resonance is near 145 Hz.

V. Conclusions

By adding a single capacitor to a well-known dc-coupled buffer, it is feasible to obtain an ac-coupled buffer with very high input impedance without resorting to high-value resistors. The necessary formulas for adapting this circuit to any particular need when dealing with low-frequency signals are relatively simple. By using the appropriate equations, it is possible to choose the value of the input impedance, the maximum overshooting in the frequency response, and the "low corner" frequency.

The effective input impedance will, in fact, be limited by common mode input capacitances associated not only with the operational amplifier, but also with input protections, RF filters, and circuit layout. These capacitances will, however, provide an increased impedance near the frequency of resonance.

References

[1] M. R. Neuman, "Biopotential electrodes," in *Medical Instrumentation Application and Design*, J. G. Webster, Ed. Boston, MA: Houghton Mifflin, 1978, ch. 5.

[2] B. B. Winter and J. G. Webster, "Reduction of interference due to common mode voltage in biopotential amplifiers," *IEEE Trans. Biomed. Eng.*, vol. BME-30, pp. 58-62, 1983.

[3] R. van Heuningen, H. G. Goovaerts, and F. R. de Vries, "A low noise isolated amplifier system for electrophysiological measurements: Basic considerations and design," *Med. Biol. Eng. Comput.*, vol. 22, pp. 77-85, 1984.

[4] M. R. Neuman, "Biopotential amplifiers," in *Medical Instrumentation Application and Design*, J. G. Webster, Ed. Boston, MA: Houghton Mifflin, 1978, ch. 6, p. 309.

[5] N. V. Thakor and J. G. Webster, "Ground free ECG recording with two electrodes," *IEEE Trans. Biomed. Eng.*, vol. BME-27, pp. 699-704, 1980.

Two-Dimensional Fourier Spectrum of *QRST* Integral Maps in Classification of Patients Prone to Ventricular Arrhythmia

SHALINI S. PERIYALWAR, SHERWIN T. NUGENT, AND B. MILAN HORACEK

***Abstract*—Two-dimensional Fourier spectra of *QRST* integral maps, obtained by body surface potential mapping, were analyzed to identify subjects prone to ventricular arrhythmia, when they have not been identified by the extrema count method. The diagnostic performance (84.38 percent) of the peak value of the Fourier spectrum as a classifier for subjects prone to ventricular arrhythmia showed an improvement of 3.65 percent over the use of the extrema count method as a classifier.**

Introduction

Body surface potential maps have been found to reveal more information about the electrical activity of the heart than can be found from conventional electrocardiograms [1], [2]. The extensive amount of data involved in a total body surface potential map permits its visual analysis only in a global fashion. The maps are qualitatively analyzed in terms of simple parameters such as the location of maxima and minima [3], [4]. The application of analytical representation techniques to body surface potential mapping allows visual study of the maps in an orthogonal or transform domain and the assessment of the maps on the basis of other criteria; for example, these techniques have been applied to the determination of potentials at sites between electrodes [5].

Manuscript received March 28, 1988; revised October 10, 1988. This work was supported by grants from the Natural Science and Engineering Research Council of Canada and the Nova Scotia Heart Foundation.

S. S. Periyalwar is with the Department of Electrical Engineering, Technical University of Nova Scotia, Halifax, N.S. Canada B3J 2X4.

S. T. Nugent is with the Department of Engineering, Dalhousie University, Halifax, N.S. Canada B3H 3J5.

B. M. Horacek is with the Department of Physiology and Biophysics, Dalhousie University, Halifax, N.S. Canada B3H 4H7.

IEEE Log Number 8825622.

One way of summarizing the vast amount of information contained in body surface potential maps is to analyze distributions of the deflection areas; such distributions provide a summary of the events that take place in a given interval of the cardiac cycle [6], [7]. The study of the *QRST* deflection area (or the *QRST* integral) as a ventricular gradient was first proposed by Wilson *et al.* [8] in 1934. The *QRST* deflection area reflects primary repolarization properties, and may be a significant classifier of certain cardiac states with increased vulnerability to arrhythmia [9].

In this paper, we discuss the results of application of the two-dimensional Fourier transform to the *QRST* integral maps (represented as 64 × 36 arrays of potential values) of a population of normal subjects, subjects with ventricular tachycardia, and subjects with myocardial infarction.

Methods and Analysis

The population used in this study comprised 16 normal subjects with no evidence of heart disease on history or physical examination (Group I), 16 subjects who had maps recorded in close temporal proximity to an episode of ventricular fibrillation or sustained ventricular tachycardia requiring cardioversion (Group II), and 16 subjects whose maps were recorded 6–12 months after uncomplicated myocardial infarction (Group III). See [10] for a more complete description of the study population.

The digitized ECG data available for analysis were collected from 117 torso and 3 limb electrodes with the use of Wilson Central Terminal as reference, at a sampling rate of 500 samples/s/channel. The data were processed off-line on a Xerox Sigma 5 computer, artifacts and ectopic beats were eliminated, and average ECG complexes were constructed from 15 continuous s of recorded ECG for each lead.

The *QRST* time integral was calculated for each lead, with the physical units expressed in microvolt seconds. The set of *QRST* integral potential values resulting from measurements at the 117 sites on the torso were interpolated to form a 65 × 37 display grid. Isopotential contour maps (Fig. 1) were drawn using these data. For the purpose of two-dimensional Fourier analysis, an array of 64 × 36 data values, corresponding to the points of the 65 × 37 display grid (leaving out the last row and the last column), was used.

The two-dimensional Fourier transform is a well-established computational tool used in signal analysis. Before the application of the Fourier transform to the spatial time-domain data, periodicity of the data had to be ensured to avoid spectral leakage. The best method to eliminate the artifactual frequency shifts which occur due to discontinuity of the spatial time-domain data at the boundaries is to use windows which smooth the data to zero at the boundaries. The four-term Blackman–Harris window [11], with its low sidelobe level of −74 dB and low worst case processing loss was used, and is defined as

$$w(n) = a_0 - a_1 \cos\left(\frac{2\pi}{N} n\right) + a_2 \cos\left(\frac{2\pi}{N} 2n\right) - a_3 \cos\left(\frac{2\pi}{N} 3n\right), \quad (1)$$

$n = 0, 1, 2, \cdots, N-1$ where $a_0 = 0.40217$, $a_1 = 0.49703$, $a_2 = 0.09392$, $a_3 = 0.00183$.

The simplest method of application of a two-dimensional window to a rectangular array is the application of a one-dimensional window along the rows and columns of the rectangular array. This approach is similar to defining the two-dimensional Fourier transform as two one-dimensional transforms along the rows and columns, respectively, of a two-dimensional array [5]. The application of the four-term Blackman–Harris window in this manner provided a suitable window along the two dimensions of the array [12].

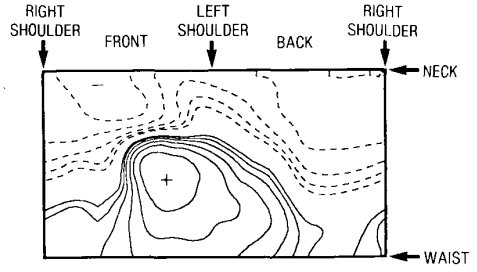

Fig. 1. *QRST* integral map of a normal subject.

The mixed-radix FFT algorithm [13] was used to compute the two-dimensional Fourier transform of the *QRST* integral body surface potential maps. This enabled the application of the FFT algorithm to the 64 × 36 array $f(x, y)$ of the *QRST* integral potential values without imposing a constraint on the array dimensions to be radix-2 quantities.

The origin of the Fourier transform was moved to the center of the frequency plane by multiplying $f(x, y)$ by $(-1)^{(x+y)}$. The Fourier transform property of separability [14] was used to compute the two-dimensional Fourier transform.

The Fourier spectrum was obtained by using

$$\left|F(u, v)\right| = \left[R^2(u, v) + I^2(u, v)\right]^{1/2}. \quad (2)$$

In order to enhance the high-frequency components of the Fourier spectrum [14], amplitude equalization was carried out using

$$D(u, v) = \log\left(1 + \left|F(u, v)\right|\right). \quad (3)$$

The Fourier spectrum was plotted as a 64 × 36 array in the frequency plane, with the origin at the center of the plane. Isopotential contours were used to represent the values in the frequency spectrum in the range from the 10 dB level to the maximum value in the spectrum. Values lower than 10 dB occurring in the higher spatial frequency range of the spectrum were not displayed. The contours were plotted on a linear scale as the frequency spectrum values are in logarithmic units (decibel).

Statistical analysis was performed using the Statistical Analysis System (SAS) [15]. All statistical results are expressed as mean ± standard deviation (SD). Statistical comparisons of group means was accomplished using the TTEST procedure in the SAS package.

Results and Discussion

The maps of all the 48 subjects, each comprising a 64 × 36 array of *QRST* integral potential values, were windowed by the application of the Blackman–Harris window. The mixed-radix FFT algorithm was then applied to the windowed arrays.

Fig. 2 shows the two-dimensional version of the Blackman–Harris window and its Fourier spectrum.

Figs. 3–5 show the Fourier spectra of the subjects considered in this study. In most magnitude spectra, the spatial frequency components tend to be concentrated about the origin, and attenuate at higher frequencies in the spectrum. This result was observed in the Fourier spectrum of the *QRST* integral arrays. The spectrum was observed to have a very high dynamic range, with a mean difference of 75.84 dB between its maximum and minimum values. The maximum or peak value (indicated by the "+" sign on the figure) was found to occur consistently around the central zero frequency region.

The peak of the Fourier spectrum of 14 normal subjects had a uniformly elliptical distribution. One normal subject (subject number 10) out of the 16 studied exhibited a double peak in the Fourier spectrum. One normal subject (subject number 11) exhibited a nearly elliptical distribution with a different inclination as compared to the rest of the normal maps.

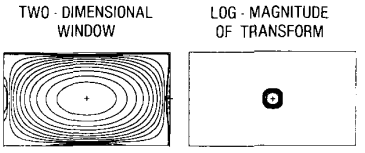

Fig. 2. The Blackman–Harris window applied in two dimensions and its Fourier spectrum.

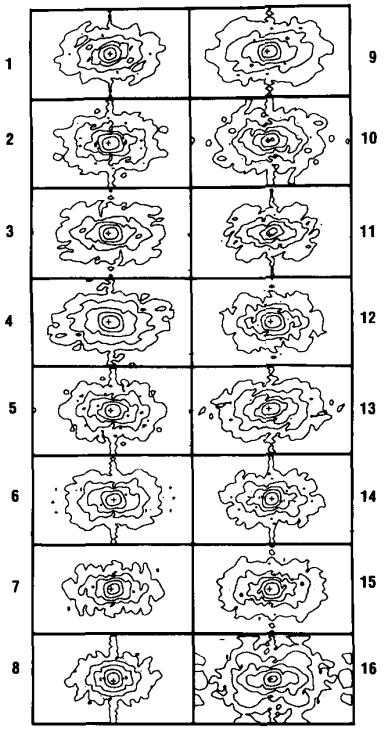

Fig. 3. Fourier spectrum of a 64 × 36 array of the *QRST* integral map of *normal* subjects.

The Fourier spectrum of 5 out of 16 subjects (subject numbers 4, 7, 9, 11, 15) with ventricular tachycardia (Group II) exhibited double peaks around the central region. Of the 11 remaining maps of subjects in Group II, four maps (subject numbers 1, 5, 12, 13) showed internal distributions that were not as smoothly elliptical as in maps of normal subjects. Double peak distributions were visible in 3 out of 16 subjects (subject numbers 4, 7, 9) in Group III. Nonuniform elliptical inner cores were observed in five of the remaining maps in the latter group (subject numbers 10, 12, 13, 14, 15).

The peak value of the Fourier spectrum for Group I and Group II showed a mean difference of 12.18 dB (with mean peak values of 81.99 dB for Group I and 69.81 dB for Group II). Since a *linear* scale would indicate this difference more clearly, the peak values were compared using the linear scale. The 60 dB spectral content was measured by normalizing the Fourier spectrum to have its maximum value as 0 dB, and summing the spectral components lying in the 0 to −60 dB range.

Statistics of the peak values and the 60 dB spectral content for the three groups were evaluated using SAS. Significant difference existed in the peak values of Groups I and II. The mean of the peak value for Group I was computed as 13 408 ± 4847 units, as compared to 4273 ± 3782 units for Group II and 7688 ± 5189 units

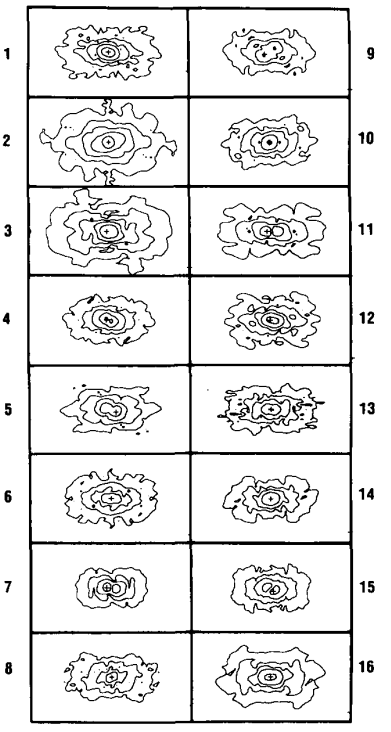

Fig. 4. Fourier spectrum of a 64 × 36 array of the *QRST* integral map of subjects with *ventricular tachycardia.*

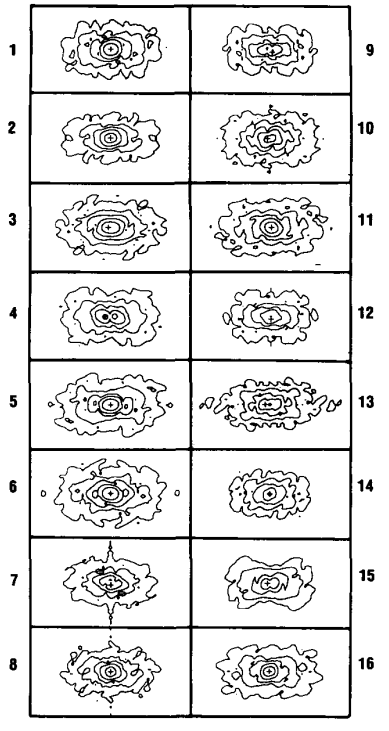

Fig. 5. Fourier spectrum of a 64 × 36 array of the *QRST* integral map of subjects with *myocardial infarction.*

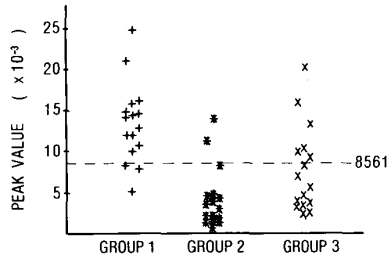

Fig. 6. Scatter plot of peak value in the Fourier spectrum of subjects in the three groups.

for Group III. Based on this result, a threshold was set as *mean* − *SD* of the normal group. Values below this threshold (8561 units) were declared as abnormal. Three subjects in Group I and 14 subjects in Group II recorded abnormal on this scale with a significance of $p < 0.0001$ (see Fig. 6). Ten subjects in Group III had peak values below the threshold ($p \ll 0.01$). No significant difference existed in the peak values of Groups II and III ($p < 0.05$).

The 60 dB spectral content for the three groups showed no significant difference in the mean with $17.5 \times 10^4 \pm 0.6 \times 10^4$ units for Group I, $16.2 \times 10^4 \pm 1.1 \times 10^4$ for Group II, and $17.2 \times 10^4 \pm 1.1 \times 10^4$ for Group III.

The *QRST* integral maps of subjects with ventricular tachycardia are characterized by multipolar distributions. The simplest method of identifying patients with ventricular tachycardia (VT) is the extrema count method, reported by Gardner *et al.* [10]. In our study, 10 of the 16 *QRST* integral maps of Group II subjects had a multipeak (more than one maximum and one minimum) distribution. Of the six subject maps with a single maximum and minimum (similar to normal maps, and therefore not characteristically VT), four maps (map numbers 10, 11, 15, 16) were characterized abnormal by the peak value of the Fourier spectrum, and two maps were characterized abnormal by the presence of double peaks (map numbers 7, 11). Therefore, the peak value of the Fourier spectrum and a visual analysis of the Fourier spectrum for double peaks may be successful markers for *subjects with ventricular tachycardia whose integral maps are not characterized by the extrema count method.*

Using the peak value of the Fourier spectrum as a classifier for Groups I and II, the diagnostic performance was evaluated as 84.38 percent [12]. The diagnostic performance was not evaluated for an independent test set due to lack of a sufficient subject population. The result obtained indicates an improvement in performance of 3.65 percent when compared to a study conducted on the same subject set in [10].

Random noise can be a major source of artifactual frequencies, hampering reliable spectral analysis. The processed electrocardiograms used in this study had a reduced level of random noise as a result of signal averaging. The other major source of artifactual frequencies relates to the introduction of step discontinuities of the spatial time-domain data at the boundaries, as the use of the discrete Fourier transform requires the assumption that the signal contained in the sample interval is a periodic function. The application of the four term (−74 dB) Blackman–Harris window to the 64 × 36 array of *QRST* integral values resulted in the data being smoothly brought to zero in the spatial time domain, with the effect that the periodicity desired as an inherent property of the discrete Fourier transform was satisfied. The loss of information due to the window attenuating the data at the boundaries was considered insignificant, as the occurrence of maxima and minima at the boundaries is considered artifactual, and is ignored in the analysis of maps by the extrema count method.

Two-dimensional frequency analysis of *QRST* integral maps of the three groups provided a simple classifier in terms of the peak value of the Fourier spectrum to aid in classification of Groups I and II and Groups I and III. The likelihood of double peaks in the Fourier spectrum was observed to be greater in Groups II and III. Group III subjects could not be classified with respect to Group II subjects in this study. Quantitative FFT analyses of signal-averaged electrocardiograms [16], [17] of subjects with ventricular tachycardia and myocardial infarction have revealed very subtle differences only in the terminal *QRS* and *ST* segments of the electrocardiogram for the two groups. Thus, it is conceivable that the two-dimensional frequency analysis of the terminal *QRS* and *ST* integral maps may yield classifiers for the separation of Groups II and III. This possibility remains to be explored.

References

[1] B. Taccardi, L. DeAmbroggi, and C. Viganotti, "Body surface mapping of heart potentials," in C. V. Nelson and D. B. Geselowitz, Eds., *The Theoretical Basis of Electrocardiography.* Oxford: Clarendon, 1976, ch. 19, pp. 436–466.

[2] M. S. Spach, R. C. Barr, R. B. Warren, D. W. Benson, A. Walston, and S. B. Edward, "Isopotential body surface mapping in subjects of all ages: Emphasis on low-level potentials with analysis of the methods," *Circulation*, vol. 59, pp. 805–821, 1979.

[3] H. Pam-Huy, R. M. Gulrajani, F. A. Roberge, R. A. Nadeau, G. E. Mailloux, and P. Savard, "A comparative evaluation of three different approaches for detecting body surface isopotential map abnormalities in patients with myocardial infarction," *J. Electrocardiol.*, vol. 14, pp. 43–56, 1981.

[4] D. W. Benson and M. S. Spach, "Evolution of QRS and ST-T wave body surface potential distributions during the first year of life," *Circulation*, vol. 65, pp. 1247–1258, 1982.

[5] D. M. Monro, R. A. L. Guardo, P. J. Bourdillon, and J. Tinker, "A Fourier technique for simultaneous electrocardiographic mapping," *Cardiovasc. Res.*, vol. 8, 1974.

[6] J. A. Abildskov, A. K. Evans, R. L. Lux, and M. J. Burgess, "Ventricular recovery properties and QRST deflection areas in cardiac electrocardiograms," *Amer. J. Physiol. (Heart Circ. Physiol. 8)*, vol. 239, pp. H227–H231, 1981.

[7] B. M. Horacek, E. R. Smith, D. A. Cameron, H. Gewirtz, and P. M. Rautaharju, "Iso-integral analysis of body surface potential maps," in P. W. Macfarlane, Ed., *Progress in Electrocardiography*, Kent: Pitman Medical, 1979, pp. 22–27.

[8] F. N. Wilson, A. G. Macleod, P. S. Barker, and F. D. Johnson, "The determination and the significance of the areas of the ventricular deflections of the electrocardiogram," *Amer. Heart J.*, vol. 10, pp. 46–61, 1934.

[9] J. A. Abildskov, L. S. Green, and R. L. Lux, "Detection of disparate ventricular repolarization by means of the body surface electrocardiogram," in *Cardiac Electrophysiology and Arrhythmias*, D. P. Zipes and J. Jalife, Eds. New York: Grune & Stratton, 1985, pp. 495–499.

[10] M. J. Gardner, T. J. Montague, C. S. Armstrong, B. M. Horacek, and E. R. Smith, "Vulnerability to ventricular arrhythmia: Assessment by mapping of body-surface potential," *Circulation*, vol. 73, pp. 684–692, 1986.

[11] F. J. Harris, "On the use of windows for harmonic analysis with the discrete Fourier transform," *Proc. IEEE*, vol. 66, 1973.

[12] S. S. Periyalwar, "Two-dimensional Fourier and eigenvector analysis of body surface potential maps," Master's thesis, Tech. Univ. of Nova Scotia, Canada, 1987.

[13] R. C. Singleton, "An algorithm for computing the mixed radix fast Fourier transform," *IEEE Trans. Audio Electroacoust.*, vol. AU-17, 1969.

[14] R. C. Gonzalez and P. Wintz, *Digital Image Processing.* Reading, MA: Addison-Wesley, 1977.

[15] SAS Institute Inc., Box 8000, Cary, NC 27511.

[16] M. E. Cain, H. D. Ambos, F. X. Witkowski, and B. E. Sobel, "FFT analysis of signal averaged electrocardiograms for identification of patients prone to sustained ventricular tachycardia," *Circulation*, vol. 69, p. 711, 1984.

[17] M. E. Cain, H. D. Ambos, J. Markham, A. E. Fischer, and B. E. Sobel, "Quantification of differences in frequency content of signal averaged electrocardiograms in patients with compared to those without sustained ventricular tachycardia," *Amer. J. Cardiol.*, vol. 55, p. 1500, 1985.