The Stacked Frame Display for Optimizing the Display and Interpretation of Analog Data

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1. Abstract
This paper describes the stacked frame display (SFD), a method for improving the accuracy and speed of interpreting analog data. The SFD involves the replacement of sequentially recorded traditional analog waveforms with narrow single lines. The amplitude and duration information that had been shown in the traditional analog waveforms is provided in the SFD by encoding this information using colors or the brightness of pixels in the linear display of the data. The method was tested by comparing its ability to interpret ambulatory electrocardiographic (ECG) data to that of traditional methods of interpreting such data. Compared to the traditional method of interpreting ambulatory ECG data, the SFD resulted in more accurate and efficient interpretations of these data. The SFD improves the accuracy and efficiency of interpreting sequentially recorded analog data.

Keywords: analog data, stacked frame display

2. Introduction
In medicine and in other fields such as seismology and engineering, it is frequently necessary to examine large amounts of data to detect important patterns in the information. These data often represent time series in which the data points are acquired sequentially over a given period. For example, many patients with known or suspected cardiac disease undergo ambulatory electrocardiographic (ECG) monitoring to detect, characterize and quantify episodes of arrhythmias or ischemia whose presence may put the patient at increased risk for disability or death. It is widely accepted that ambulatory ECG monitoring, which may last for hours or days, is a useful clinical tool. [1-3] However, studies have shown that current methods of detecting both arrhythmias and ischemia using the ambulatory ECG are suboptimal.[4-6] Improvements in electromagnetic and optical storage have permitted the collection of large amounts of clinically important data generated by ambulatory monitoring. This has made the use of accurate and efficient methods for reviewing these data especially important. For example, consider a three-day recording of data recorded by two standard ECG leads from a patient whose average heart rate is 70 beats per minute. The number of individual ECG complexes to be reviewed is:

2 leads x 70 beats/min. x 60 min./hr. x 24 hrs./day x 3 days = 604,800 ECG complexes

Furthermore, each ECG complex has multiple components, any combination of which may exhibit transient or persistent abnormalities in amplitude and/or duration. The considerable time required to review recordings such as these not only makes the process inefficient and therefore costly, but can also compromise the accuracy of the interpretations. First, the tedium associated with examining very large amounts of data can lead to intermittent inattention to the task at hand. Second, because of the large amounts of time required, it's often decided that it isn't feasible for a physician expert in electrocardiography to review all the ECG complexes that have been recorded during hours or days of monitoring. Therefore, it is common practice to have less highly trained technicians review the data first and then select portions of the original recording for subsequent review by a physician. Therefore, if a technician happens to miss important recorded events because of either the tediousness of the task or a relative lack of expertise in electrocardiography, the physician never even gets to examine the important data. In other words, the current system of reviewing ambulatory ECG data does not provide “full disclosure” of the data to the experts who are the most qualified to interpret the information.

The present paper describes a method of producing a meaningful display of even large amounts of sequentially acquired electronic data in a much smaller space than that which is required to display traditional analog tracings. The display is highly intuitive and, because of its compactness, it enables one to both review recorded data rapidly and to easily identify diagnostically useful patterns that otherwise would have been very difficult to detect. These features of the display eliminate the need for preliminary review of the data by a technician. Therefore it provides full disclosure of the data to the individuals who have the greatest expertise in the interpretation of the data.

3.0 Methods
3.1 Description of the method
The method to be described and evaluated is called the stacked frame display (SFD) of analog
data and Figure 1 illustrates the rationale upon which it is based. The top panel of Figure 1 shows the P wave, QRS complex and T wave of a typical ECG complex. The SFD rotates an analog display $90^\circ$ such that the previously upright portions of the original waves now point directly toward the observer and the previously downward portions now point directly away from the observer. This results

![Figure 1](image)

in the total height of the original analog display being reduced to the width of a single line. To restore the amplitude and duration information that had been shown in the pre-rotation analog display, one encodes the amplitude information using a system of colors, shades of gray or, in the case of a dichromatic display, the brightness of the pixels. For example, the portions of the waves that have rotated toward the observer could be colored red and those that have rotated away from the observer could be colored blue. The intensities of each of these colors are proportional to the amplitudes of the waves being depicted. As shown in Figure 1, information about the durations of each part of the original analog display is conveyed by the widths of the colored portions of each line.

In a sequential display of analog data, each set of rotated and encoded waves is placed either directly beneath or directly above its predecessor. In this way, the sequentially acquired data become stacked upon each other in chronological order. Also, the lower half of Figure 1 shows that the resulting rows of data can be aligned vertically along a common fiducial point, e.g. the onset or the peak or nadir of the QRS complex in a long recording of ECG data. Several advantages of the SFD are immediately apparent. First, an entire analog display (e.g. an ECG complex) of any amplitude is now represented on a screen or a printout by a thin single line that is placed immediately below or above the previously acquired data. This permits one to display and review in a given space on a screen or printout much more information than would have been possible using the original analog representation of the data. Second, the color, grayscale or pixel intensity coding of the information retains the amplitude and duration information that was present in the original analog display. Third, as Figure 2 shows, the compactness and arrangement of the display of data not only increases the speed with which the data can be reviewed, but also permit easier identification of important patterns in the data that might otherwise have not been apparent. Figure 2 shows analog displays of sonar signals that were being used to detect an undersea object. Panels 1 and 2 show the traditional appearance of these signals as they sweep from the left to the right side of the screen. In both Panels 1 and 2, the detected signals sweep across the screen and then disappear to accommodate the next set of detected signals. The transient nature of such displays of data on a screen make it difficult to detect patterns in the signals. However, Panel 3 represents a SFD encoded by pixel brightness of a series of screens of data from Panel 1. In this case, the earliest recorded signals are at the bottom and the most recently recorded signals are at the top of Panel 3. Throughout most of the display on Panel 3, the accumulated recorded signals appear random. However, the four vertical arrows show distinct horizontal lines that represent reflected signals of a consistent type from an underwater object that is moving from left to right. In contrast to the traditional analog displays of data in Panels 1 and 2, the SFD makes it possible to identify the presence, direction and (because of the known rate of acquisition of the data) the speed of the underwater object.

An additional feature of an SFD displayed on screen allows the user to click with a mouse on any part of the display and show the more familiar traditional form of the analog signal represented by that part of the SFD. This capability further increases the ease with which SFD displays can be interpreted. In addition, each click of the computer's mouse on a portion of the SFD would show the date and time at which those data were recorded. This feature permits one to measure precisely the times at which any event of interest began and ended. Besides being presented on the screens of electronic monitors, one can choose to print or make screen shots of any portion of the display. This enables one to analyze data that had previously filled multiple screens, examine the data in sites remote from the electronic monitors and compile permanent records of the data that have been acquired.
3.2 Empirical evaluation of the method

I evaluated the SFD using 24-hour ambulatory ECG data and compared it to the traditional method of reviewing such records with respect to both accuracy and efficiency. I studied 21 randomly selected patients: 11 males and 10 females, ages 18 to 87 years (mean = 56) who had been cared for between September, 1997 and August, 1998 at the Baptist Memorial Hospital of the Bowman-Gray School of Medicine in Winston-Salem, North Carolina. Each patient had received a 24-hour ambulatory 2-channel ECGs for detecting possible arrhythmias and myocardial ischemia. The data from each tape were then transferred to a GE Medical Systems-Information Technologies (GEMS-IT), MARS 8000 Arrhythmia Review Station™. A technician then scanned the resultant standard ECG waveforms on the screen of the Holter review station and selected segments of the 24-hour record for subsequent review by one of several cardiologists. Each cardiologist then generated a diagnostic report as part of each patient’s medical record. Each of these diagnostic reports was based entirely on the traditional method of reviewing ambulatory ECG data aided by sophisticated commercial diagnostic algorithms. These reviews, analyses and reports of the ECG findings were augmented by the system’s automated arrhythmia and ischemia detection algorithms and by graphs that depicted any changes in cardiac rate and ST segment displacement. I then reviewed the same 24-hour record after the data had been converted to the SFD for display on an electronic monitor. I was blinded to the standard ECG waveform, the above graphs and the diagnostic reports before I examined the SFD for the patients. During my initial review of the SFD, I recorded both my diagnostic findings and the amount of time required to review the entire 24-hour record using the SFD. Finally, I compared the findings obtained by reviewing only the SFD to those recorded in the original diagnostic report. To determine whether I had correctly identified an abnormality using the SFD, I then examined the traditional analog ECG complex that corresponded to each pattern of interest revealed by the SFD.

4. Results

Comparing the SFD to the original diagnostic reports shows that the SFD missed no abnormalities except for several clinically insignificant sinus pauses up to 2.8 seconds long in one patient. Conversely, the SFD detected a total of 9 episodes of consecutive ventricular beats (from 3 to 7 beats in duration) and a total of 10 episodes of sustained ST segment depression (from 1.5 to 25 minutes in duration). All these episodes of sustained ventricular beats and ST segment depression were clinically significant, but the patients’ official diagnostic reports did not mention any of them. Also, the SFD correctly revealed the artifactual nature of what the official reports had incorrectly identified as a total of 4 episodes of consecutive ventricular beats (reportedly from 3 to 6 beats in duration). The estimated typical time for the initial scanning of the standard ECG waveforms by the technician plus their subsequent review by the cardiologist was 90 minutes. In contrast, the mean time required by me to review each 24-hour ambulatory record using the SFD and to record my findings was 12 minutes, 32 seconds (range = 5 minutes, 13 seconds to 25 minutes, 30 seconds).

5. Discussion

The study shows that the SFD is more accurate than the traditional method of analyzing 24-hour ambulatory ECG data for identifying consecutive ventricular beats, ST segment displacement and artifact. In addition, the mean time required to achieve this superior performance using the SFD is only about 14% of that typically required to analyze the same ECG data using the traditional method of analysis. The better performance of the SFD occurred despite the fact that the original, traditional analysis of the data had been augmented by the use of sophisticated commercial ECG diagnostic algorithms.

The simultaneous improvement in diagnostic accuracy and efficiency is consistent with the basic nature of the SFD. The traditional way of reviewing large numbers of serially acquired ECG complexes, i.e. observing the complexes as they scroll across a
screen, is very laborious. Therefore, in reviewing ECG data recorded by ambulatory monitors, a technician typically first reviews the ECG waveforms on a screen and selects specific portions of the record to show to a physician for subsequent interpretation. Thus, no matter how skilled the physicians are at interpreting ECG signals, they are able to see only those data that less highly trained technicians have chosen to show them. Furthermore, because of the monotony involved in reviewing ECG signals that have been recorded for long periods, even very experienced technicians are likely to miss some clinically significant events. In contrast, the ability of the SFD display to compress a large amount of data in a small space makes it possible to review effectively as many as 24 hours of accumulated ECG data much more rapidly than previously, even without prior screening by a technician. Therefore, the SFD can provide full disclosure of the ECG data directly to the physician who must generate the diagnostic report. This full disclosure probably contributes to the improved diagnostic accuracy for both arrhythmias and ischemia that the SFD exhibits.

Another factor that can increase the accuracy of the SFD is the user’s ability to use the computer’s mouse to toggle between any portion of the SFD and the corresponding traditional ECG waveform as illustrated in Figure 3 where the familiar ECG waveform is located near the bottom of the screen. This toggling feature allows the users of the SFD to elucidate any changes in the pattern of a patient’s SFD by instantly examining the more familiar analog ECG complex. It also quickly teaches the users what features of the ECG the various types of these patterns displayed by the SFD represent. Because of this immediate instructional feedback, it’s likely that the user’s skill and efficiency will increase with continued use of the method.

Figure 3 illustrates a screen of some of the SFD data that were used in this study. There are four columns of sequentially acquired data that are aligned vertically using the peak of the ECG R wave as a common fiducial point. Each separate column is located between a pair of thick black lines. The temporal sequence of the recordings is from top to bottom of the first column, then from top to bottom of the second column and so on. In Figure 3, Arrow 1 shows the location of the array of the P waves, Arrow 2 shows the R waves and Arrow 3 shows upright T waves. Arrow 4 shows a rectangle at the beginning of a region of the SFD that is markedly different from the preceding and most of the subsequent portions of the SFD. The SFD suggests that the ECG complexes that compose this small region have comparatively broad P waves, longer QT segments and intervals and lower T waves. Arrow 5 shows the traditional analog tracing at the point of transition to the above small region and confirms the morphological changes that the SFD suggest. The duration of the above episode lasted 15 seconds.

Figures 2 and 3 demonstrate that the ability of the SFD to compress a large number of sequentially acquired ECG data in a small space permits the reviewer to observe patterns that may not have been apparent from watching series of individual ECG complexes scroll across a screen. Furthermore, these patterns yield important quantitative information. The number of similar occurrences on one or more screens gives the frequency of an event during the period of recording. The duration of each episode of an event is proportional to the amount of vertical space that it occupies in a column. The magnitude of the change in amplitude of a portion of the ECG complex is proportional to the intensity of the change in color (or in the brightness of the pixels) that is associated with it. Finally the rapidity with which any changes take place show whether they are gradual or instantaneous. The ability to identify such patterns can have considerable diagnostic importance. For example, ST segment displacement that begins, gradually worsens and then gradually resolves over a period physiologically consistent with the known duration of myocardial ischemia would strongly suggest that the patient had had an episode of ischemia, whether symptomatic or silent. Conversely, ST displacement that occurred and ended abruptly or persisted for a very brief period would be much more consistent with transient artifact than with the diagnosis of ischemia. Figure 3 illustrates an episode associated with marked ST depression. However since this episode lasted only a few seconds and had a sudden onset and termination, it is unlikely that ischemia was the cause of the observed change in this patient’s ST segments. Arrow #3 in Figure 3 shows how easily the SFD simultaneously demonstrates the abruptness, direction, severity and duration of an episode of ST displacement in a patient.

After one identifies patterns of interest using the SFD, one can then quantify the relevant features of the ECG even more accurately. This is because the system’s computer has stored the digital data needed to generate the SFD and can therefore retrieve the precise computerized measurements of the analog signals associated with the identified patterns.

Besides using the SFD to detect and analyze ECG abnormalities in the initial evaluation of
a patient, one can also use it to assess the safety and efficacy of therapeutic interventions in the daily management of patients and in the performance of clinical trials. Other investigators have used the traditional ambulatory ECG to evaluate the treatment of arrhythmias and ischemia. The full disclosure and ease of review of accumulated ECG data that the SFD provides makes it ideal for analyzing the large numbers of ambulatory ECGs that those clinical trials can generate.

Although the present study specifically demonstrates the use of the SFD in ambulatory monitoring, it is likely that we can extrapolate our findings to the monitoring of hospitalized patients, e.g. in coronary or intensive care units. In these settings, nurses or monitor technicians often try to detect clinically important changes in the tracings of multiple patients who are being monitored simultaneously. If a given ECG complex remains on the monitor screen for only a few seconds, it is likely that some episodes of arrhythmia or ischemia will be missed. Even if all the patients’ traditional ECG waveforms that had been obtained during a prolonged period were recorded, the task of subsequently reviewing them would be laborious and could diminish the ability of the professional staff to perform their other duties. Alternatively, using the SFD in conjunction with the real-time displays of monitored patients could facilitate the detection of arrhythmias and ischemia so that timely and clinically effective interventions would be more likely.

The superiority of the SFD method for reviewing ECG data compared to the more traditional method that used sophisticated commercial diagnostic ECG algorithms emphasizes an important point. The human eye and brain are extremely adept at quickly and accurately recognizing both simple and complex patterns. For example, it is common for a person to instantly recognize the face of an acquaintance even though that he might not have seen that acquaintance for a long time. This is because the person is able to easily discriminate the
acquaintance’s face from the thousands of other faces that the person has seen during his life. The basic function of the SFD is to present sequentially acquired analog data in a compact and intuitive way. By doing this, the SFD permits the eye and the brain to perform the task of pattern recognition for which they are so well equipped.

6. Limitations of the Study

The number of patients evaluated in the study was small. Despite this, however, the improvements in both the detection of abnormalities and the time required for the review of the data are striking. This is especially remarkable since sophisticated diagnostic algorithms augmented the reviews that used the traditional analog displays. Also, the portion of the present study that involves the review of the patients’ recorded diagnostic reports is retrospective. A consequence of this is that the individuals who generated these reports could only provide estimates of the amount of time required to perform the traditional reviews of the ECG data. On the other hand, this aspect of the study probably makes the results of the traditional reviews more typical of day-to-day clinical practice than if the individuals had known that they were participating in a research study.

7. References