Clinical Assessment of a New Method for Pacing Pulse Detection Using a Hybrid Circuit in Digital Holter Monitoring

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Holter monitoring is widely used for the detection of arrhythmia and ischemic episodes. Traditionally, analog amplitude-modulated Holter devices have been used for detecting arrhythmia, but they produce signal distortion due to contour effects and phase distortion caused by the tape recorders. A digital Holter device without these disadvantages has been developed and can reproduce clinically accurate electrocardiographic waveforms useful for assessment of arrhythmia and ST segments. However, their reliability is questionable when detecting pacing pulses in pacemaker patients. Because electrocardiographic signals are digitized based on sampling rate, pacing pulses are occasionally missed. Therefore, the FM-300 was developed, a new device for detecting pacing pulses on digital recordings that has both digital and analog circuits in one system and indicates pacing pulse timing with arrows. This device can automatically detect and recognize pacing pulses from various artifacts and pacing modalities, making it easy to identify pacing pulses on digitally recorded electrocardiograms. The FM-300 is useful in the diagnosis and assessment of pacemaker function and has improved the reliability of pulse detection in digital Holter monitoring. (*Jpn Circ J* 2000; 64: 583–589)

Key Words: Analog; Digital; Holter monitoring; Pacemaker

Holter monitoring is widely used for the noninvasive assessment of cardiac disorders, especially detecting myocardial ischemia, diagnosing arrhythmia and assessing pacemaker function, during daily activities.^{1–7} Various analog amplitude-modulated Holter devices have been developed since Holter's original method was reported in 1961⁸ but, as the analog Holter devices use magnetic tape as the recording medium, they have some disadvantages.⁹ Distortion of the electrocardiographic wave occurs during recording and playing back and thus the ST segment may not be accurately reproduced. This may be caused by deflection due to a recording head (called contour effect), time lag in the analog circuit (called phase distortion), or by crumpled tape or a dirty recording head, which produces noise. Device portability is limited because of the magnetic tape system.

Accurate recording and reproduction of the cardiac signal are the most important requirements in the assessment of ST segments and arrhythmias. An improvement over the analog Holter devices, digital Holter recording systems, has been developed. Because there is no phase distortion of the electrocardiographic wave on digital recordings, they are suitable when applying automatic recognition and assessment of the QRS complex and ST segment. Digital Holter devices also have an advantage in portability

because they eliminate the use of magnetic tape, so they are smaller and lighter than analog Holter devices.³ Thus, digital recording has superseded analog recording in the Holter monitoring field.

However, every digital Holter device is limited by its digital sampling rate. The sampling interval of a digital Holter monitor is usually set at 8 ms, but because the pacing pulse width, typically set at 0.5 ms, is shorter than the sampling interval, the digital system may fail to accurately detect the pacemaker pulse in the electrocardiogram. Fig 1 illustrates the detectability of pacing pulses at different sampling intervals in a digitally-recorded pacemaker electrocardiogram. Pacing pulses were generated by a Medtronic 5311 at an amplitude of 5 mV and pulse width of 0.5 ms. The signals were digitized after changing the sampling interval from 100 μ s to 5 ms. The pacing pulse was detectable in the digital recordings when the sampling interval was shorter than 500 μ s, but not when the sampling interval was longer than 1 ms. Consequently, any currently used digital recording system with a sampling interval of 8 ms could fail to detect the pacing pulses. Fig 2 shows a pacemaker electrocardiogram recorded by analog and digital Holter devices. Positive pacing pulses are observed before the QRS complex on the analog recording, whereas on the digital recording, pacing artifacts of variable voltage and polarity are seen or do not appear at all. Indeed, the digital system failed to consistently detect the pacemaker pulse in the electrocardiogram. For this reason, recording of ambulatory electrocardiograms has until now been limited to analog recording in pacemaker patients.

Coupling the advantages of both digital and analog devices was needed for better Holter performance, so we developed a new pacing pulse detection device, the FM-300 (Fukuda Denshi Co), by applying a hybrid circuit that

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Fig 1. Relation between pacing pulse detection and sampling interval. The sampling interval must be less than 500 μ s to detect a pacing pulse.

Fig 2. Pacemaker electrocardiograms recorded by analog (Top) and digital (Bottom) devices. On the analog recording, regular pacing pulses are observed, but on the digital recording they are variable in voltage and polarity.

combines digital and analog circuits within the same Holter recording system. The aim of the present study was to evaluate the reliability of the FM-300.

Methods

Principle of Signal Processing

The principle of signal processing in the newly developed FM-300 is illustrated in Fig 3. The electric signal is amplified and sent to both the analog and digital circuits. In the digital circuit, the electrocardiographic signals are digitized through an analog-to-digital (A/D) converter with a sampling rate of 125 Hz. Pacing pulse voltage rises quickly over a very short duration of 0.5 ms. This change in voltage over time is termed slow rate. In the analog circuit, after filtering the electrocardiographic signals through the 2-kHz high-pass filter, the pacing pulses are detected based on their high slew rate, amplitude, and width. Whether or not pacing pulses are detected, these data are sent to the digital circuit

and digitized at a sampling interval of 8 ms. All coded data are stored on a memory card device. The pulses detected in the analog circuit are recorded only for the purpose of timing of the pacing pulses. When these data are displayed, an arrow indicating the timing of the pacing pulse is marked below the pacing pulse on the electrocardiogram.

Evaluation 1: Reliability of Pulse Detection by the FM-300 Using Various Artifact Inputs

Pulses were evoked from a Medtronic 5311 pulse generator. Artifacts input from a Kenwood FG-273 function generator included (a) drift wave, (b) sine wave, (c) square wave, and (d) triangular wave. The pulses and each of the artifacts were synthesized and sent to the FM-300 through an attenuator.

Evaluation 2: Reliability of Pulse Detection in the Clinical Situation

Electrocardiographic data was recorded for 24 h from 7

Fig 3. Signal processing in the FM-300. The electric signal is sent to analog and digital circuits. The pacing pulse is detected by its high slew rate in the analog circuit.

Fig 4. Detection of the pacing pulse on various artifacts by the FM-300. Arrows under the pacing pulse indicate that the FM-300 detected the pacing pulse. 'P' means that the FM-300 recognizes a pacing stimuli. All pacing pulses are detected and recognized on 4 different artifacts.

pacemaker patients using the FM-300. The recorded leads included lead CM5 on channel 1 (a bipolar, V_s-like lead with positive electrode at V_s and negative electrode on the sternum) and a V₁-like lead on channel 2 (positive electrode at V₁, negative electrode on left distal clavicle). Playback and analysis were performed with a Holter ECG analyzer (DMW-9000H, Fukuda Denshi Co) on a UNIX computer

(AV350 series, Data General).

Results

Evaluation 1

Fig 4 illustrates the results of pulse detection using the FM-300 with various input artifacts. Arrows below the

Fig 5. Example of analysis in a patient with a DDD pacemaker by the FM-300. On channel 1 (CM5), the pacing pulses are stable in amplitude and polarity. Arrows indicate that the device recognizes all atrial and ventricular pacing.

Fig 6. Example of analysis of artifacts occurring with daily activity. Although disruption of the electrocardiographic wave due to activity is present, the FM-300 recognized all pacing pulses as arrows. 'P' means pacing pulses were detected by this system.

Fig 7. Example of analysis of fusion beats. The ninth beat (large arrow) is a fusion beat. 'F' is marked above the ECG wave when the FM-300 recognizes the wave as a fusion beat.

pulse waves are marked when the spike is detected by this system, and 'P' is marked when the spike is correctly detected as a pacing pulse. On recordings of drift wave, sine wave, square wave, and triangular wave artifacts, all pacing pulses are indicated as arrows, indicating that the FM-300 successfully detected all pacing pulses regardless of artifact type.

Evaluation 2

Pulse detection results in 7 pacemaker patients using the FM-300 are shown in Figs 5–11.

Case 1: Pulse Detection in a Normal ECG The ECG from a complete atrioventricular (A-V) block patient with DDD-mode pacemaker is analyzed. The pacing pulses on channel 1 (Fig 5, top) are stable in amplitude and polarity, and the arrows coincidental with the pulses show that the

Fig 8. Example of analysis of the Vario function. In a patient with Chorus & Opus Pacing Generator (ELA Medical), the output amplitude is decreased by 0.25 V. The FM-300 recognizes all pacing pulses to the pacing threshold.

Fig 9. Example of analysis in a patient with auto capture function. The pacing amplitude is 0.9 V. Pacing pulses are correctly detected.

Fig 10. Example of analysis of a patient with a myocardial bipolar electrode. The top trace displays the CM5 and the bottom shows the CC5 lead. The pacing pulse is detected as indicated by the arrows. The FM-300 discriminates the paced QRS complex from the inherent QRS complex.

atrial and ventricular pacing pulses were detected by the FM-300. We believe that the atrial and ventricular pacing were correctly detected and recognized by the FM-300.

Case 2: Pulse Detection With Artifacts The ECG is recorded in a patient with paroxysmal atrial fibrillation and a DDIR-mode pacemaker. The CM5 lead (Fig 6, top) is apparently influenced by artifacts caused by body movements. The electrocardiographic baseline is wandering, and

several pacing pulses cannot be clearly identified. In addition, this artifact produces a fast, transient edge resembling a pacing pulse in shape, making it difficult to distinguish pacing pulses from artifacts. However, arrows placed below the pulses, which were marked when this system detected atrial or ventricular pacing pulses, help to identify the pacing pulses. The V₁-like lead (Fig 6, bottom) shows that the arrows marked in the CM5 lead are correctly

Fig 11. Example of analysis of pacemaker malfunction. S, sensing; F, fusion beat; U, undersensing; PF, pacing failure. The FM-300 recognizes all pacing pulses as indicated by the arrows.

described under artifacts.

Case 3: Pulse Detection in the ECG With Fusion Beats Fig 7 illustrates a Holter recording from a complete A-V block patient with a DDD-mode pacemaker. From the first to the eighth beat, spontaneous P waves were sensed and regular ventricular stimuli occurred. The ninth beat (large arrow) is considered a fusion beat. The 'F' above the QRS means that the FM-300 recognizes and marks this QRS as a fusion beat. This trial demonstrates that this system is useful in identifying fusion beats. Furthermore, before the ninth beat, a small, edge-like, rising waveform, which is suspected to be an atrial pacing pulse, is recognized on the V₁-like lead (Fig 7, bottom). It can not be identified on the CM5 lead (Fig 7, top), meaning that the digital circuit has failed to detect this atrial pacing pulse. However, the analog circuit correctly detects this pacing pulse and indicates pacer timing with an arrow.

Case 4: Pulse Detection During Vario Function Fig 8 illustrates a Holter recording in a patient with a Chorus & Opus Pacing Generator (ELA Medical) as it decreases pulse amplitude during threshold analysis. The output amplitude automatically decreases by 0.25 V with each pulse, which ELA calls the Vario function. The pacing threshold was set at 0.25 V of the pacing amplitude, and 0.49 ms of the pulse duration. Pulse amplitude decreases up to eleventh beat. The twelfth beat is a spontaneous QRS complex. On channel 1 (Fig 8, top), the arrows are placed correctly. There is no time-lag between pacing pulses on the electrocardiogram and the arrows. This means that all pulses of more than 0.25 V were correctly detected.

Case 5: Pulse Detection During Auto-Capture Function Fig 9 illustrates a Holter recording in a patient with a Solus Micro Pacing Generator (Pacesetter). The pacing amplitude was set at 0.6 V. Spontaneous QRS complexes can be seen occurring the first to the 16th beat after which a ventricular pacing rhythm appears (Fig 9, top). The 13th beat is a fusion beat, and the next beat is a spontaneous QRS complex (Fig 9, bottom). In this case, detected pacing pulses were marked with a 'P'. The pacing stimulus of the 14th beat occurs within the blanking period. Though the pacing amplitude was set as low as 0.9 V by the auto-capture

function, the FM-300 correctly detected all pacing pulses occurring over 24 h in this patient.

Case 6: Pulse Detection During Myocardial Bipolar Pacing Fig 10 illustrates a Holter recording during myocardial bipolar pacing. Channel 1 (Fig 10, top) is the CM5 lead and channel 2 (Fig 10, bottom) is the CC_s lead. On both electrocardiograms, pacing pulses are not apparent. However, the arrows indicate the presence of pacing pulses. The FM-300 correctly detects and recognizes the pacing pulses. The FM-300 can detect all pacing and can discriminate pacing pulses from spontaneous QRS complexes.

Case 7: Pulse Detection on Pacemaker Malfunction Fig 11 illustrates a Holter recording in a patient who underwent DDD-mode pacemaker implantation due to an A-V block. This electrocardiogram records pacemaker malfunction due to dislocation of the lead. It shows idioventricular rhythm (from beats 5 to 8), ventricular ectopic complexes (beats 1, 2, 4 and 9), fusion beats (beats 3 and 10), and 8 pacing pulses (pacing 1–8). Beats 4 and 9, which are ventricular ectopic complexes, were not sensed (undersensed) and pacing 3, 4, 6, and 8 failed to capture. The FM-300 detected all the pacing pulses by marking them with arrows below the waves. This system is useful in pulse detection for pacemaker malfunction.

Discussion

Digital Holter devices have advanced in recent years. This type of recording system acquires an electric signal at a fixed sampling interval, digitizes it through an A/D converter, and records the digitized signals on semiconductor memory. This process introduces no phase distortion on digital monitoring.^{3,10–13}

Many authors refer to diagnosis of ischemic episodes on digital monitoring systems^{9–13} but few reports discuss digital recording with pacemaker patients.¹⁴ This may explain why the reliability of digital Holter devices is questionable in the detection of pacing pulse waves. In pacemaker patients, it is important to detect arrhythmias and pacemaker malfunction during daily activities, because these conditions can lead to such serious events as ventric-

ular fibrillation or cardiac failure. Pacemaker malfunction sometimes indicates inappropriate lead position that can result in myocardial perforation by the pacemaker lead. Identification of the pacing pulse under various circumstances may assist in the diagnosis and treatment of certain clinical entities. The digital Holter device has not fully met these clinical demands.

Thus, we developed the new device called FM-300 to detect the pacing pulse. As our results show, our device is possible to accurately detect and automatically recognize all type of pacing pulses. The ability of the FM-300 to detect pacing pulse waves under difficult situations was excellent. In daily life, artifacts that occasionally produce sharp, fast upsloping edges and that resemble pacing pulses in shape may arise due to positional change, activity, or a loose electrode. In our study, the arrows, which were marked if this device recognized atrial and ventricular pacing pulses, clearly indicated these pulses and made it easy to identify pacing pulses on the electrocardiogram. Furthermore, no false positives or time-lag between arrow and pacing pulse were observed, and pacing pulses were accurately distinguished from several complicated artifacts. The reason is that our device discriminates the pacing pulse based on the pulse's high slew rate. This device can accurately detect pacing pulses under various pacing modalities such as decreased pulse amplitude, auto capture function, pacing by myocardial electrode, and during pacemaker malfunction. This study shows that the FM-300 is technically feasible and clinically useful for assessment of pacemaker function in pacemaker patients.

Conclusion

Our newly developed device, the FM-300, combines a digital recording system with an analog circuit for pacing pulse detection. In digital Holter monitoring of all daily life activities, our device was able to automatically detect and recognize all pacing pulses. This device is useful in and reliable for the assessment of pacemaker function in

various pacemaker types and has improved the reliability of pulse detection in digital Holter monitoring.

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