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A Comparison of Three Cardiac Ambulatory Recorders Using Flight Data

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Several ambulatory recording devices are available to record pilots' electrocardiograms (ECG) during flight. The procedures these devices use to record these data vary a great deal. Some record the data in analog form, others in digital form, and others save only the interbeat intervals. With the variety of available devices the comparability of their resulting data needs to be verified for researchers to be confident of their results when sharing data among laboratories. Three ECG recording devices were compared using data collected from pilots during an approximately 60-min flight. The data were simultaneously recorded from the pilots by all 3 recorders. The results show that the devices provide essentially identical heart rate data.

The ability to share in-flight heart rate data from several laboratories is appealing for a number of reasons. Coordinating efforts among laboratories permits more rapid advancement of research goals among the cooperating agencies. This also reduces costs for the participating laboratories, which is advantageous. Cooperation among laboratories makes possible a wider range of flight situations than may be possible in any one laboratory. It can also be used to compare and contrast flight procedure and training differences among participating agencies. To provide the most information, the data from the different laboratories must be directly comparable. When several laboratories share data from independent testing of a new aircraft, it is crucial that the actual heart rate values be correct. To permit these comparisons, the quality of the data must be high. The sharing of information necessitates that all laboratories have highly reliable data, which requires that the recording devices and analysis procedures produce comparable data.

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In the flight environment, heart rate is the most widely used psychophysiological measure. A number of investigations have used heart rate to study the effects of flight on the pilot and other crew members (see Roscoe, 1993; Wilson, 2002; Wilson & Eggemeier, 1991). Heart rate typically increases with increasing job demand and can help identify high-workload segments of flight (Hankins & Wilson, 1998; Rokicki, 1987).

To share data, researchers in the field need to ensure that the different devices accurately represent the data. The flight environment is associated with high heart rates during takeoff and landing, whereas cruise segments are associated with low heart rates. Recording devices must be able to accurately represent the electrocardiograph (ECG) over a wide dynamic range. In transport and other large aircraft, crew members must be able to move about the aircraft freely. In these cases self-contained, ambulatory recorders are essential. Additionally, flight can produce numerous types of artifacts. Because crew members have to move to perform their jobs, they sometimes walk about the aircraft. These movements can result in artifacts such as muscle and baseline shifts that may create extra or missing beats during analysis. When different laboratories are collaborating on common projects, this issue is important.

It is expeditious to purchase commercially manufactured ambulatory data recorders rather than to design and construct them in the laboratory. These devices are specially made for ambulatory situations and can be used to record crew members' ECGs during flight. Basically two types are available: those made for clinical recordings in a patient's natural environment and those made for research purposes. The clinical units record only ECG, whereas research recorders usually have several programmable channels that permit the recording of different electrophysiological signals such as electroencephalography, electrooculography, and electromyography. The clinical or Holter monitors typically have the capacity to record at least 24 hr of data on several channels. Research devices are able to record for a number of hours; the actual length depends on the number of channels, the sampling rates, and the capacity of the storage device. A common characteristic of these devices is that they amplify the ECG and filter it prior to recording. The method of recording varies. For example, some devices use analog techniques to record the ECG data on magnetic tape. Other devices digitize the ECG and store the data in this form on a disk or memory card. A third procedure is to have the device detect the R wave of the ECG, calculate, and then store the interbeat intervals (IBIs) in digital form in the device's memory. Research, clinical, and specially made recording devices have been use to record physiological data during flight in a number of studies (Caldwell & Lewis, 1995; Comens, Reed, & Mette, 1987; Hankins & Wilson, 1998; Hart & Hauser, 1987; Rokicki, 1987; Roscoe, 1975; Wilson, 1993, 2001a; Ylönen, Lyytinen, Leino, Leppäluato, & Kuronen, 1997).

The goal of this project was to compare the ability of three different clinical and research ambulatory recording devices to record pilots' heart rates during actual flight. Although examination of equipment specifications and laboratory tests is necessary when selecting ambulatory recorders, in-flight data collection was believed to be crucial to the evaluation of these devices if they are to be used during flight tests. To determine the uniformity of results among the three different recording devices, a study was conducted in which they simultaneously collected data from the same pilots during a flight of approximately 60 min. To test the dynamic range of the devices, the scenario included segments that placed both low and high cognitive demands on the pilots and resulted in a wide range of heart rates.

METHODS

Three civilian pilots served as participants. They were part of a larger study that involved collecting other psychophysiological data in a flight workload study. The pilots flew a Piper Arrow—a high-performance, piston-engine aircraft—in a prescribed scenario that lasted about 60 min. The pilots were licensed and current in the Arrow. A safety pilot flew in the right seat of the aircraft. For purposes of analysis, the flight was divided into 20 two-min segments that represented different levels of cognitive workload for the pilots. The segments were preflight baseline, engine start, preflight checklists, visual flight rules (VFR) takeoff, VFR climb-out, VFR air work (navigation), VFR cruise, VFR approach, VFR touch and go, instrument flight rules (IFR) climb-out, IFR air work (navigation), IFR holding, IFR distance measuring equipment arc, IFR instrument landing system tracking, IFR touch and go, VFR climb-out, VFR pattern, VFR approach, VFR landing, and postflight baseline. All three pilots flew the same scenario. Other psychophysiological data were recorded as part of a larger study and included electrooculograms, electroencephalograms, electrodermal activity, and respiration. Those data are reported elsewhere.

Three ambulatory biological recorders were used. One was a Del Mar Avionics Holter monitor, model 463. The recorder amplified and filtered two channels of ECG, and these data were stored on analog tape microcassettes. Following the flights, the data were played back and digitized using the Del Mar 563 Holter Analysis hardware and software system. The best channel was selected for further processing. A Polar R-R recorder was also used. The ECG data were amplified, filtered, and digitized with this unit. R waves were detected online, and the R-to-R IBIs were calculated and stored in the device's memory. The stored IBIs were later transferred to a personal computer. The third recording device was a Vitaport II eight-channel physiological recorder.

One of the device's eight available channels was programmed to record the ECG data. The device amplified, filtered, digitized, and stored the data on a removable PCMCIA hard disk. The data were later transferred to a personal computer.

The electrodes used with the Del Mar and Vitaport recorders were disposable, infant-sized, Ag/AgCl disposable electrodes manufactured by ConMed, Inc. The skin under the electrodes was cleaned with alcohol and mildly abraded with a gauze pad. The electrodes were placed at the upper margin of the sternum and the intercostal space between the eighth and ninth ribs on the left side of the chest. The electrodes were connected to the recorders with snap leads. The Polar electrodes were contained in an elastic strap that was placed around the chest at the lower margin of the sternum under the chest muscles. K-Y jelly was used to moisten the electrodes. A ground electrode was placed next to the rib electrodes. Fig-

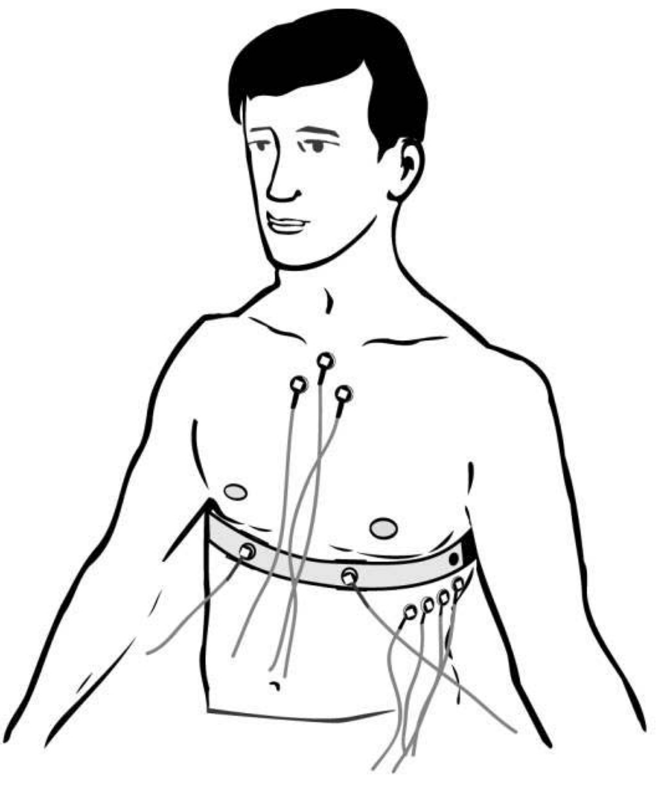

FIGURE 1 Diagram showing the placement of the ECG electrodes for data collection. The Polar electrodes were held in place by the chest strap. Two channels were recorded by the Del Mar recorder and one by the Vitaport II recorder. The ground electrode was the most posterior on the left side of the chest.

ure 1 shows the electrode placement. This arrangement permitted the simultaneous recording of the cardiac electrical activity on three different devices during flight. All three recorders were time synchronized, which permitted direct comparison of the data.

The data from the Del Mar and Vitaport II recorders were analyzed with a Workload Assessment Monitor (WAM; Wilson, 2001b). The ECG data formats were converted into a form acceptable to the WAM, which was then used to detect R waves and measure the IBIs. The output of the Polar recorder was already in the form of IBIs. The files containing the IBIs from all three devices were corrected for artifacts. Missed and extra beats were detected by the software. A software routine in WAM was used to detect IBIs that exceeded thresholds for being too long or too short. For each IBI, a running average was calculated over a defined window and compared to threshold values to determine whether an individual IBI exceeded the upper or lower boundary of acceptable variation. IBIs that were judged to be too long were divided into equal portions to correspond to the surrounding IBIs. IBIs that were too short were added to the preceding or following IBI(s) to correspond to the surrounding IBIs. These edited IBIs were evaluated to determine the comparability of data from the three recorders. The corrected IBIs were visually inspected, and additional corrections were made if necessary. Additionally, the means of the IBIs for 2 min surrounding each of the 20 segments were calculated and converted to heart rate.

RESULTS

Figure 2 shows the IBIs from the three recorders representing the data from one flight. These IBIs have not been edited to correct missed or extra beats. The IBIs are displayed with the equivalent beats per minute (bpm) on the ordinate. The IBI spikes above and below the surrounding data values are artifacts caused by missing beats (downward deflections) or extra beats (upward deflections). Note that the artifacts occur at different times during the flights for each recorder. Figure 3 shows the edited data. These data from the three recorders are remarkably similar. The major peaks in heart rate show the same timing and shape and were associated with takeoffs and landings. The data for the other two pilots exhibited similar results.

The mean IBIs during the 22 two-min segments were calculated and converted to bpm. Figure 4 shows the means of the 2-min segments. These data represent the 22 two-min segments for all three recorders. The curves are essentially identical. Averaging across 2 min has the effect of smoothing the data. The peak heart rates in the curves occur during the expected segments, which were takeoff, touch and go, and final landing. The IFR segments were associated with higher heart rates than the VFR segments. The resting baseline heart rates were noticeably lower than those of the flight segments. These data are representative of the data

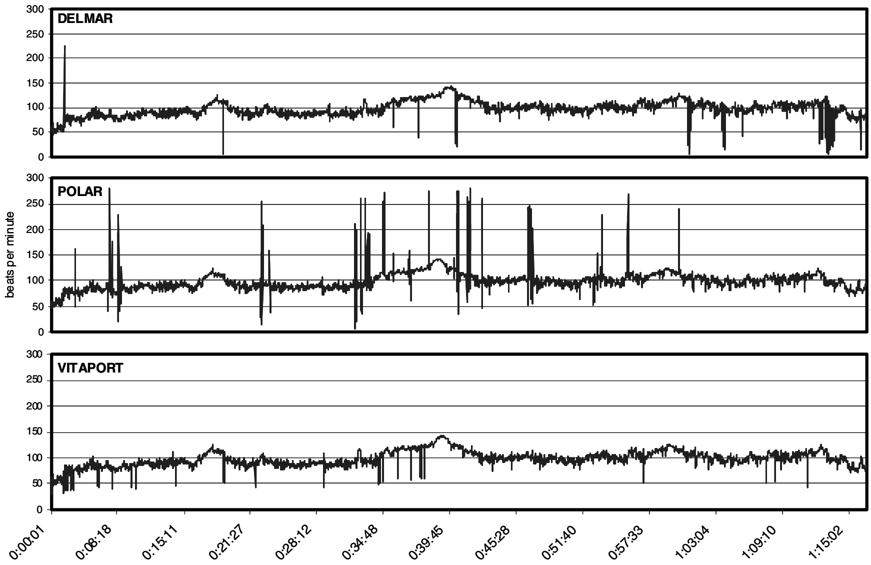

FIGURE 2 IBIs from Pilot 3 recorded with three different ambulatory recorders. The spikes are artifacts caused by missed or extra beats. The timeline is shown on the abscissa.

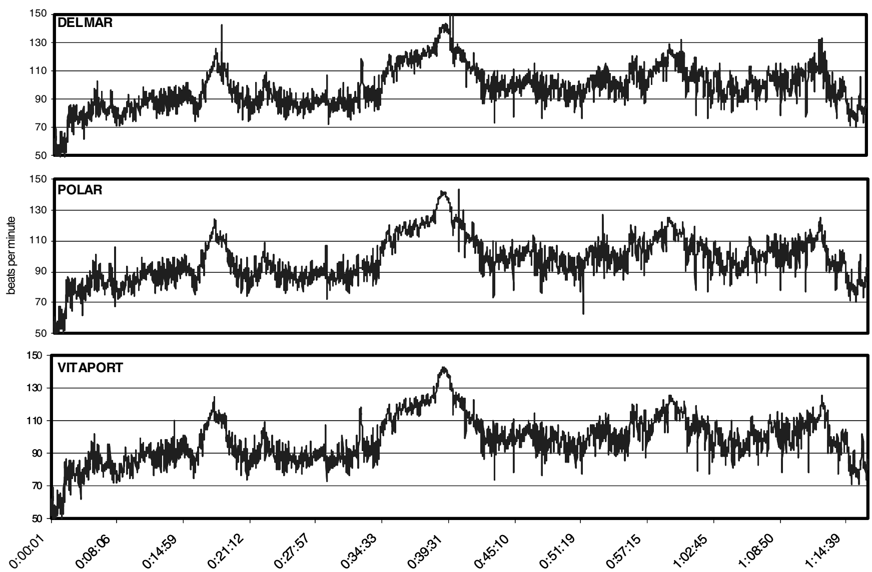

FIGURE 3 Corrected IBIs for the data shown in Figure 2. Note the very high degree of similarity of the curves.

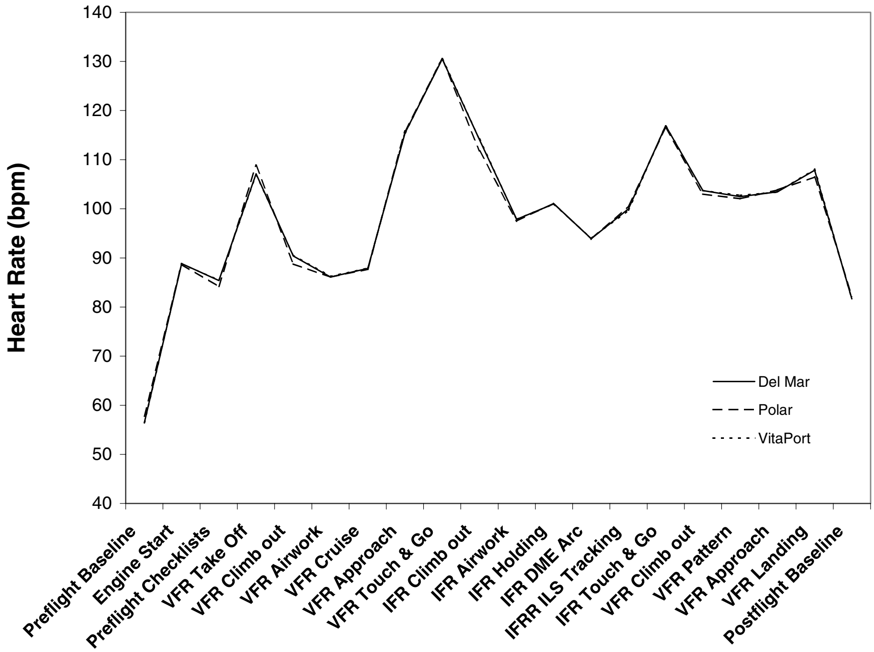

FIGURE 4 Two-min mean heart rates for the 20 flight segments for the data shown in Figure 3. Note the peaks during the takeoffs and landings and the wide range of heart rates shown.

from the other two pilots. The heart rate levels were different, but the pattern of activity across the 20 segments was the same. Figure 5 shows the grand means for the 3 participants across all 20 segments for the three recorders. The overall means for the three pilots are essentially identical for all three recorders.

DISCUSSION

These data show that three different cardiac recorders provided essentially identical data while the participants flew an aircraft. This supports the idea of sharing data among laboratories using different ambulatory recording devices. The three devices that were compared in this project provided essentially identical results from the three pilots during a flight of approximately 60 min. The range of demands on the pilots varied from resting baseline to executing touch-and-go maneuvers. The recorded heart rates covered a wide range of values. The 2-min mean data, shown in Figure 4, ranged from a low of 56 bpm to a high of 130 bpm. This is a very wide range and is typical of the heart rate range found during actual flights. Laboratory

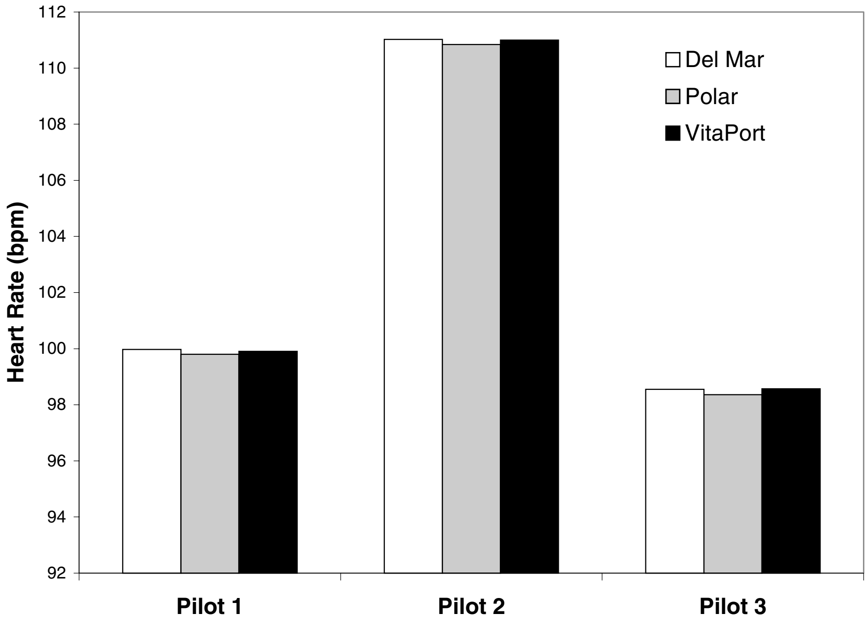

FIGURE 5 Grand mean heart rate averages across the 20 two-min segments for the three pilots. Note the high degree of similarity in the data from the three devices for all three participants.

data characteristically exhibit a much more limited range of values. The wide range and dynamic nature of the flight data provided an excellent environment in which to evaluate the comparability of the three recorders. The similarity of the data from the three recorders supports the legitimacy of sharing data among different laboratories. Although only three pilots participated in this investigation, the high degree of similarity of the data for each pilot from the tested recorders implies that similar results would be found across a larger sample of pilots.

Software analysis packages are available, often with clinical systems, that provide averaged heart rates but not the individual IBIs. The IBI averaging purges the individual IBIs and removes the possibility of performing artifact detection and correction. This can lead to a distorted depiction of the results. During clinical evaluation, the 1-min periods with obvious artifacts can be discarded and a meaningful evaluation can still be performed. However, artifacts occurring during critical segments of flight cannot be discarded because of the critical nature of the data. Once the IBIs have been averaged it is not possible to recapture the individual IBIs to detect and correct artifacts. Having only these averaged data can lead to incorrect conclusions. Access to IBIs permits the detection and correction of artifacts, which permits more accurate evaluation of these critical events.

Clinical Holter monitors can be used to record ECG data during flight that are comparable to the ECG data recorded using a research recorder. Access to the

IBIs is essential so that artifacts can be detected and corrected. With this capability, the data are essentially identical. This was found over the wide range of heart rates that were recorded during the approximately 60-min flights. The clinical recorders are small and rugged, making them suitable for flight research.

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