HYBRID COMPUTER ANALYSIS OF ELECTROCARDIOGRAPHIC DATA

INTRODUCTION

This Study describes the application of the EAI HYDAC® 2000 (HYbrid Digital-Analog Computer) System to the analysis of electrocardiogram (EKG) data. The type of analysis employed in the study represents one of a class of data reduction techniques which can be instrumented effectively on this general purpose hybrid computer.

The overall area of data analysis is an essential one to the Bio-Medical Engineering profession since most of the work being done at present is on an empirical basis. Thus, large quantities of data, representing measurements from various sections of the body, must be gathered, and detailed analyses of this data, as is necessary to establish significant correlation between physiological malfunctions and data irregularities, must be performed.

A typical but self-limiting approach to a project of this type has been to make use of special purpose equipment designed specifically for cardiogram analysis, for autoradiographic analysis, for pulmonary circulation transport studies or, indeed, for investigating any of the physiological processes within the scope of bio-engineering. The basic limitations of this approach, of course, are: 1) the impossibility, or very great difficulty, of adapting the equipment for any data analysis other than that for which it is designed, and 2) the extensive hardware requirement for obtaining valuable but, at best, partial information.

The HYDAC program to be described (block diagram shown in Figure 1) is an economically-attractive alternative approach to satisfying the need for physiological data reduction in general, and electro cardiographic data analysis in particular. Furthermore, since the HYDAC computer is a general purpose computer, there is the additional capability for complete system simulation of physiological functions. As in industry, where the mathematical simulation of processes and mechanisms is rapidly being adopted as a standard procedure in modernization and optimization projects, so in bio-engineering is such system model-building assuming a place of importance. In this way, the computer can provide still greater insight into the operation of the human body by making possible, say, the analysis of subsystem interaction in the function of the entire organism or the introduction of some control functions.

Indeed, these two aspects of computer operation--data analysis and direct simulation--enhance each other in the furtherance of bio-engineering accomplishment. That is, the development of mathematical models for simulation will require the analysis of vast quantities of empirical data. Analysis of the model, however, will point out areas about which more or different information is needed in order to complete the mathematical description. Thus, the quality of data would be upgraded and the mathematical model continuously refined to the point where the simulated system most closely approached the actual physiological process.

PROBLEM STATEMENT

There is a great deal of current interest in methods for analyzing human electrocardiograms. The basic signal to be analyzed (e.g., a magnetic tape record) is a measure of the voltages determined by three or more leads placed in contact with the skin of a human body. These voltages are generated within the heart, and the specific sequence of the pulses generated is indicative of stages in the expansion-contraction cycle of heart action. Actually, the sequence is produced by an electrical polarization and subsequent depolarization of the muscle tissue which contracts during the pumping action of the heart. The *height* of the pulses so generated and the *time intervals* between them are affected by various disease states of the human body. In order to derive statistical correlation between these pulse measurements and human disease--in order, that is, to make the cardiographic analysis meaningful--it is necessary that a large number of cardiograms be analyzed in minimal time so that the information obtained corresponds as closely as possible with actual, real-time heart action. This is of special importance in physiological studies where the cardiographic analyses are part of an on-line

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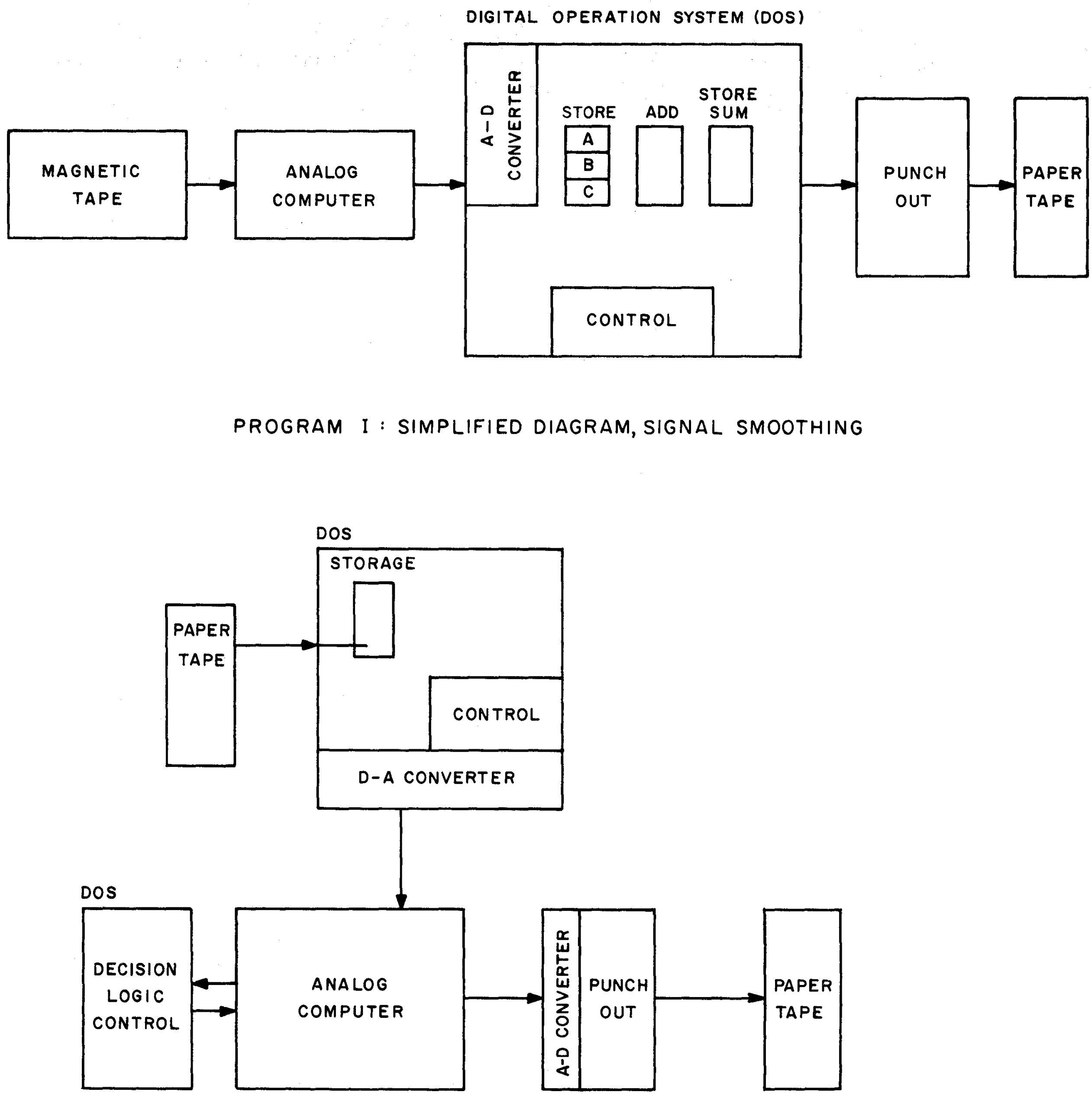


PROGRAM I : SIMPLIFIED DIAGRAM, SIGNAL SMOOTHING

PROGRAM II : SIMPLIFIED DIAGRAM, PARAMETER MEASUREMENT

Figure 1: Block Diagrams of Programs I and II of HYDAC Cardiographic Data Processor

system in a complete system simulation, and must proceed in real-time to keep pace with complementary and/or supporting bodily functions. Furthermore, in order to remove possible bias in the analysis of cardiograms as might be desireable, say, in insurance investigations where the bias of advanced age in the subject, for example, might cause an over-critical interpretation of a trace, it is necessary to standardize the measurement of the critical *pulse heights (amplitudes)* and *time durations* in the recorded waveform.

The HYDAC program described here was prepared to satisfy these two requirements, viz: to process cardiogram records at essentially the same rate that they are generated by human patients, and to establish criteria by which critical pulse heights and time durations can be measured and interpreted consistently. The program is divided into two sections: Program I preprocesses the data in order to circumvent a basic "noise" problem--signal distortion caused by spurious EKG baseline variations; Program II performs the actual pulse measurements. Figure 1, above, shows a simplified block diagram of the HYDAC Cardiographic Data Processor.

The diagram makes evident one additional benefit of this general purpose hybrid approach. The use of two separate programs has the advantage that the data smoothing operation in Program I produces its own paper tape output which can be processed further in a variety of ways not considered by Program II, thus adding to the versatility of the entire computer operation.

PROGRAM I: *Data Pre-Processing*

A. Signal Composition – generation of a standard waveform: The various systems for locating leads on the human body for EKG examinations make possible a number of different methods for obtaining a composite signal from the several voltages measured. The objective, in any event, is to relate this composite signal to the "resultant heart potential vector"...the quantity involving direction as well as magnitude of the average polarization potential of the heart as a function of time.

For illustrative purposes, an orthogonal lead system will be considered in this paper. For an orthogonal lead system, the leads are placed in positions on the body so that the resulting amplitude of the heart vector is obtained by the simple formula

$$\text{EKG3D} = \sqrt{x^2 + y^2 + z^2} \qquad (1)$$

where EKG3D = amplitude of resultant waveform
x, y and z = amplitudes of voltages obtained from orthogonal lead system

This formula destroys information about the phase (or sign) of the voltages x, y and z and, since the *phase inversion* of a particular pulse is a significant medical event, some method of remembering the phase must be introduced. For example, either a logic signal indicating plus (+) or minus (-) for each x, y and z wave must be produced, or else (as done in this study) x, y and z can be shifted by a *small* amount until they become voltages which are always positive.

By using the shifted waveforms, i.e., $x + e_1$, $y + e_2$, and $z + e_3$, the phase of the resultant will follow the dominant phase of x, y and z at the expense, only, of a small amount of signal distortion. The process is performed by an analog computer producing

$$\text{EKG3D} = \sqrt{(x + e_1)^2 + (y + e_2)^2 + (z + e_3)^2} \qquad (2)$$

which, for specific standard values of e_1, e_2 and e_3, is the basic single waveform processed by the computer.

B. Data Smoothing: A primary problem in the accurate determination of pulse heights and durations is the elimination of spurious baseline variations in the electrocardiogram.

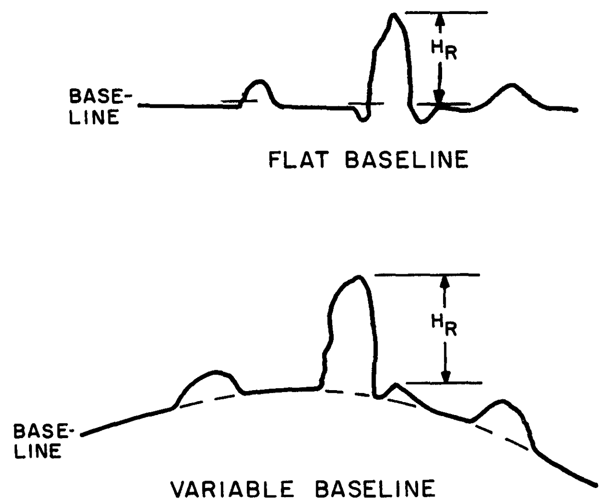


Figure 2: Typical EKG Baseline Variations

Since it is the height of the pulse above the variable baseline which is desired (Figure 2), it is necessary to remove the effect of baseline eccentricities. Simple filter circuits fail to remove this baseline component without altering significantly the waveshapes to be measured. Consequently, an averaging scheme was adopted instead, in an attempt to remove these variations without distortion. This task is the primary one performed by Program I.

The basic scheme, as shown in Figure 3, is to operate on the almost-periodic waveshape of the EKG* after resetting the zero reference level after each period. This resetting procedure removes a considerable portion of the long term baseline variations. However, short term variations exist within periods and, to remove these, the HYDAC program averages each period of the waveform with all previous wave periods.

In this manner, the remaining baseline variations are averaged out to produce a clear, noiseless,

*Actually, 3 cardiogram potentials have been combined to form EKG3D as described previously.

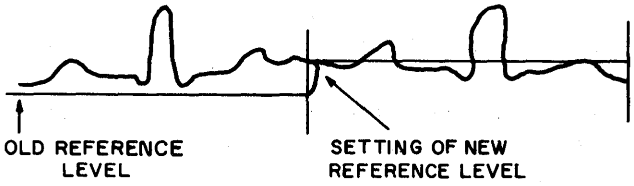


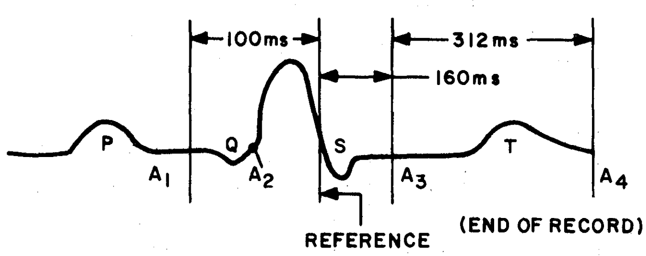
Figure 3: Basic Averaging Scheme Used in Program I

average representation of a cardiogram waveform which is punched out on paper tape. A large number of records can be processed in this manner. The resulting averaged waveforms then can be inputted either directly to Program II to complete the EKG analysis or to other devices for further processing, as desired.

PROGRAM II: Parameter Measurement

Program II accepts the paper tape output of Program I and stores it in 'memory'. The average waveform then is played back through a digital-to-analog (D/A) converter into an analog computer where the occurence of the various pulses is detected, and their amplitudes and appropriate time intervals are measured. An analog differentiator detects the peaks and creates signals controlling time-interval measurement by integrators.

This data is transferred to the Digital Operations System (DOS) of the HYDAC Computer and again punched onto paper tape. A series of logic controls in the DOS oversees the measurement process on the analog computer, detects the need to abandon the search for a particular pulse (i.e., determines that this pulse is not present), and begins expecting a succeeding type of peak. These non-detected peaks are remembered and an appropriate tape code indicates that their measurement has not been performed.



ABANDON POINTS

A_1: ABANDON SEARCH FOR P PULSE

A_2: ABANDON SEARCH FOR Q PULSE

A_3: ABANDON SEARCH FOR S PULSE

A_4: ABANDON SEARCH FOR T PULSE

Figure 4: Pulse Search Procedure

Measurement is made of five pulse amplitudes, five basic time periods and, where detected, the variance of critical time measurements (defined below). These analog-calculated quantities then are punched onto a paper tape output record along with appropriate patient identification. An analog plot of the average waveform is generated also as a further piece of output data.

GENERAL PROGRAMMING CHARACTERISTICS

Certain characteristics of the EKG record, as well as a desire for real-time processing, dictate special programming restrictions in the parameter measurement phase of the program. The most basic characteristics of the cardiogram are that it contains five separate pulses labelled P, Q, R, S and T, and that only one of these (i.e. the R pulse) is necessarily present and readily detectable in human cardiograms (Figure 5). The P, Q, S and T pulses may be extremely small or not present at all in some cases. Thus, schemes which detect the R pulse are the only ones considered reliable on the unaveraged waveform. This means that a given point on the R pulse (say, a point of given negative slope) must be used as a reference and that all averaging of pulse waveforms must be accomplished about this reference point.

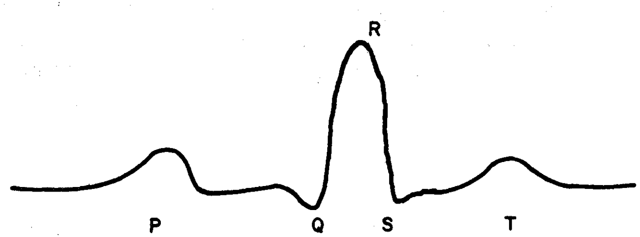


Figure 5: Sketch of EKG Pulse Form

However, when the R pulse is detected, the P and Q pulses have already passed by. Thus, adequate memory of the P and Q pulses must be available so that they will be represented in the averaging which must be performed relative to the reference point on the R pulse, if detected.

Since the HYDAC System operates with serial memory, the speed necessary for the averaging must be obtained by adding the incoming period to the accumulated sum of all previous periods in *one* rotation of the serial memory line. This demands that corresponding numbers to be added must be present simultaneously at the output of the sum memory and the input buffer memory. This, in turn, requires an alignment of the data in the two memories which, at worst, can take 256 memory cycles or about 500 milliseconds. Thus, the arithmetic calculations take

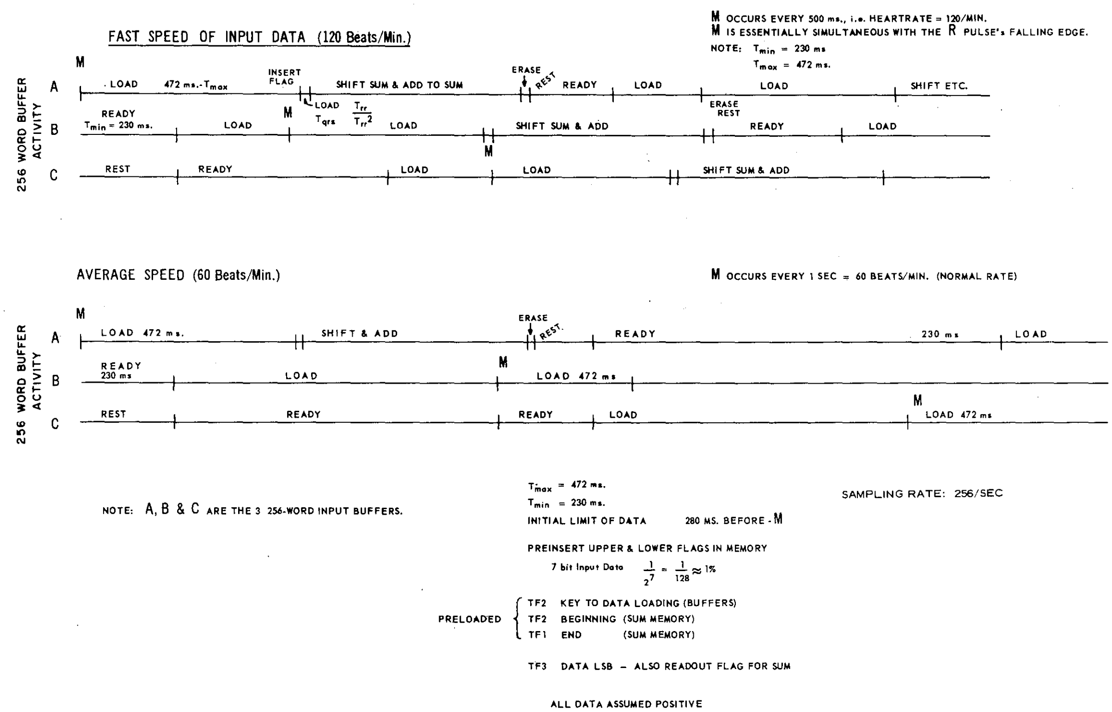


Figure 6: Cardiogram Timing Diagrams

500 ms or less to perform. Since cardiac periods lasting nominally from 500 ms to 2 seconds must be accommodated and, since it is not clear *a priori* how long a given record's period will be, a total of three input buffers are required. (See Figure 6 for timing diagrams.) These input buffer memories must be adequately controlled by a set of flip-flop state controls so that the appropriate memory either is being filled with data or is dumping data into a summer leading to an accumulation or sum memory. Further, appropriate down-counting must be available to detect an appropriate time interval following the R pulse. When this time, T_{min} (the time of the shortest expected remaining period after the R pulse), is reached, a new memory begins accepting data. Loading of the original memory continues to time, T_{max} (the maximum time after the R pulse when significant parts of the waveform may still occur). This process is continued for *n* times (where n = 16, 32 or 64) when the sum memory contains the desired average waveform. In addition to the EKG signal, the mean heart rate, T_{RR}, mean square heart rate, T_{RR}^2, and mean square QRS time must be computed since these quantities are not available on the average waveform. One-word buffers store the three associated pieces of input data to reduce access time to the 256 word buffers. The results then are punched out onto the paper tape as a more representative *average* waveform.

CONCLUSIONS

A general purpose HYDAC program for the analysis of electrocardiogram data has been described. The major features of this program include:

- The extension of this high-speed capability to permit on-line use of the computer program in complete system simulations that must proceed in real-time.
- The capability for processing large quantities of data at high speed to provide statistically-significant results for meaningful cardiograph analyses.
- The versatility provided by this general purpose approach...the output of Program I can be used as input to Program II or as input to any of a variety of other analytical devices, or the entire program can be modified for use in the analysis of other physiological processes.
- The availability of adequate memory and timing controls to accomodate varying cardiac periods lasting nominally from 500 ms to 2 seconds and thus to account for individual differences.

APPENDIX I

THE MEASURED DATA

Times... All times are measured from the beginning of the pulse whose letter is given first until the end of the pulse whose letter is given last. Thus, T_{QRS} lasts from the beginning of the Q pulse to the end of the S pulse. One exception to this definition is the timing signal T_{RR} which equals the time between succeeding R pulses.

Amplitudes... The peak values of the P, Q, R, S and T pulses are measured if detected. Otherwise appropriate abandon search records are generated and recorded onto the paper tape.

Height of the ST Segment... The average height of the segment of the cardiogram between the S and the T pulses is computed on an integrator. The exponentially weighted average is used with an appropriate RC time constant (1 sec.). This generates a value for h_{ST} practically identical to the normal arithmetic average height since the ST segment is generally less than about 0.3 seconds.

Variances... The variances of the T_{QRS} time and the T_{RR} time over a record are calculated using the relationship

$$\sigma^2_{T_{RR}} = \overline{T^2_{RR}} - (\overline{T}_{RR})^2$$

where σ^2 = variance

$\overline{T^2_{RR}}$ = mean or average of T^2_{RR}

$\overline{T}_{RR}$ = mean or average of T_{RR}

APPENDIX II

CRUCIAL EVENTS DETECTED ON THE AVERAGED WAVEFORM BY THE DECISION LOGIC

Baseline Definition... The height of the $EKG3D_{AV}$ averaged waveform when its slope first lies between $\pm\epsilon$ (a small number).

Pulse Detection Definitions... (All events are expected in the following sequence):

P Pulse... Start $= EKG3D \geq P_c$ (a small positive threshold). This is only recognized *after* the zero level baseline section has been detected and *until* 'abandon point #1' is passed.

Peak $= \frac{d}{dt}(EKG3D)_{AV} = 0$

End $= EKG3D_{AV} \leq P_c$

Q Pulse... The search for the Q pulse begins after passing 'abandon point #1' or directly after P pulse ends, if it is detected.

Start $= EKG3D_{AV} \leq N_c$ (a small negative threshold), and

$\frac{d}{dt}(EKG3D)_{AV} \leq 0$

Peak $= \frac{d(EKG3D)AV}{dt} = 0$

End $= EKG3D \geq N_c$

Abandon search (A_2) when $EKG3D_{AV} \geq P_c$. Also start QT and QRS time measurements if they have not already begun by a detected Q pulse.

R Pulse... Peak $= \frac{d(EKG3D)}{dt} = 0$

End $= EKG3D \leq P_c$

R negative slope = critical level - defines basic reference point.

S Pulse... Start $= EKG3D_{AV} \leq N_c$ (Following the R pulse)

Peak $= \frac{d(EKG3D)_{AV}}{dt} = 0$

End $= EKG3D \geq N_c$

Abandon search if S pulse does not occur within 160 ms past the R pulse.

ST Segment... Lasts from the end of the S pulse or 160 ms past the R pulse if the S pulse does not occur, until the beginning of the T pulse.

T Pulse... Start $= EKG3D_{AV} \geq P_c$ (After R pulse)

Peak $= \frac{d(EKG3D)AV}{dt} = 0$

End $= EKG3D \leq P_c$