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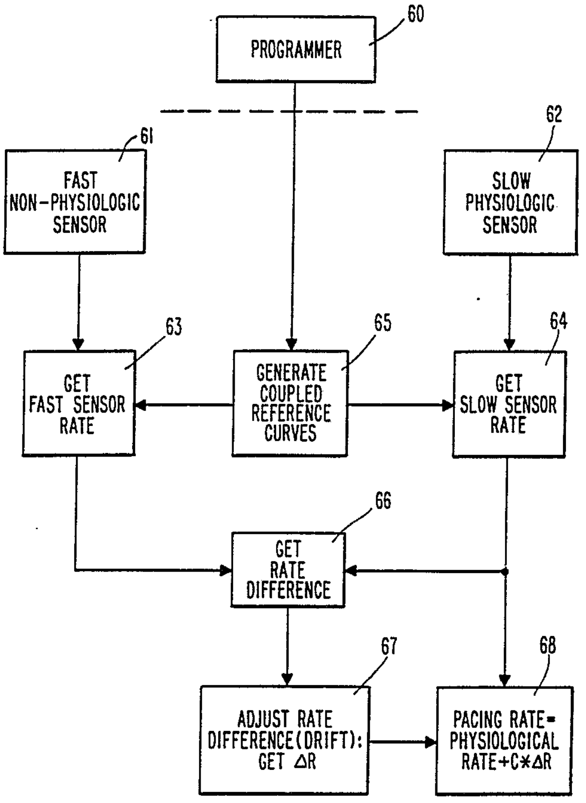
(57) Abstract

A pacemaker system is provided for rate responsive pacing, wherein rate is controlled as a function of two or more sensor inputs (61, 62), each sensor providing a signal representing a respective different control parameter. Preferably a first sensor signal represents a physiologically accurate although slow response signal such as QT interval, and a second sensor represents a relatively fast response such as activity. The two parameter signals are processed so that they are directly comparable and can be compared as indicators of pacing rate throughout the desired pacing range (63, 64). The algorithm utilizes a parameter control reference curve for each respective parameter, such reference curve representing the desired correlation between pacing rate and the parameter signal (65). Rate control is accomplished by determining the difference between each processed parameter signal and its corresponding reference point for the current pacing interval (76), and logically analyzing the two differences to determine which is used to indicate change in pacing rate (77, 79, 80, 82). Each parameter reference curve is automatically adjustable to correspond to patient conditions (Fig. 17). Automatic drift correction of the fast response parameter, such as activity, is used to compensate for conditions where the fast response signal is not likely to be physiologically reflective of the patient condition (67, Fig. 18A).



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PACEMAKER WITH OPTIMIZED RATE RESPONSIVENESS AND METHOD OF RATE CONTROL

BACKGROUND OF THE INVENTION

Field of the Invention

The subject invention relates to cardiac pacemaker systems and, more particularly, implantable cardiac pacemakers which deliver pacing stimulus pulses at an adjustable rate based upon monitoring of patient conditions.

Description of the Background and Prior Art

Rate responsive pacemaker systems are widely available in the art. Rate responsive systems contain means for monitoring at least one patient variable and for determining an indicated pacing rate as a function of such sensed pacing variable, so as to control pacing rate optimally in terms of the patient condition. Such rate responsive pacemakers have gained wide acceptance as providing an improved response to the patient's physiological needs, as compared to programmable fixed rate pacemakers. Although atrial-based pacemakers, i.e. atrial synchronous or atrial sequential pacemakers, as well as DDD pacemakers, may in some patients provide an ideal form of rate responsiveness, such pacemakers are not satisfactory for many patients with cardiac conditions.

A number of patient variables or rate control parameters have been suggested in the technical literature and used commercially. One of the first physiological parameters utilized for rate control is the QT interval, as disclosed in the U.S. patent to Rickards, No. 4,228,803 and the U.S. patent to Wittkampf et al., No. 4,305,396. The QT interval is in fact the interval between a delivered pacing stimulus and the subsequent evoked T-wave, and has been utilized as the parameter indicative of physiological demand for heart output, and thus pacing rate. Additionally, activity sensors have been widely utilized for detecting the general activity level of a patient with a pacemaker, and for controlling the pacing rate or escape interval in response to detected activity level. See the U.S. patent to Anderson et al., No. 4,428,378. Other parameters which have been utilized or investigated for suitability as controlling pacing rate include respiration rate, thoracic impedance changes, venous blood temperature, pH, oxygen saturation and stroke volume.

In addition to the selection of a desired monitored parameter, and the corresponding sensor to be used, the algorithm utilized by a pacing system is of great importance. An example of an improved rate adaptive algorithm used in a pacing system is set forth in U.S. Patent 4,972,834, S.N. 252,643, filed September 30, 1988, which discloses a QT pacemaker with dynamic rate responsiveness, incorporated herein by reference. As set forth in this referenced patent, the algorithm which correlates the monitored or sensed parameter with indicated pacing rate may be adapted as a function of history, and particularly can be readjusted with respect to limits such as lower rate limit (LRL) and upper rate limit (URL).

Another approach to optimizing rate responsiveness is to use dual or plural sensors, in order that the drawbacks or deficiencies of a given sensor and/or algorithm may be compensated by the use of a second or other sensors having different characteristics. This approach is set forth in the patent to Rickards, No. 4,527,568, which discloses switching control of rate responsiveness from one monitored parameter, e.g. atrial rate, to another control parameter, e.g. QT interval. There are many other examples of dual sensor approaches in the literature, and reference is made to U.S. Patents Nos. 4,926,863, 4,905,697, and 4,884,576; EPC application 0 222 681; and UK application GB 2216011. These references are characterized by designs which switch control from one sensor to another, or from one algorithm to another, depending upon monitored values of the rate control parameters. While this approach may produce increased efficiency and improvement over the single sensor approach, it still does not provide a continuous optimization of information such as is potentially available from two or more sensors, so as to continuously optimize and adapt the actual pacing rate for all foreseeable conditions. As used in this specification, "sensor" or "sensor means" refers to any means for obtaining a control parameter, including the lead means such as is used for obtaining the QT interval, or other sensors such as in use for detecting body activity and the like. The techniques for sensing rate control parameters, and developing and processing therefrom signals useful for pacemaker control, are well known in the art.

A longstanding unsolved problem in this art area, for which there is a need for improvement, is thus to provide either a sensor or combination of sensors which more nearly fulfills the requirement of the ideal rate adaptive system. For example, a rate adaptive system should provide a quick and accurate initial response to situations such as start of exercise. The QT interval, as a rate control parameter, provides only a gradual response, as compared to an activity sensor which provides a fast, i.e., quick response. Another requirement is that the parameter or parameters chosen should provide an indication of pacing rate which is proportional to the work load. The QT interval provides a very good indication of work load, whereas the activity sensor approach is not as good, and may be subject to false indications. Another important requirement for a rate control parameter is specificity, i.e., that the characteristics of the parameter signal are specific to the conditions of rest and exercise of the patient and are thus physiologically appropriate. For example, the QT interval has a high specificity, whereas activity as a parameter has a medium specificity. Yet another requirement is providing an optimum indication of rate decrease following cessation or reduction of the condition compelling higher rate, such as exercise. It is important that the speed of rate decay after the cessation of exercise be properly related to the patient's physical condition. It is known that a patient in relatively poor physical condition experiences a slow decrease of the heart rate after exercise, while a person in relatively good physical condition experiences a more rapid decrease of the heart rate after exercise. A pacemaker controlled by an activity sensor is less than optimal in this regard, since a cessation of exercise results in a sharp drop in the activity signal which, if not modified, would lead to a non-physiological step-like reduction in pacing rate. As a consequence, it is necessary to program a fixed time period for gradually decreasing the pacing rate when the activity sensor stops delivering information calling for a higher rate. The pacemaker which is controlled by the QT interval exhibits the inverse relationship as known from exercise physiology, but tends to provide too slow a pacing rate decay.

What is thus sought in this art area is a pacer having two or more sensors and an algorithm for deriving information from each so as to optimize the determination of desired pacing rate. At the start of exercise, for example, it is desired to have the algorithm force an initial but limited fast rate increase. Thereafter, it becomes important to ensure that the pacing rate correlates proportionally to work load, and that if continuous exercise is not confirmed, the pacing rate will slowly decrease toward a lower limit. The algorithm, combined with the sensing means, should also force a faster, although limited rate decrease when stop of exercise is detected, with further rate decrease following the physiologically inverse relationship.

As is well known, the microprocessor and logic circuit technology for dealing with these problems in a pacemaker environment is available. What is needed is a pacemaker system which utilizes this technology so as to optimize the translation of plural sensor information into pacing rate control.

SUMMARY OF THE INVENTION

The pacing system of this invention provides an improvement in rate responsive pacemakers so as to more optimally adapt rate control to patient conditions. Specifically, the object is to combine information from two or more sensor sources so that during all phases of the patient's activity and rest there is provided information accurately reflective of the physiological state of the patient, as well as fast response information from which more appropriate time control of pacing rate can be derived and accomplished.

A specific object of this invention is to provide a pacing system which is rate responsive to a quick response sensor which monitors a parameter such as activity, as well as a slower response sensor which monitors a more specific parameter such as QT interval, having an algorithm and control means for detecting which sensor source provides the optimum information under any given patient condition, and controlling pacing rate in response to the detected optimum information so as to provide physiologically optimal pacing.

It is a further object of this invention to provide rate control pacing where the pacing rate is primarily controlled in response to first sensor information which is highly specific to patient physiological conditions and provides an indication proportional to work load, and wherein the controlled pacing rate is modified according to further information from one or more other sensor sources which provide a quicker response to patient conditions, than does the first sensor source.

It is yet a further object of this invention to provide an inplantable pacemaker which is rate controlled as a function of at least two parameters reflective of patient condition, the pacemaker utilizing an algorithm adapted to provide primary control on the basis of a first of said parameters, and having means for adjusting and coupling the control information derived from the second parameter so as to be adapted for use in the same algorithm, thereby giving the pacemaker the advantage of continual comparison of comparable information from at least two parameter sources for logically deciding what pacing rate is appropriate.

In accordance with the above objectives, there is provided a pacemaker system and method of controlling pacing rate wherein at least two rate control parameters are utilized. The system incorporates means, if required, for processing a second one of the parameter signals so that the respective parameter signals are comparable, i.e. can be compared by a logic analysis as part of an algorithm in determining how to control pacing rate. This system includes establishing parameter control reference curves for each respective parameter, each reference curve representing pacing rate (or pacing interval) as a function of the respective parameter signal, and each of the two or more parameter curves being coupled so that each parameter indication is logic comparable over a range of pacing rates. Primary rate control is based on a first physiological parameter such as QT interval, and rate control is modified by information from a secondary source such as an activity sensor. Each reference parameter curve is automatically adjustable to correspond to patient conditions and patient history, while maintaining the curves coupled. Automatic drift correction of the secondary parameter, such as activity, is used where there is a difference between the variable and its corresponding reference curve point whereby one can choose to correct only positive differences, only negative differences or both, so as to maintain comparability of the variables, permitting continuous interval-to-interval comparing and decision making on rate control.

Primary rate control by the physiological parameter can be achieved either by programming it to have a greater influence than the fast-response parameter, or by applying the drift factor just to the fast-response parameter, or both. By primary control, it is meant that the physiological parameter is weighted relative to the fast-response parameter so that normally a comparison between the physiological rate indication and the fast-response rate indication results in control by the physiological parameter, except for short periods following changes in patient condition that produce relatively large changes in the fast-response parameter. By this technique, a comparison can be made every pacing cycle, and throughout the pacing range, so as to optimize the rate response in terms of the greater accuracy of the physiological parameter during steady patient conditions, and in terms of the quicker change of the fast-response parameter during more transient conditions, i.e., onset of exercise or rapid change in the level of exercise. The weighting may be done, for example, by setting the correlation curve (reference curve) of the activity sensor at a relatively low slope, such that only when activity jumps up significantly does the activity-indicated rate exceed the slower-responding physiological rate, until the physiological rate also responds to the increased activity.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic block diagram of a pacing system with microprocessor control, such as can be used for this invention.

Figure 2 is a generalized flow diagram showing some of the main features of the system and method of this invention.

Figure 3 shows a set of curves representing QT as a function of pacing interval for different patient stress levels.

Figure 4 shows the QT reference curve (QT_{ref}), which is a function of pacing interval, in relation to curves of QT for rest and maximum exercise.

Figure 5 shows a curve of ACT_{ref} as a function of interval in relation to curves of ACT for different exercise levels.

Figures 6A and 6B show coupled curves of QT_{ref} and ACT_{ref} as a function of pacing interval, as used in the combination sensor algorithm of this invention.

Figures 7A and 7B illustrate graphically, with respect to the coupled reference curves, a first situation where both sensor variables indicate an increased rate.

Figures 8A and 8B illustrate graphically a second situation where both sensor variables indicate a decreased rate.

Figure 9A and 9B illustrate graphically a third situation where the algorithm indicates an increased rate.

FIgures 10A and 10B illustrate graphically a fourth situation where the algorithm indicates a decreased rate.

Figures 11A and 11B illustrate graphically a fifth situation where the algorithm indicates a decreased rate.

Figures 12A and 12B illustrate graphically a sixth situation where the algorithm indicates an increased rate.

Figures 13A and 13B illustrate graphically a situation where the ACT variable has a lesser influence than the QT variable.

Figures 14A and 14B illustrate graphically a situation where ACT and QT have about the same influence.

Figures 15A and 15B illustrate graphically a situation where ACT has a greater influence than QT.

Figure 16 is a flow diagram of the portion of the preferred algorithm of this invention for changing pacing rate as a function of sensed QT and activity signals.

Figure 17 is a flow diagram of the portion of the preferred algorithm of this invention for adjusting operation of the pacer at URL, and of a portion of the algorithm of the preferred embodiment of this invention for setting the activity drift (ACRdr) factor under predetermined conditions.

Figures 18A and 18B illustrate graphically a situation where the algorithm indicates start of ACT drift, causing ACT to decrease.

Figures 19A and 19B illustrate graphically the situation sometime following that of Figures 18A and 18B, where rate has decreased and ACT drift has increased to the stable condition where ACT = ACT_{ref} and QT = QT_{ref}.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

In discussing the pacemaker system of this invention, reference is made to the prior art which teaches the use of microprocessor capability in an implantable pacemaker system, as well as the art of external programmer communication with an implanted pacemaker. Reference is made to U.S. Patents Nos. 4,527,568 and 4,503,857, incorporated herein by reference, which describe operations of pacemaker embodiments incorporating microprocessor logic and software algorithms. U.S. Patents Nos. 4,228,803 and 4,305,396 describe the operation of embodiments of a Tx pacemaker, i.e., one which is rate responsive to the QT interval, and are incorporated by reference. Generally, the prior art teaches and discloses various means of using microprocessors and software in controlling the operation of an implanted pacemaker. Accordingly, the specification does not contain a detailed description of the commercially available and known techniques of programming a microprocessor, storing data in memory and retrieving it, carrying out such operations as timing time intervals and setting up sensing windows, the logic of resetting the escape interval when a natural heartbeat is sensed, etc. These operations are well known in the art and are taught by the above references as well as other published patents and articles in this area. Reference is also made to the commercially available ACTIVITRAX pacemaker, of Medtronic, Inc. and the QUINTECH pacemaker of Vitatron Medical B.V., as commercial embodiments of software controlled pacers which are rate responsive to activity and QT interval respectively, and to the literature describing these pacemakers.

The following Glossary defines terms which are referred to in the description of the preferred embodiments:

GLOSSARY OF TERMS

ACT:	Control parameter representing activity
ACT_{ref}:	Reference value of activity control parameter at a given interval (pacing rate)
ACT_{dif}:	ACT_{ref} - ACT
ACTdr:	Drift factor used to adjust
ACTmpl:	Conversion factor by which activity counts (Nact) is multiplied to convert to units of ms
B:	second order constant in polynomial relating QT_{ref} to interval; primary factor in determining value of QT_{ref} at URL
Dact:	value of incremental change in ACT_{ref} for decremental change in interval
Dpt:	first order in polynomial relating to QT_{ref} and interval; value of incremental change in QT_{ref} for incremental change in interval

Fact: Activity frequency for activity sensor

Int: Pacing interval in ms

LRL: Lower rate limit of pacing range

N: Number of intervals or number of 3.3 second periods counted in determining Nact

Nact: Number of counts of activity sensor

QT: Interval between delivered pacing pulse and evoked T wave; also referred to as QT interval.

QT_{ref}: Value of QT reference curve corresponding to a given interval (Ttx).

QT_{dif}: $QT_{ref} - QT$

$QT_{STR(max)}$: Maximum difference in QT due to increase in stress, i.e., difference in QT at a given interval as between patient at rest and patient at maximum exercise.

QT_{max}: Lowest value of QT for a patient at maximum exercise and URL

QT(m): Maximum value of QT at LRL and patient at rest

QTsave: QT_{ref} - CRVMAX

Ttx: Interval on QT_{ref} and ACT_{ref} curves corresponding to pacing interval

TwA: Amplitude of T wave

T_{URL}: Interval at upper rate limit

T_{LRL}: Interval at lower rate limit

URL: Upper rate limit of pacing range

LOOP: Software number corresponding to step size of increase in pacing interval

CRVMAX: Programmable value representing threshold change in QT at URL for determining whether QT_{ref} should be changed at URL

In the subject invention, the improvement lies primarily in an algorithm for processing data from two or more sensor sources, so as to optimize rate control. The algorithm is structured so as to go through routines each pacing cycle, making rate change decisions based on a comparison of indications from each of the sensors. In the preferred embodiment as illustrated, pacing rate is adjusted each cycle, or interval, but the invention is not so limited. Thus, the principles of the invention can likewise be applied to adjusting pacing rate every N cycles, every elapsed predetermined time period, etc. Also, while the preferred embodiment illustrates a two sensor mode where the pacemaker is responsive to QT and activity information, it is to be understood that other combinations of two or more sensor inputs may be utilized. As used herein, sensor, or parameter sensor, broadly refers to obtaining rate control information and processing for use as control signals, and embraces systems such as the QT system where the pacing lead is utilized, as well as other systems where two or more separate sensors are utilized.

Referring to Figure 1, there is shown a schematic representation of a pacer system as utilized in this invention. A pacemaker, preferably an implantable pacemaker 50, is used with an external programmer 51, the external programmer operating in a known manner to program pacemaker variables. A lead 53 is illustrated as being a ventricular lead, which lead delivers stimulus pulses to the ventricle and also provides sensed patient heartbeat signals to the pacemaker in a known manner. A lead 54 may also be used for a dual chamber pacemaker, connecting the pacemaker to the atrium. Leads 55 and 56 are shown connected to sensors S1 and S2 in the patient, for providing control parameters as discussed above. For a system using the QT and activity parameters, only leads 53 and 55 would be required. The pacemaker is illustrated as having a microprocessor 57, which includes memory for carrying the software of the algorithm of this invention. A block 58 is also indicated for signal processing of signals derived from lead 53 and sensors S1 and S2 in the known manner. The pacemaker contains the conventional means for generating stimulus pulses, inhibiting on demand, controlling rate, pulse width, etc.

By way of overview, the algorithm of the preferred embodiment of this invention is based upon several principles, or premises. A first working premise is that one of the parameters is taken as the primary control parameter, e.g. QT, and the other parameter is converted into corresponding units so as to be comparable for control purposes. Thus, in the preferred embodiment the ACT variable is derived by first obtaining counts from an activity sensor. See U.S. Patent No. 4,428,378, incorporated herein by reference. The count is converted into a variable having units of ms, the same as QT, and is adjusted by a multiplier factor so as to provide a comparison of the two variables throughout the anticipated pacing range between lower rate limit (LRL) and upper rate limit (URL).

Another principle of the algorithm of this invention is that a reference curve is established for each variable, the reference curve establishing desired correlation of the control variable and the pacing interval. Actual control of pacing is preferably accomplished on the basis of the determined difference between the value of each respective control parameter at a given interval compared to the corresponding reference value of that parameter at the point on the reference curve corresponding to the pacing interval. Thus, for the QT parameter, the algorithm operates each interval to determine the difference between the QT reference value (QT_{ref}) for the pacing interval and the measured QT, to get QT_{dif}. Likewise, the algorithm makes a determination of the difference between the activity reference (ACT_{ref}) and the determined ACT parameter, to obtain a value of ACT_{dif}. Change of pacing rate, which in the preferred embodiment is accomplished each interval or pacing cycle, is determined as a function of these difference values, and not as a function of a comparison of the variable for the current interval versus the variable for the prior interval. Each interval, or cycle, the reference value for each pacing parameter is updated, or adjusted. Thus, for each new interval, the corresponding reference value is either incremented or decremented in accordance with a predetermined formula which establishes the reference curve for each respective parameter.

The reference curves are coupled in the sense that each reference curve represents a predetermined relation, or correlation, between pacing interval and its respective parameter between LRL and URL. In a preferred embodiment, the reference curve for the primary parameter, QT, is established in accordance with measured patient response to stress, and the second reference curve is scaled with respect to the first reference curve in a manner such as to adjust the influence of each parameter in determining control of pacing rate. Thus, the invention embraces the use of two or more control parameters, and an algorithm for establishing a respective reference curve for each such parameter. The reference curves are coupled so as to represent respective predetermined relationships between pacing rate and the control parameters between the programmable rate limits of the pacemaker, the algorithm determining change in pacing rate as a function of determined differences between each parameter and its respective reference value at the current pacing interval in accordance with predetermined logic.

Referring now to Figure 2, there is shown a generalized flow diagram which represents the basic steps of the algorithm of this invention for determining pacing rate as a combined function of two control parameters derived from separate sensor sources. An external programmer 60 communicates with the pacemaker device. In general, the programmer is used for programing different pacing operating constants as is conventional in the use of programmable pacemakers. In this case, the programmer provides data which is used for generating the coupled reference curves, as indicated in block 65. A fast non-physiological sensor, such as an activity sensor, is indicated at block 61, and provides a signal which is operated on to get a fast sensor rate indication, as indicated at block 63. Note that the step of obtaining the fast sensor rate utilizes reference curve information, i.e., the sensor indication is compared to the reference information and the difference is used to determine the fast sensor rate. Likewise, a slow physiological sensor, such as means for obtaining the QT interval, is indicated at 62. Its output is processed at 64 to get a slow sensor rate, utilizing the correlation information generated at block 65. The fast sensor rate and the slow sensor rate are compared at 66, and the rate difference is adjusted at block 67. This adjustment constitutes changing the difference by a drift factor to get a differential adjustment indicated as ΔR. At block 68, the pacing rate is determined as the physiological rate (the slow sensor rate) plus an increment determined by multiplying ΔR by a factor C. Thus, the pacing rate is determined as a primary function of the physiological, or slow rate, and adapted as a function of the fast sensor rate, the adaptation being adjusted by the drift factor. It is to be understood that the adjustment of the contribution of the secondary sensor may be obtained by different procedures other than the drift factor as used herein, e.g., by differentiation of the rate difference or another mathematical operation.

As used herein, drift refers to a periodic change in the contribution of the fast, or secondary sensor rate. For example, where the fast sensor indicates a rate higher than the physiological rate, such that the value of ΔR is positive, the pacemaker may decrement the positive value of ΔR once every predetermined number of seconds, causing ΔR to drift toward zero and thus reduce over a period of time the differential effect of the fast sensor. Likewise, where the Δ rate is negative, meaning that the pacing rate is below the physiological rate due to the contribution of the fast sensor rate, the drift factor would increment Δ rate so that the negative Δ rate drifted toward zero with time. The effect of introducing such a drift factor is thus to initially permit the influence of the fast sensor on the premise that its fast response is more accurate than that of the slow sensor in reacting to changes, but to diminish with time the differential influence of the fast sensor on the grounds that after a while the slow sensor is more reliable. By only allowing a decremental drift of ΔR or only an incremental drift of ΔR one can choose to only diminish rates which are higher or lower than the physiological rate.

It is known that the QT interval is in fact influenced both by the pacing interval and by mental and physical stress. Thus, when the pacing interval shortens, QT shortens likewise, and vice versa, in a non-linear manner. Both mental and physical stress cause QT to shorten, and for this invention it is assumed that the relation between stress change and QT change is substantially linear. Figure 3 shows curves for this relationship corresponding to the patient at rest (1), medium exercise (2) and maximum exercise (3). $QT_{STR(max)}$ indicates the change in QT at URL between rest and maximum exercise. The QT interval is obtained in the ordinary manner, with circuitry and/or software for timing out the interval between the delivered stimulus pulse and the sensed T wave. See, for example, U.S. Patent No. 4,527,568.

The QT_{ref} curve, which correlates QT as a function of interval, is illustrated in Figure 4. The QT_{ref} curve must be maximum at LRL and zero stress (patient in rest condition) and must be minimum at URL and maximum stress (maximum patient exercise). The QT_{ref} curve between these two limits is chosen such that the relation between QT_{ref} and interval is a second order polynomial function, providing that the step change in QT_{ref} is a linear function of interval:

$$QT_{ref} = QT(m) - Dpt\ (T_{LRL} - int) - B'\ (T_{LRL} - int)^2$$
$$\Delta QT_{ref} = -Dpt - B\ (TLRL - int)$$

Figure 4 illustrates the determination of $QT_{dif} = (QT_{ref} - QT)$ at a given interval. Thus, if at the pacing interval designated I_0, the actual QT is less than the reference curve, as indicated at point 3i, then QT_{dif} is greater than 0, indicating a desired increment in the pacing rate (decreasing pacing interval). On the other hand, if the measured QT is greater than the reference value, then QT_{dif} is negative, indicating a decrease in pacing rate (increase in interval). This is summarized as follows:

Point 3i: $QT < QT_{ref}$
$QT_{dif} = (QT_{ref} - QT) > 0$
increment pacing rate

Point 3d: $QT > QT_{ref}$
$QT_{dif} = (QT_{ref} - QT) < 0$
decrement pacing rate

To obtain the second pacing parameter (ACT) a piezo-electric element (which may be S1 in Figure 1) is suitably glued inside the pacemaker can. The activity sensor delivers an electrical signal that depends on vibrations of the can, which in turn are caused by movements of the patient and thus relate to exercise. The electrical signal is sensed by a sense amplifier, and the number of activity senses is counted. This number, Nact, is assumed to be proportional to the physical stress, and thus a measure thereof. Reference is made to U.S. Patent No. 4,428,378, assigned to Medtronic, Inc., which discloses a rate adaptive pacer utilizing an activity sensor, and which is incorporated herein by reference.

The activity signal Nact, which is a unitless number, is converted in the practice of this invention to have the same units as QT, i.e. ms, by the following formula:

$$ACT = ACTmpl * Nact$$

By this conversion, Nact can be compared to the QT variable in a combined QT plus ACT algorithm. It is noted that the number of activity senses can be counted in two ways. In a first method, a programmable time is utilized, providing the following formula:

$$Nact = Fact * (\Delta t) = counts;$$

$$ACT = ACTmpl * Fact * \Delta t,$$

where Fact = activity frequency (S^{-1}), and Δt is the programmable time in seconds.

Alternately, Nact can be a counted over predetermined number (N) of intervals, resulting in the following equations:

$$Nact = Fact * N * int/1000$$

where int is in ms; and N is the number of counting intervals;
ACT = ACTmpl * (Fact * N * int/1000)

In a preferred embodiment, means for obtaining the ACT signal are controlled by a software routine which is entered once every cycle. If the system is programmed to utilize the activity signal, the routine checks to see if Nact is to be read on an interval or time basis. If the moment to read has not arrived, the routine skips out. However, if the moment to read is present, the routine gets the counts (Nact) from the activity sensor and resets the activity counter for the next cycle. Then, optionally, the routine may limit any change in Nact compared to the prior value, if pacing rate is close to URL. Following this, the ACT signal is generated on the basis of the following equations:

temp: (Nact - ACTdr)
ACT = ACTmpl * temp,

where ACTdr is a drift factor, as discussed more fully below.

Referring to Figure 5, there is shown the relation between activity frequency (Fact) and ACT, with ACT presented as a function of interval. Curve (1) represents ACT for medium activity, while curve (2) represents ACT for maximum activity. This figure illustrates how Fact increases as a function of patient activity, and it shows the conversion from Fact to ACT. It is noted also that in this case Nact is counted over N intervals, and that ACT increases as a function of interval (if ACT were determined per a given time period, each ACT line corresponding to a given activity level would be horizontal, and not a function of pacing interval). Figure 5 also shows the ACT_{ref} curve (3) superimposed on the ACT curves for maximum and medium activity. It is noted that the ACT_{ref} curve must be at zero at LRL, corresponding to no activity when the patient is at rest. The curve must extend to the maximal ACT at URL, corresponding to the highest pacing rate at maximum patient activity. The ACT_{ref} relation is chosen to be linear, according to the following formula:

$$ACT_{ref} = Dact\ (T_{LRL} - int)$$

Figure 5 indicates, at point 4i, a situation where the measured activity level at a given interval (I_0) is greater than ACT_{ref}, indicating that the pacing rate should be incremented; and the situation at point 4d, where the activity level is less than ACT_{ref}, indicating that the pacing rate should be decremented. This is summarized as follows:

Point 4i: $ACT > ACT_{ref}$
$ACT_{dif} = ACT_{ref} - ACT < 0$
increment pacing rate

Point 4d: $ACT < ACT_{ref}$
$ACT_{dif} = ACT_{ref} - ACT > 0$
decrement pacing rate

In the preferred embodiment, as discussed above, there are two coupled reference curves, as shown in Figure 5. Thus, at the programmable LRL, the QT reference curve correlates minimum stress patient QT at rest and the LRL interval; and the ACT reference curve correlates the minimum patient activity signal at rest and LRL. Likewise, at URL, the QT reference curve correlates patient QT reached at maximum stress and URL, and the ACT reference curve correlates maximum stress ACT and URL. The curves are coupled in the sense that each is designed to indicate approximately the same pacing rate within the LRL-URL range for varying activity or stress levels.

The decision as to whether to increase or decrease pacing rate depends upon comparisons of QT_{dif} and ACT_{dif}, as illustrated in Figures 7A, 7B - 12A, 12B. Figures 7A and 7B illustrate the situation where ACT is greater than ACT_{ref} and QT is less than QT_{ref}. Note that when QT is less than QT_{ref}, a higher rate is indicated; when ACT is greater than ACT_{ref}, a higher rate is also indicated. Thus, in this situation, both difference indicators signal an increasing exercise level, calling for an increase in rate. In Figures 8A and 8B, ACT is less than ACT_{ref} and QT is greater than QT_{ref}. Again, both difference values indicate a decreasing exercise level, so the algorithm prescribes that the rate goes down. In Figures 9A and 9B, ACT_{dif} indicates a decremented pacing rate, while QT_{dif} indicates an increased pacing rate. In accordance with this invention, since QT_{dif} is greater than ACT_{dif}, the QT influence prevails and the algorithm calls for the rate to go up. In Figures 10A and 10B, the situation is the same as in that of Figures 9A and 9B, except that ACT_{dif} is greater, and the alogrithm responds to prescribe that the rate goes down. In Figures 11A and 11B, ACT_{dif} signals increasing exercise while, QT_{dif} signals decreasing exercise. Since the QT influence is the largest, the algorithm calls for the rate to go down. In Figures 12A and 12B, the situation is the same as Figure 11A and 11B, but since the ACT influence is the largest, the algorithm prescribes that the rate goes up.

As seen from Figures 9A, 9B - 12A, 12B, the relative influence of the QT and ACT signals are compared by the algorithm to determine, in certain situations, whether the activity parameter or the QT parameter prevails in causing pacing rate to increase or decrease. The relative influence of the activity sensor on the pacemaker response depends upon the comparison between the maximum value of ACT_{ref} at URL, and QT for the highest stress level at URL ($QT_{STR(max)}$). The value for $QT_{STR(max)}$ may not be precisely known for the patient, but generally can be estimated to be approximately 30 ms. The maximum value of ACT_{ref} at URL can be set so as to give any fixed relation to $QT_{STR(max)}$. The pacer variable ACTmpl then must be set such that ACTmpl * Nact matches such maximum ACT_{ref} at URL. Note that ACTmpl determines the ACT signal, so if ACTmpl is small, this minimizes the influence of ACT. Likewise Dact, which represents the linear variation of ACT_{ref} with interval, establishes desired variations of pacing rate with change in activity level, and if Dact is small, this also minimizes the influence of ACT. On the other hand, if both Dact and ACTmpl are relatively large, then ACT has a relatively greater influence on the decision made by the algorithm to increase or decrease pacing rate.

Referring to Figures 13A, 13B, 14A, 14B, and 15A, 15B, there are represented three situations which illustrate the relative influence between QT and ACT. In all three figures, ACT indicates an increasing exercise level, whereas QT indicates a decreasing exercise level. In the situation of Figures 13A, 13B, ACTmpl and Dact are small ($A < B$), so ACT has little influence ($C < D$). Since QT has the greater influence, the rate is caused to go down. In Figures 14A, 14B, ACTmpl and Dact are chosen such that ACT and QT have substantially equal influence ($A = B$), and the algorithm will maintain pacing rate the same (except that each single step it will increment or decrement). In the situation of Figures 15A, 15B, ACTmpl and Dact are relatively large ($A > B$), causing ACT to have greater influence ($C > D$). This results in the algorithm causing the rate to increase. Thus, relative influence is established by the choice of ACT_{mpl} and Dact.

Referring now to Figure 16, there is shown a flow diagram of a preferred rate algorithm incorporating both the QT and activity (ACT) variables. The steps of this specific algorithm are carried out each cycle following delivery of a pacing stimulus. Reference is also made to Figures 7-15 which illustrate the effect of the algorithm under varying situations.

As indicated at 71, it is first determined whether the pacing rate is near LRL. This is done by comparing the measured time interval (Ttx) to the value of the interval corresponding to LRL (T_{LRL}) minus 25.6 ms. If Ttx is smaller than this interval, meaning that it is not within 25.6 ms of lower rate limit interval, then the program branches to block 72 where it is determined whether the T wave has been sensed. If yes, or if the actual pacing interval is within 25.6 ms of T_{LRL}, the program branches to block 76. If no T wave has been sensed, such that QT rate information is not available, the program branches to block 73 where the last measured QT value is increased by an arbitrary amount, e.g. 50 µs. Thus, the pacer provides a drift to the QT value which causes it to increase toward T_{LRL} when no T waves are sensed. However, when the pacing rate comes near to LRL, the drift in QT stops. In practice, the drift of QT is limited to a predetermined value, since a high activity level sensed by the activity sensor could maintain the pacer far from LRL, in which case a prolonged period of absence of T wave sensing would cause the variable QT otherwise to drift lower than a value corresponding to T_{LRL}.

Following the decision as to whether to cause QT to drift, the software makes a decision as to whether to increment or decrement the rate, in accordance with the steps carried out at blocks 76, 77, 79, 80 and 82. As indicated at block 76, the difference variables, ACT_{dif} and QT_{dif} (as defined above), are determined by subtracting the ACT and QT values from their respective corresponding reference values at the current interval, Ttx. As per the above discussion, an increase in the ACT variable so that it has a higher value than the ACT_{ref} variable is an indication of increase of rate, such that a negative ACT_{dif} indicates a desired rate increase, and vice versa. At the same time, a decrease in sensed QT value to the point that it is less than QT_{ref}, causing a positive QT_{dif}, indicates a rate increase, and vice versa. Thus, while the difference variables are comparable in the sense that ACT is treated as a substitute parameter to QT, the difference in sign needs to be taken into account. At block 77, the pacemaker determines whether it is in the QT mode, i.e. whether the QT parameter is being utilized. If no, the program branches to block 82 where further logic is based on the activity signal alone. If yes, the program goes to block 79 where the signs (plus or minus) of ACT_{dif} and QT_{dif} are compared. If these signs are found not to be equal, in other words unequal, the program branches to block 82. In such case, both variables point to the same direction of change (Figures 7 and 8), and at 82 ACT_{dif} is utilized to determine whether the rate should be increased or decreased. If ACT_{dif} is negative, then an increase in rate is indicated, and the program branches to block 88. If ACT_{dif} is not negative, then a decrease in rate is indicated, and the program branches to block 84. Note, as discussed above, there can be two situations where the difference values have equal signs, namely where QT is less than QT_{ref} and ACT is greater than ACT_{ref}; and where QT is greater than QT_{ref} and ACT is less than ACT_{ref}. However, if at 79, the difference variables have unequal signs, which happens in four situations, the program branches to block 80. There it is determined which parameter has the greatest influence, by determining whether QT_{dif} is greater than ACT_{dif}. If yes, an increase in rate is called for, and the program branches to block 88. If no, a decrease in rate is called for, and the program branches to block 84. Note that, as discussed above, influence can be programmed, e.g., by the setting of ACT_{mpl} and Dact. See also blocks 60, 65 of Fig. 2.

At block 84, the current interval Ttx is increased by 5 ms, i.e. the pacing interval is increased by 5 ms. Then, at block 85, new points on the QT reference curve and ACT reference curve are calculated, to correspond to the new interval. The new QT_{ref} is calculated by increasing QT_{ref} by an incremental amount "curve" calculated as follows:

$$\text{Curve} = \text{Dpt} + \text{B}\ (\text{TLRL} - \text{Ttx})$$

At the same time, a new point on the activity reference curve is calculated by decreasing ACT_{ref} with the value Dact. ACT_{ref} cannot be decreased below a predetermined minimum. Thus, the decision to decrease rate results in increasing the interval by 5 ms, and adjusting the reference points on the reference curves of both QT_{ref} and ACT_{ref}.

If the comparisons made at blocks 79 and 80 indicate an increase in rate, the program proceeds to block 88 where a calculation of step size is made. The interval change during increase of rate is made dependent upon the interval, i.e., Ttx. This feature limits change of pacing rate at very high rates (corresponding to short intervals) and permits larger pacing interval changes with increasing intervals. For the preferred embodiment, the correspondence between interval and step size is set forth in the following table:

Interval	Stepsize
< 614.4 ms	5 ms = 1*5 ms
614.4 - 819 ms	10 ms = 2*5 ms
819.2 - 1024.0 ms	15 ms = 3*5 ms
> 1024.0 ms	20 ms = 4*5 ms

A computer value "LOOP" is set to N = 1, 2, 3 or 4 depending upon the selected step size. Following determination of step size, the software goes into a loop comprising blocks 92, 94 and 95. At 92, a new value of QT_{ref} is determined. QT_{ref} is decremented by the amount indicated as "curve", being the same amount set forth below with respect to block 85. A computer value "temp" is determined, which is used to increment ACT_{ref} if URL has not been reached (as discussed below in connection with block

102). Temp, which is initialized at zero when the LOOP value is set, is incremented by the constant Dact. Next, at block 94, the pacing interval is decremented by 5 ms. The variable LOOP is decremented by one, and then at 95 it is determined whether LOOP is zero. If no, the software loops through blocks 92 and 94 again, until LOOP variable is zero, at which time it exits. Thus, for every step decrease in interval a corresponding step in QT_{ref} and ACT_{ref} is calculated, to adjust the reference curves. Thus, QT_{ref} is decremented and ACT_{ref} is incremented in the loop a number of times corresponding to the calculation of step size at block 88.

Referring now to Figure 17, there is illustrated a portion of the algorithm for adjusting operation at URL. The QT_{ref} curve at URL is controlled by the factor B, such that QT response at URL can be adjusted by changing the value of B. The algorithm of this invention utilizes the logic that if QT shortens more than a programmable threshold (pacer variable CRVMAX) after pacing rate reaches URL, then URL was reached too quickly for the patient. Thus, the condition is met if

$$QT < QTsave,$$
$$\text{where } QTsave = QT_{ref} - CRVMAX.$$

The QT_{ref} curve is adjusted by incrementing B, which effectively lowers the value of QT_{ref} at URL. B is incremented if:

1) the pacing rate has reached URL;
2) after reaching URL, QT shortens additionally by at least an amount equal to CRVMAX; and
3) $QT_{ref} - ACT_{dif} < QTsave$.

Note that if the third condition is not met, then decrementing the value of B would mean that the pacemaker could not reach a stable point on the reference curves where $QT_{ref} - QT = ACT_{ref} - ACT$.

The activity response may also be adjusted as a function of conditions at URL. Note that ACTmpl * Nact must match the maximum ACT_{ref} value at URL. Since the coefficient Dact is programmed and cannot be automatically changed, ACTmpl is decremented one step whenever the pacer reaches URL and ACT exceeds the programmable variable ACTmax. Whenever ACT mpl has been decremented, it will automatically be incremented once later, e.g., after 8 days.

Still referring to Figure 17, following an increase of the rate (decrementing interval), the software goes from block 95 (Figure 16) to 97, where it is determined whether pacing rate has reached URL. Thus, if Ttx is smaller than TURL, upper rate limit has been reached and the program branches to 105. If no, upper rate limit has not been reached and the program branches to block 98. At block 98 it is determined whether the pacing rate has come within 25.6 ms of upper rate limit. If yes, at block 101, a "new URL adapt" is enabled. Since Ttx is less than T_{URL}, ACT ref is adjusted by adding "temp" as calculated at block 92.

Returning to block 105, if URL has just been reached, and new URL adapt is enabled, the program branches to block 109. At this point QT is compared to QTsave, as defined above. If QT is less than QTsave, a software save register is set so that during the next cycle at 105 the answer is no, and the program exits. In the next cycle, at 105 the program branches to block 106. If URL has already been adapted, the program exits; if not, it branches to 112 where it is determined whether ACT_{dif} is positive. If yes, the program branches to block 114. There the difference between QT_{ref} and ACT_{dif} is compared to QTsave. If this difference is positive, the program exits. If this difference is less than QTsave, it means that ACT_{dif} is greater in magnitude than the increment CRVMAX, such that QT_{ref} at URL can be decremented. The program then proceeds to 118 to determine whether the B variable can be incremented. If it can, at 122 B is incremented, and then at 124 the new URL adapt flag is disabled. Returning to block 112, if ACT_{dif} is not positive, at 113 the algorithm determines whether the negative of ACT_{dif} is greater than the maximum value of ACT. If no, then B can be incremented and the program branches to 114. If yes, it means that the NACT counts exceed a predetermined value and the program goes to 117 where it is determined whether automatic decrementing of ACTmpl is enabled. If yes, at block 121, ACTmpl is decremented, and the program branches through to 124.

The pacemaker of this invention also provides for automatic adjustment of rate response at LRL, as set forth in application S.N. 252,643, issued as U.S. Patent 4,972,834 (Docket V-166) on November 27, 1990. When the patient is at rest (and the pacing rate is near LRL, the pacemaker paces for a while at LRL and calculates an average QT at LRL. The pacemaker then decreases the pacing interval by a small amount and calculates a second QT average at the second interval, near LRL. The difference in two QT averages and the difference in the two intervals are divided to provide the coefficient corresponding to pacer variable Dpt. This is compared to the prior value of the coefficient, and the value of Dpt is then adjusted one step in the direction of the indicated change. Thus, if the ratio indicates a greater slope at LRL than had previously represented by the value of Dpt, Dpt is increased so that the QT_{ref} curve near LRL is steeper. By this technique, after a number of such slope measurements the QT_{ref} curve near LRL is adapted to substantially match the QT curve of the patient's heart.

Referring now to Figures 17, 18A, 18B, 19A and 19B, there is illustrated the drift action incorporated in the preferred embodiment, for adjusting the ACT parameter in situations where the activity signal does not correlate with QT. It is known that the activity sensor is not always a proportional indicator, and excessively high activity level may be indicated in several situations. For example, if the patient is in rest and yet activity signals are counted, e.g., caused by respiration or the patient's heartbeat, the activity indication is too high and should be decremented. Likewise, there are situations where Nact may be too high to correspond to the actual exercise level, such as where vibrations are sensed which are caused by external forces. To account for these influences, and decrease the ACT signal accordingly, ACT is periodically compared to ACT_{ref}, as seen in block 150. Since the QT_{ref} curve and the ACT_{ref} curve are coupled so that movements along the QT_{ref} curve should be matched with movements along the ACT_{ref} curve, if ACT does not match ACT_{ref}, this is an indication that the sensed activity signal is incorrect. By causing the ACT signal to drift in such a situation, i.e., by adjusting it to decrease the magnitude of ACT_{dif}, the activity information is correlated with the QT information. To accomplish this, ACT is adjusted by a drift signal, referred to as ACTdr, according to the following formula:

$$ACT = ACTmpl * (Nact - ACTdr)$$

As can be seen, the drift factor, ACTdr, essentially compensates for any inaccuracy in the sensed Nact variable. If ACT is measured to be larger than ACT_{ref}, ACTdr is increased, thereby causing ACT to decrease, bringing it back into correlation with QT. At block 152 of Figure 17, if ACT_{ref} is found not to be greater than ACT, the program branches to block 153, where ACTdr is incremented by one unit, which results in a decreased value of ACT. The algorithm checks at block 153 to set an upper limit on the value of ACTdr. If the comparison at 152 is such that ACT is less than ACT_{ref}, then the program branches to block 155, and decrements ACTdr. A limit is placed on ACTdr such that it cannot go below zero. In this embodiment drift compensates only for false positives: a rate indication by the activity sensor which is high compared with the QT information. Thus, the algorithm periodically introduces the drift factor compensation into the ACT signal, thereby either increasing or decreasing the ACT signal. This is illustrated in Figures 18A, 18B and 19A, 19B for the situation where ACT is greater than ACT_{ref}. As indicated in Figure 18B, the QT signal is greater than QT_{ref}, indicating that the pacing rate should go down, i.e., interval should increase. However, ACT is greater than ACT_{ref}, and ACTdr is incremented. When the pacemaker stabilizes to a final situation, as shown in Figures 19A, 19B, ACTdr has been incremented so that the actual ACT has come to equal ACT_{ref}. In Figures 19A, 19B, for the increased pacing interval, the ACT curve with drift is shown at curve 6, being displaced downwardly from curve 5 without drift (which corresponds to actual Nact). Note also that the position on the QT_{ref} curve has changed so that it corresponds to a lower actual stress, and QT equals QT_{ref}. In the reverse situation where ACT is less than ACT_{ref}, ACTdr would be decremented to bring the ACT signal back into correlation with the QT signal, limited by the fact that only positive ACT_{dr} values are allowed.

The embodiment as illustrated permits drift to correct only for a false positive, i.e., the situation where the second sensor value (ACT) gives too high an indication compared to the first sensor value (QT). However, the algorithm can be adapted to apply drift for a false negative, e.g., by decrementing ACT_{dr} to a negative value. Also, it is to be understood that the drift feature may be programmed to compensate the fast sensor by other than fixed steps in order to reduce the fast sensor influence to or toward zero over time.

As discussed above, the system and method of this invention is applicable to employing two or more control parameters. It is noted that hardware simplification of the system can be achieved if a second or extra control parameter can be obtained without the need of an extra sensor means. This can be achieved in a system where QT is a primary parameter, by utilizing another parameter obtained by the sensed heartbeat signal. For example, the amplitude of the T wave (TwA) can be utilized as a control parameter separate from QT, as can other features of the Q or T wave portions of the sensed heartbeat signal. See U.S. Patent No. 4,305,396. The parameter TwA has a reasonably quick response, i.e., reacts to changing patient conditions more quickly than does the QT interval. Thus, TwA is a good choice of a second parameter to be used in combination with QT. In accordance with this invention, the amplitude of the T wave can be determined each cycle by signal processing circuitry such as illustrated at block 58 of Figure 1. Data for a TwA reference curve may be programmed into the pacing system to provide a coupled reference curve, as well as conversion data for converting the amplitude signal into a comparable signal with units of ms. Such a system has the advantage of needing no extra sensor, since both control parameters are obtained from the same pacing lead 53 as is conventionally used for introducing stimulus pulses into the ventricle. Alternately, the TwA or any other control parameter derived from the sensed heartbeat signal may be utilized as a third control parameter. Of course, while the preferred embodiment of this invention has been illustrated as using QT as a primary control parameter, it is to be understood that any other sensor signal could be the primary control parameter, and the secondary parameter would be converted into the units of the first parameter. This invention embraces control parameters such as AR interval, R wave morphology, T wave morphology, impedance changes, and other variables including those set out above under the Description of the Background, in any combination of two or more.

While the invention has been illustrated by description of preferred embodiments, it is noted that it is limited only by the claims hereto. For example, the important feature of providing comparable parameter variables may be utilized without some of the other techniques as disclosed. For example, instead of obtaining difference values (e.g., QT_{dif} and ACT_{dif}), the parameter values may be compared on another basis. Further, actual rate control may be achieved by changing pacing interval directly to the point on the reference, or correlation curve corresponding to the sensed parameter, rather than simply incrementing or decrementing by a given amount. Such variations are programmable and are within the scope of the invention.

What is Claimed:

1. A rate responsive pacemaker system adapted to provide stimulus pulses to a patient's heart, having a pacemaker (50) which produces stimulus pulses at a rate controllable by a rate control signal, sensor means (S_1, S_2; 61, 62) for obtaining parameter signals reflective of a first physiological parameter and a second fast-response parameter, algorithm means (76) for determining a first physiological control signal as a first function of said first parameter and for determining a second fast-response control signal as a second function of said second parameter, characterized by

comparing means (80) for comparing said first and second control signals and for selecting one of said control signals as said rate control signal for controlling said pacemaker.

2. The pacemaker system as described in claim 1, wherein said comparing means compares said first and second control signals each pacing cycle (Fig. 16).

3. The pacemaker system as described in claim 2, further providing means programmable by an external programmer (60) to set the influence of said first physiological parameter signal relative to said second fast-response parameter signal so that pacing rate is primarily determined by said first physiological signal.

4. The system as in claim 2, wherein said first rate means further comprises first reference means for establishing a physiological parameter reference each pacing cycle and said second rate means further comprises means for establishing a fast-response parameter reference each pacing cycle (85; 92, 102).

5. The system as described in claim 4, wherein said first rate means comprises a means for establishing a difference between said physiological parameter signal and said physiological reference and said second rate means comprises means for establishing a second difference between said fast-response parameter signal and said second reference (76), and wherein said comparing means compares said two difference values (80).

6. The system as described in claim 5, comprising correction means for automatically introducing a correction factor to said second control parameter whenever there is a difference between such parameter and its corresponding reference point (153, 155).

7. The pacemaker system as described in claim 1, comprising reference means for generating parameter control references in accordance with a predetermined reference curve (QT*ref* and ACT*ref*) for each respective parameter and means for adjusting each said reference curve when a predetermined condition exists at at least one pacing rate within said range.

8. The pacemaker system as described in claim 7, wherein said algorithm means further comprises means for determining from each of said first and second parameter signals a respective indicated direction of rate change and amount of rate change (76), and for determining said control signal as a function of said directions and amounts (79, 80, 82).

9. The pacemaker system as described in claim 8, further comprising a lead (53) having a first end with an electrode adapted for placement in the patient's ventricle, a first sensor means including said lead for detecting the QT interval of a patient's heartbeat (62,

73), and a second sensor means (63) for providing an output indicative of the patient's physical activity.

10. The pacemaker system as described in claim 1, wherein said comparing means derives a rate difference from said comparison (66), and further comprises means for adapting the selected rate by an increment of rate which is a function of said rate difference (67, 68).

11. The pacemaker system as described in claim 7, wherein said algorithm means provides a signal for changing pacing rate by a predetermined step when both said first and second sensor signals indicate a rate change in the same direction (79, 84, 94).

12. The pacemaker system as described in claim 9, wherein said comparing means has means for comparing said amount indications when said rate change directions are opposite (79), and further comprises means (80) for choosing the direction of rate change on the basis of said comparison of amounts.

13. The pacemaker system as described in claim 1, further comprising drift means (153, 155) for modifying said second rate control signal so as to reduce its effect.

14. The pacemaker system as described in claim 1, wherein said algorithm means and said comparing means are operative each pacing cycle (Fig. 16), and said pacemaker system has means for incrementing (94) or decrementing (84) pacing rate as a predetermined function of said selected rate indication.

15. The pacemaker system as described in claim 1, wherein said algorithm means converts said second rate control signal generally to have a lesser influence than said first rate control signal.

16. A rate responsiveness pacemaker system (50, 53) adapted to provide stimulus pulses at a controllable rate, having sensor means (61, 62) for obtaining parameter signals representative of a first physiological parameter and a second fast-response parameter, and first algorithm means (76) for determining a first physiological rate control signal from said physiological parameter signal and a second fast-response control signal from said fast-response parameter signal, characterized by

second algorithm means (79, 80, 82) for determining which of said rate control signals indicates a greater change of pacing rate and for selecting each pacemaker cycle the greater rate change signal for controlling said pacemaker rate.

17. The pacemaker as described in claim 16, wherein said first algorithm means further comprises adjusting means for reducing the fast response rate change indication incrementally with each pacing cycle so long as said fast response indication is selected (152, 153, 155).

18. A pacing system having rate controllable pulse generator means for generating pacing pulses, first sensor means for developing first signals indicating a first pacing rate, second sensor means for developing second signals indicating a second pacing rate, and rate control means for determining desired pacing rate and controlling the rate of said pulse generator means, said rate means further comprising algorithm means for determining (a) from each of said first and second sensor means signals a respective indicated direction of rate change and amount of rate change, and (b) for determining said desired pacing rate as a function of said directions and amounts.

19. The pacing system as described in claim 18, comprising first reference means for generating first reference data for correlating said first signals and desired pacing rate, and second reference means for generating second reference data for correlating said second signals and desired pacing rate, and wherein said algorithm means comprises

means (76) for comparing said first signals with said first reference data to provide a first difference, and for comparing said second signals with said second reference data to provide a second difference; and

means (79, 80) for comparing said first and second differences to determine said desired pacing rate.

AMENDED CLAIMS

[received by the International Bureau on 18 February 1992 (18.02.92);
original claims 1 and 8 replaced by amended claim 1;
claims 2 - 6 replaced by amended claims 2 - 6;
claims 9, 11, 12 and 14 - 19 replaced by amended claims 10, 11, 12 and
14 - 19; new claims 8, 9 and 20 - 22 added;
other claims unchanged (6 pages)]

1. A rate responsive pacemaker system adapted to provide stimulus pulses to a patient's heart, having a pacemaker (50) for producing stimulus pulses at a controllable pacing rate, sensor means (S_1, S_2; 61, 62) for obtaining first rate-indicating parameter signals reflective of a first physiological parameter and second rate-indicating parameter signals reflective of a second fast-response parameter, signal determining means (76) for determining a first physiological control signal as a first function of said first parameter and for determining a second fast-response control signal as a second function of said second parameter, and control means for controlling said pacing rate as a function of said first and second control signals, characterized by

said signal determining means determining for each of said respective control signals a component indicating direction of desired change of pacing rate and a component indicating amount of desired change of pacing rate (76), and

said control means determining said controlled rate as a function of said respective directions and said respective amounts (79, 80, 82).

2. The pacemaker system as described in claim 1, wherein said control means compares said first and second control signals each pacing cycle (Fig. 16).

3. The pacemaker system as described in claim 2, further providing means programmable by an external programmer (60) to set the influence of said first physiological parameter signal relative to said second fast-response parameter signal.

4. The system as described in claim 2, wherein said signal determining means further comprises first reference means for establishing a physiological parameter reference each pacing cycle and a fast-response parameter reference each pacing cycle (85; 92, 102).

5. The system as described in claim 4, wherein said signal determining means comprises means for establishing a difference between said physiological parameter signal and said physiological reference and a difference between said fast-response parameter signal and said second reference (76), and wherein said control means compares said two difference values (79, 80).

6. The system as described in claim 4, comprising correction means for automatically introducing a correction factor to said second parameter whenever there is a difference

between such parameter and its corresponding reference point (153, 155).

7. The pacemaker system as described in claim 1, comprising reference means for generating parameter control references in accordance with a predetermined reference curve (QTref and ACTref) for each respective parameter and means for adjusting each said reference curve when a predetermined condition exists at at least one pacing rate within said range.

8. The system as described in claim 1, further characterized by means for automatically adjusting one of said parameter signals so that it indicates a pacing rate closer to that indicated by the other signal.

9. The system as described in claim 8, wherein said adjusted parameter is said second fast-response parameter.

10. The pacemaker system as described in claim 1, further comprising a lead (53) having a first end with an electrode adapted for placement in the patient's ventricle, a first sensor means including said lead for detecting the QT interval of a patient's heartbeat (62, 73), and a second sensor means (63) for providing an output indicative of the patient's physical activity.

11. The pacemaker system as described in claim 1, wherein said control means provides a signal for changing pacing rate by a predetermined step when both said first and second control signals indicate a rate change in the same direction (79, 84, 94).

12. The pacemaker system as described in claim 1, wherein said control means has means for comparing said amount indications when said rate change directions are opposite (79), and further comprises means (80) for choosing the direction of rate change on the basis of said comparison of amounts.

13. The pacemaker system as described in claim 1, further comprising drift means (153, 155) for modifying said second rate control signal so as to reduce its effect.

14. The pacemaker system as described in claim 1, wherein said determining means and said control means are operative each pacing cycle (Fig. 16), and said pacemaker system has means for incrementing (94) or decrementing (84) pacing rate as a predetermined function of said selected rate indication.

15. The pacemaker system as described in claim 1, wherein said signal determining means converts said second rate control signal generally to have a lesser influence than said first rate control signal.

16. A pacing system having a pacemaker (50) for delivering stimulus pulses and rate adjusting means for adjusting the rate of delivery of said stimulus pulses, first sensor means (S_1, 58) for generating a first signal representative of a first desired pacing rate and at least a second sensor means (S_2, 58) for generating a second signal representative of a second pacing rate, said rate adjusting means having comparing means (79, 80) for comparing said first and second signals to provide a rate control signal for control of said rate, characterized by

drift means (150, 152, 153, 155) for changing one of said first and second signals in a direction to reduce its influence relative to said other of said first and second signals.

17. The pacing system as described in claim 16, wherein said first signal is a relatively slow response signal representative of a physiological pacing rate and said second signal is a fast response signal having a faster response than said physiological signal.

18. The pacing signal as described in claim 17, wherein said drift means changes said second rate signal by a fixed amount (153, 155) once every predetermined time period (150).

19. The pacing system as described in claim 18, wherein said drift means changes said second rate signal only when it is false positive compared to said first rate signal.

20. The pacing signal as described in claim 18, wherein said drift means corrects second rate signals which are false negatives compared to said first rate signals.

21. The pacing system as described in claim 16, wherein said second sensor means derives said second signal (ACT) from a measure of patient activity, and said drift means is operative at programmed intervals to change said second signal (ACT) whenever said second pacing rate is found to differ from the current rate of delivery of said stimulus pulses.

22. The pacing system as described in claim 16, wherein said drift means comprises means for continuously adjusting said one signal by a drift factor (ACT_{dr}), and means for incrementing or decrementing (153, 155) said drift factor.

STATEMENT UNDER ARTICLE 19

The amendments of the claims have no effect on the description and the drawings.

Main claim 1 meets the prior art problem of deriving a rate by using the information from each of two different sensors, in such a way that the new indicated rate can be determined at any time without requiring that one sensor or the other take over and control for a certain time or for a certain range of frequencies. The second independent claim 16 solves the problem of automatically correcting one of two sensors, in a two-sensor pacemaker, so that the last reliable sensor is periodically adjusted so that it is in tune with the more reliable sensor, i.e., the second sensor is automatically and continuously recalibrated with respect to the first one.

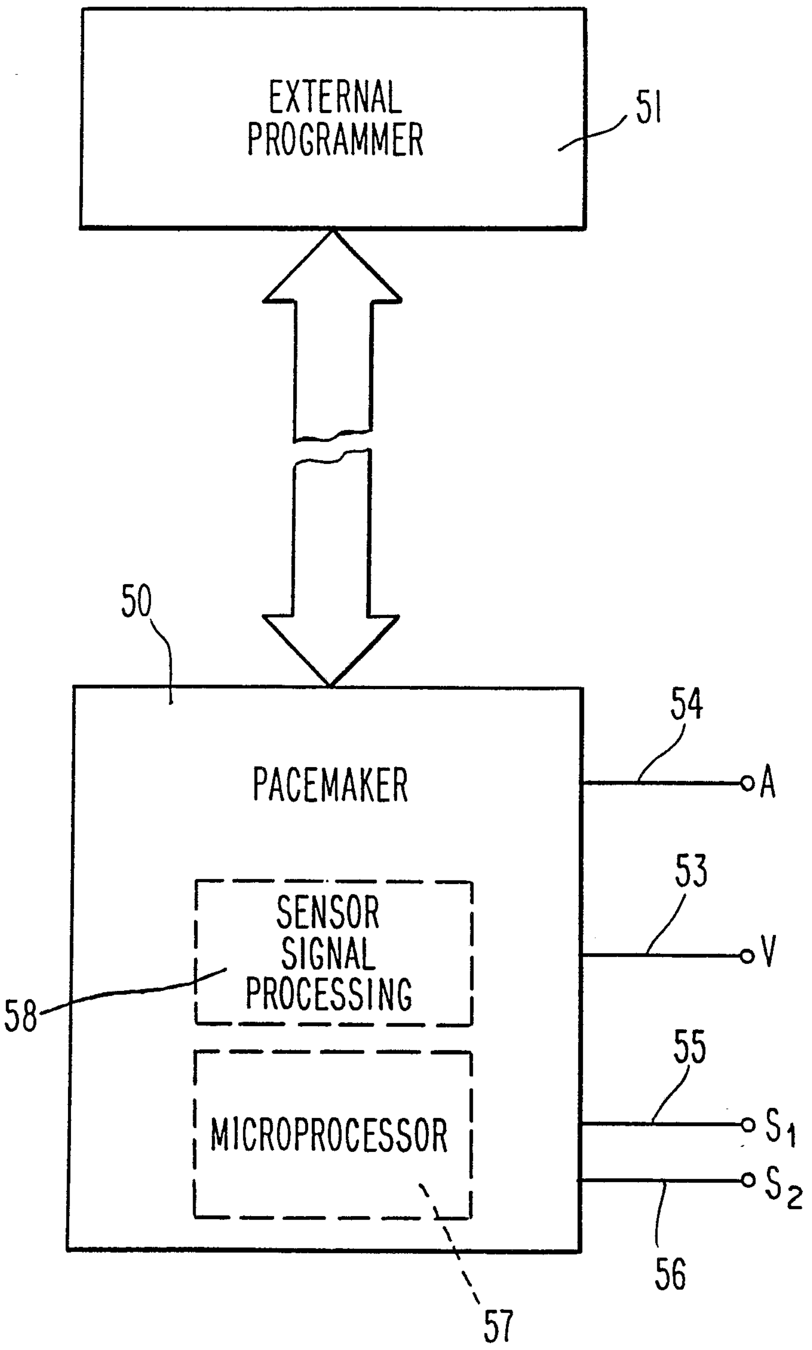
EXTERNAL PROGRAMMER
51
50
PACEMAKER
SENSOR SIGNAL PROCESSING
58
MICROPROCESSOR
57
54
A
53
V
55
S_1
S_2
56

Fig. 1

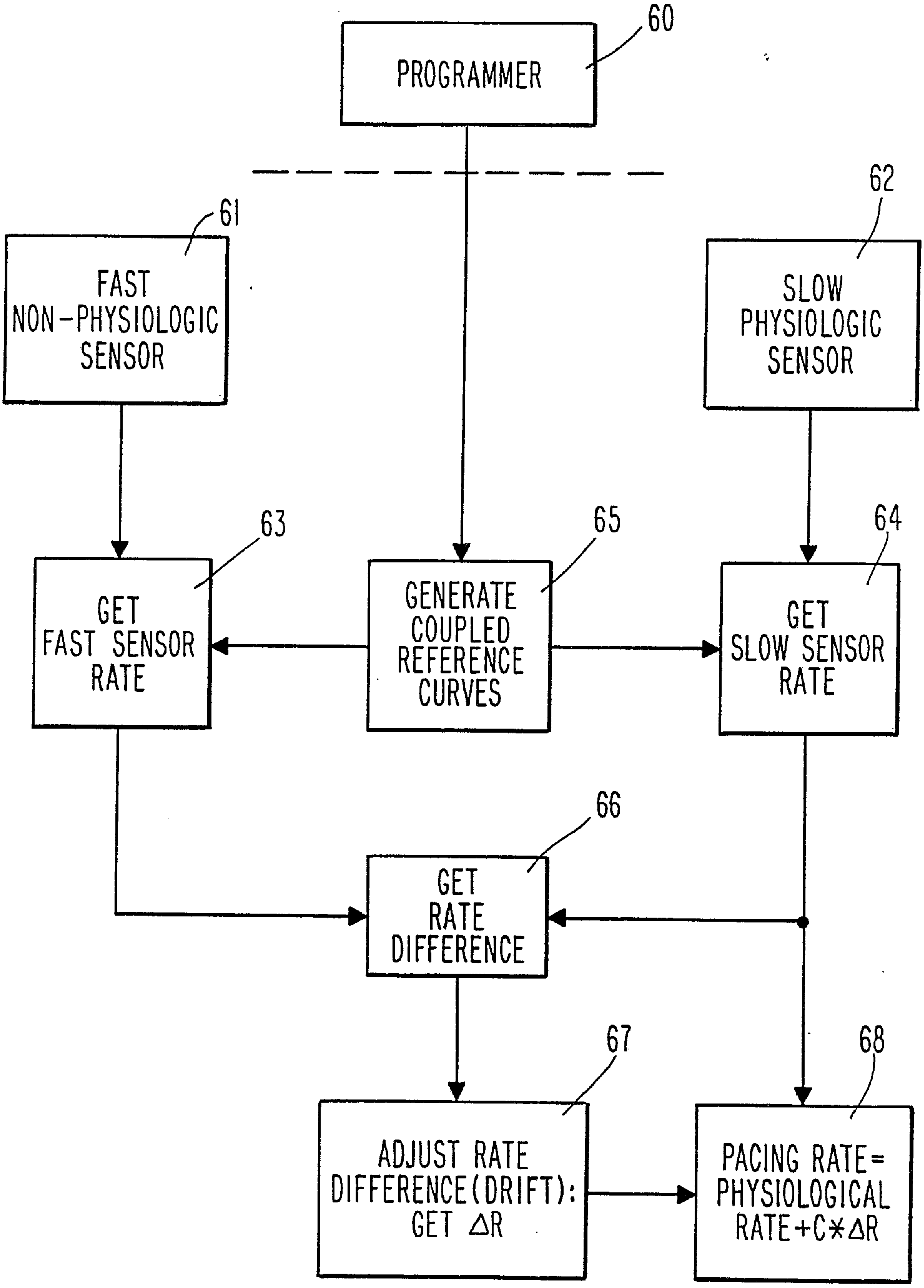
PROGRAMMER
60
FAST NON-PHYSIOLOGIC SENSOR
61
SLOW PHYSIOLOGIC SENSOR
62
GET FAST SENSOR RATE
63
GENERATE COUPLED REFERENCE CURVES
65
GET SLOW SENSOR RATE
64
GET RATE DIFFERENCE
66
ADJUST RATE DIFFERENCE (DRIFT): GET ΔR
67
PACING RATE= PHYSIOLOGICAL RATE+C*ΔR
68

Fig. 2

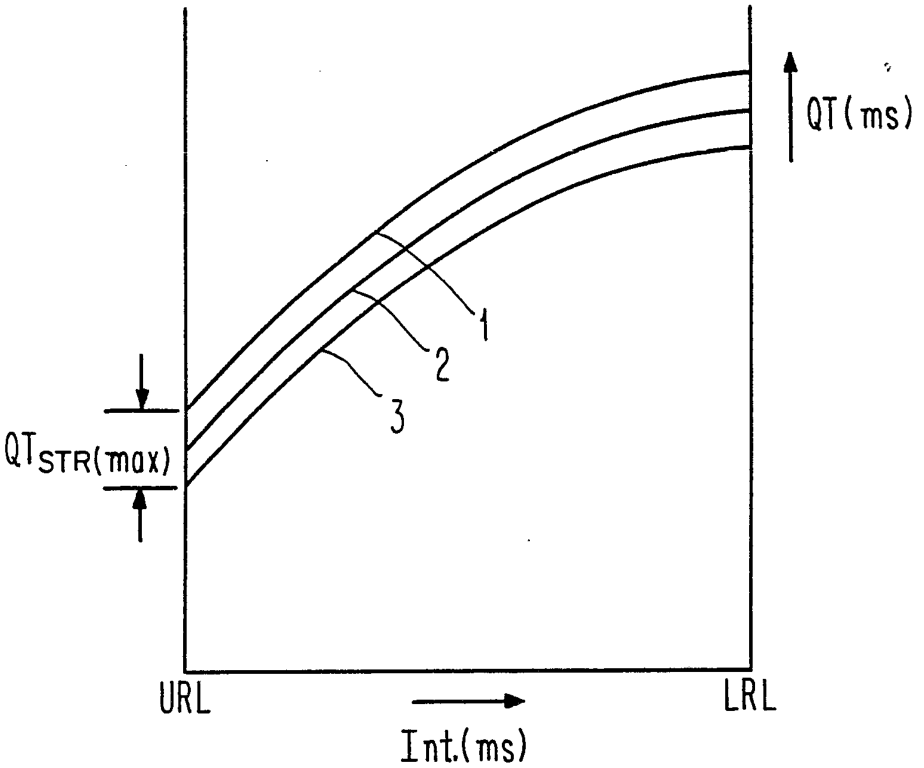
QT(ms)
1
2
3
QTSTR(max)
URL
LRL
Int.(ms)

Fig. 3

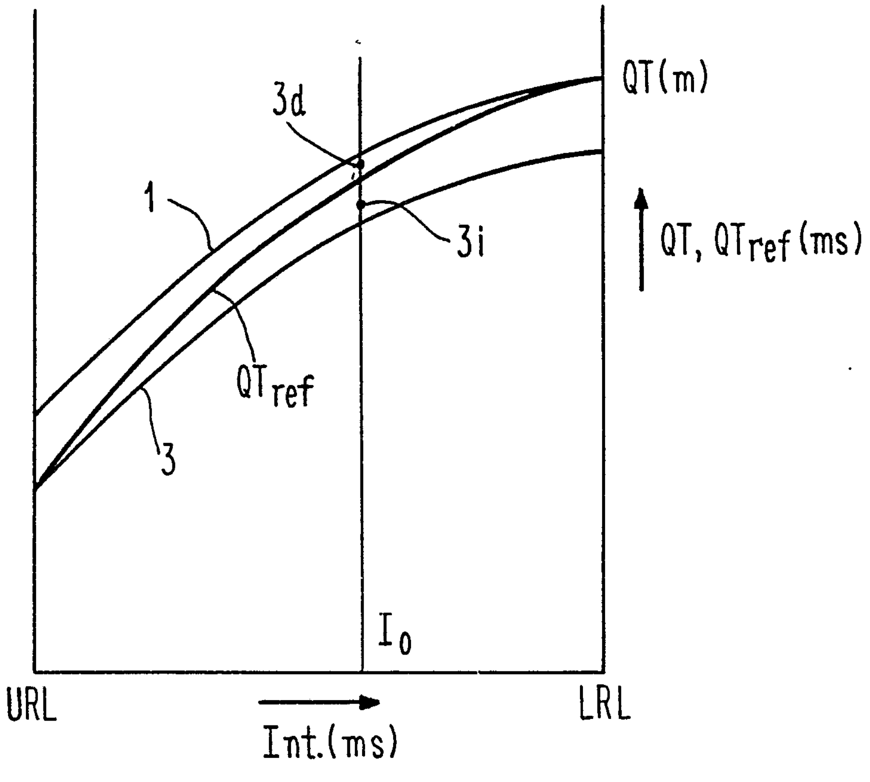
QT(m)
3d
1
3i
QT, QTref (ms)
QTref
3
I0
URL
LRL
Int.(ms)

Fig. 4

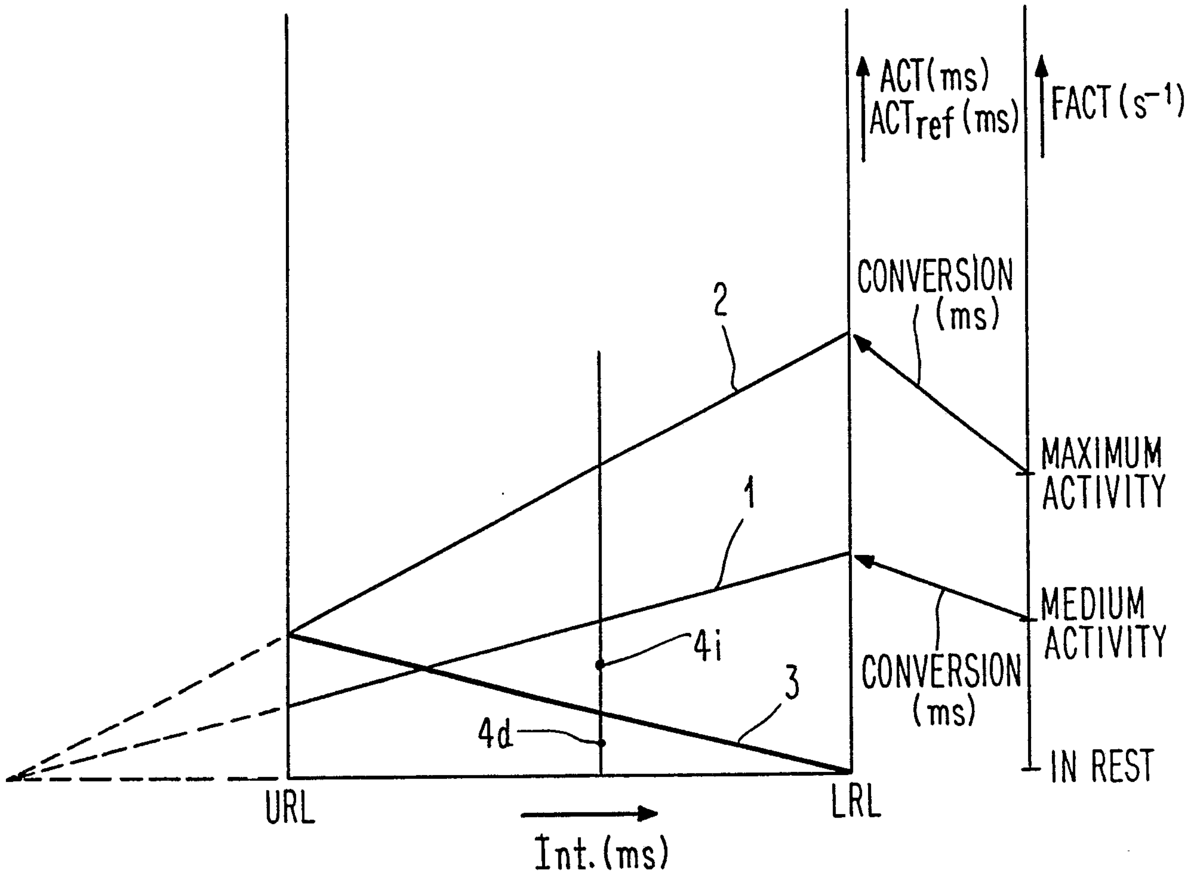
ACT(ms)
ACTref (ms)
FACT (s^{-1})
CONVERSION (ms)
2
MAXIMUM ACTIVITY
1
MEDIUM ACTIVITY
4i
3
CONVERSION (ms)
4d
IN REST
URL
LRL
Int.(ms)

Fig. 5

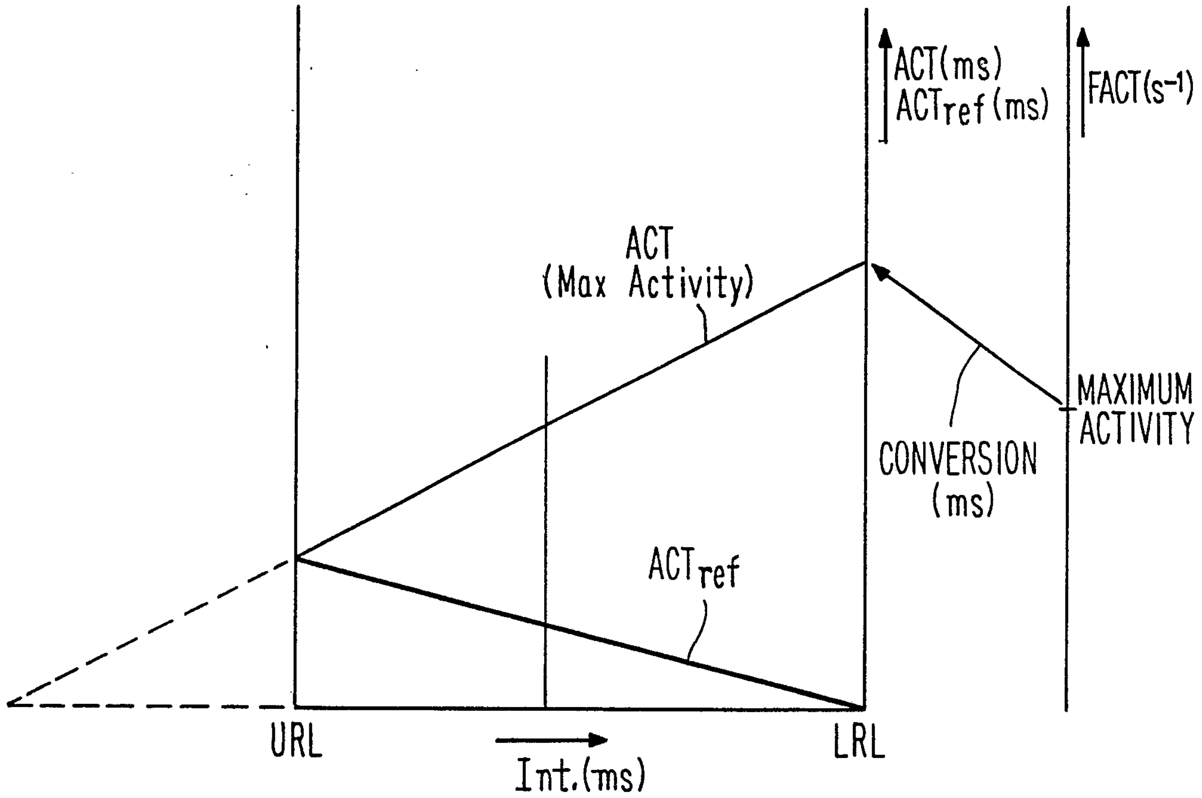
ACT(ms)
ACT$_{ref}$(ms)
FACT(s^{-1})
ACT
(Max Activity)
MAXIMUM
ACTIVITY
CONVERSION
(ms)
ACT$_{ref}$
URL
Int.(ms)
LRL

Fig. 6A

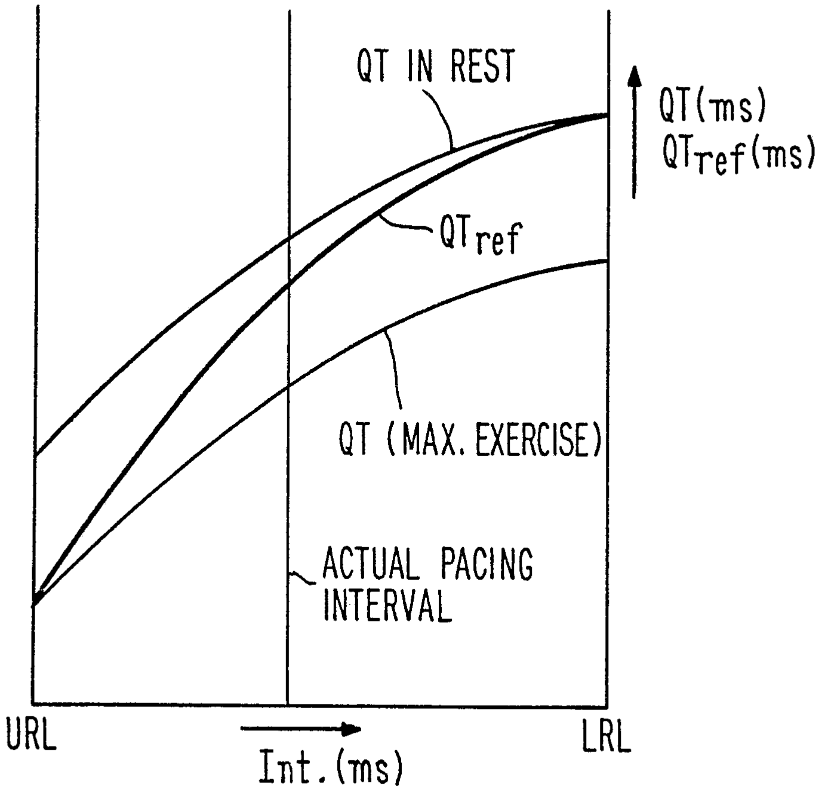
QT IN REST
QT(ms)
QT$_{ref}$(ms)
QT$_{ref}$
QT (MAX. EXERCISE)
ACTUAL PACING
INTERVAL
URL
Int.(ms)
LRL

Fig. 6B

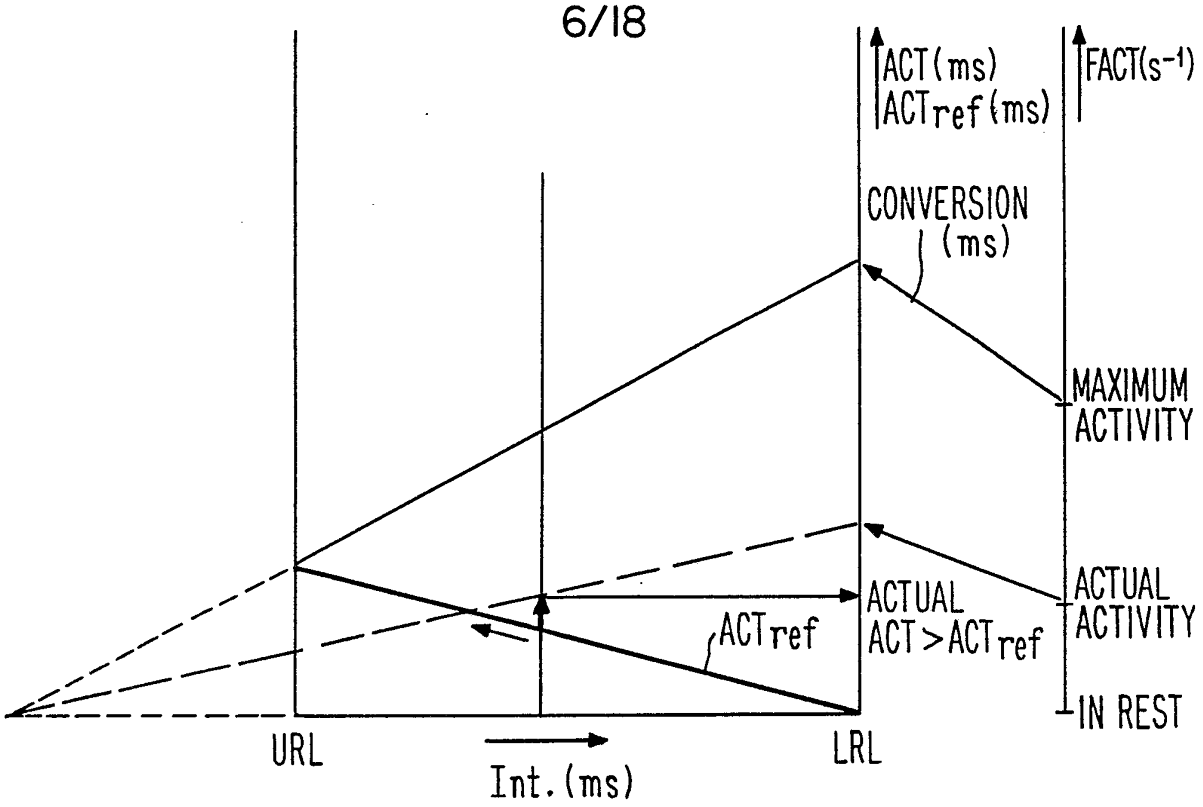
ACT(ms)
ACTref(ms)
FACT(s-1)
CONVERSION (ms)
MAXIMUM ACTIVITY
ACTUAL ACTIVITY
IN REST
ACTref
ACTUAL ACT>ACTref
URL
Int.(ms)
LRL

Fig. 7A

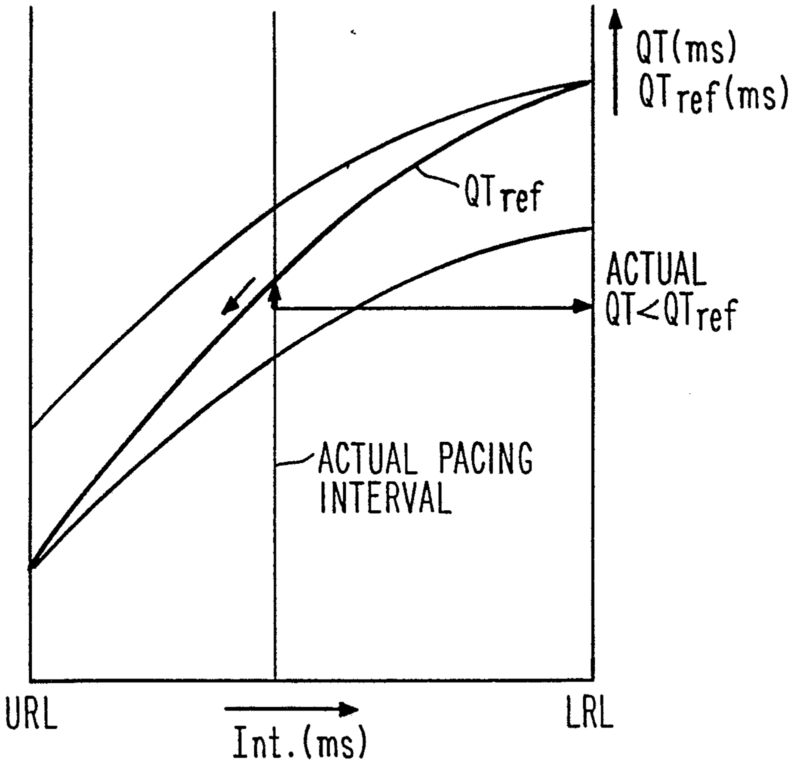
QT(ms)
QTref(ms)
QTref
ACTUAL QT<QTref
ACTUAL PACING INTERVAL
URL
Int.(ms)
LRL

Fig. 7B

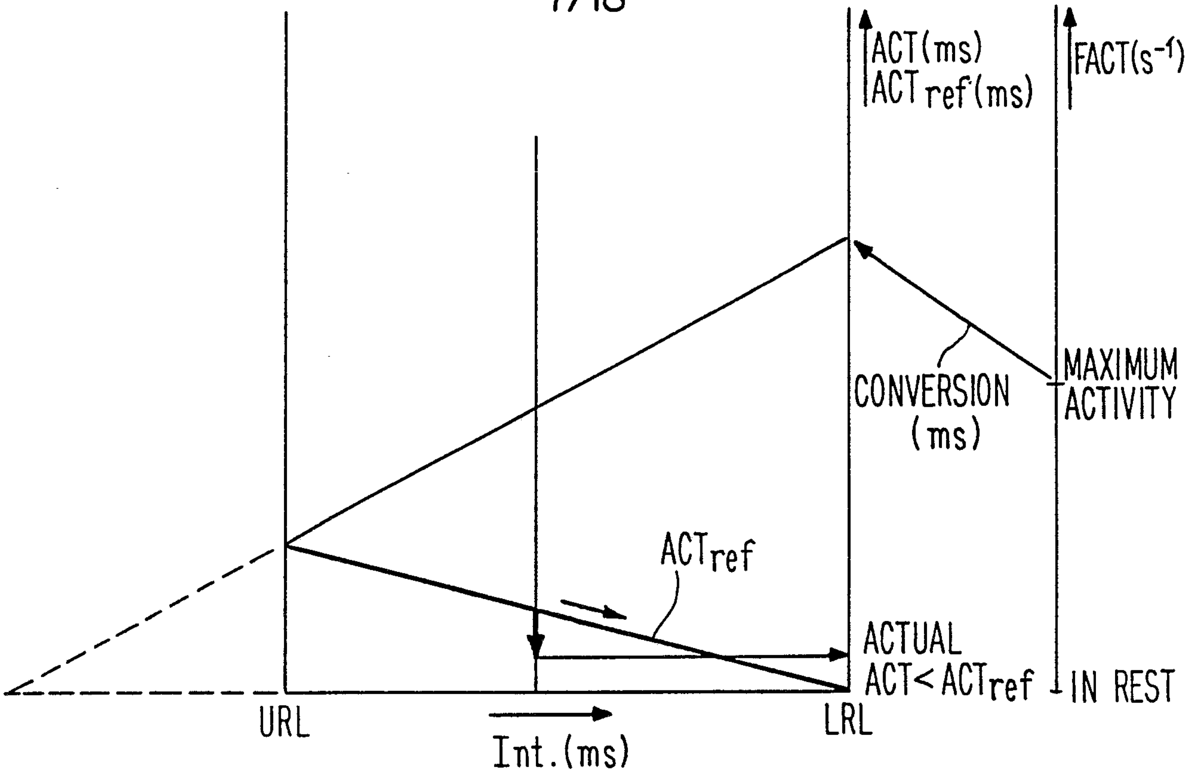
ACT(ms)
ACT ref (ms)
FACT(s-1)
MAXIMUM ACTIVITY
CONVERSION (ms)
ACTref
ACTUAL ACT<ACTref
IN REST
URL
Int.(ms)
LRL

Fig. 8A

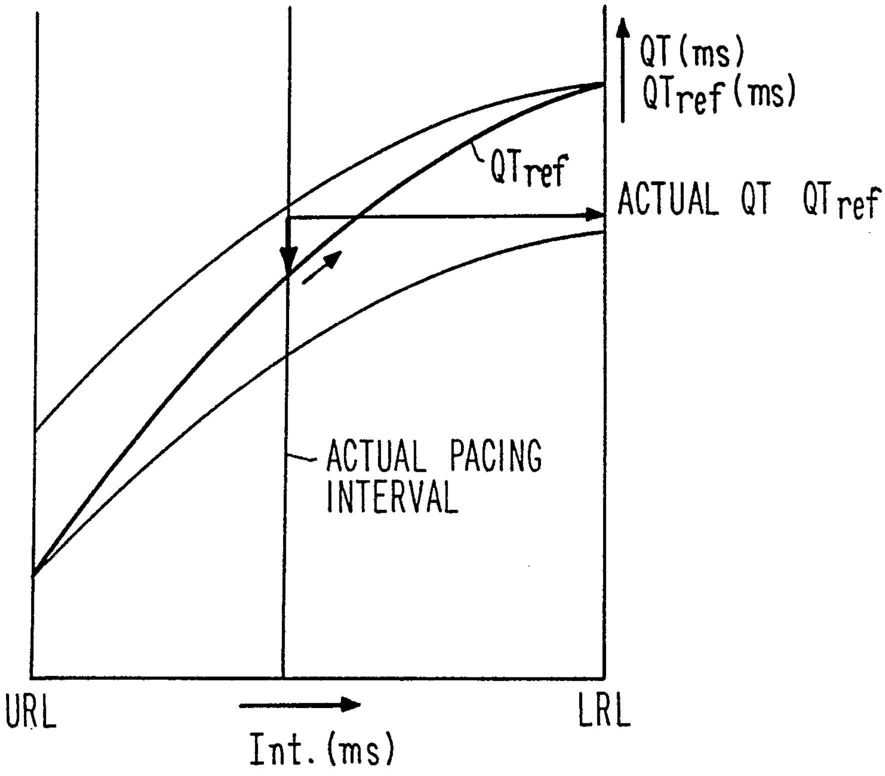
QT (ms)
QTref (ms)
QTref
ACTUAL QT QTref
ACTUAL PACING INTERVAL
URL
Int.(ms)
LRL

Fig. 8B

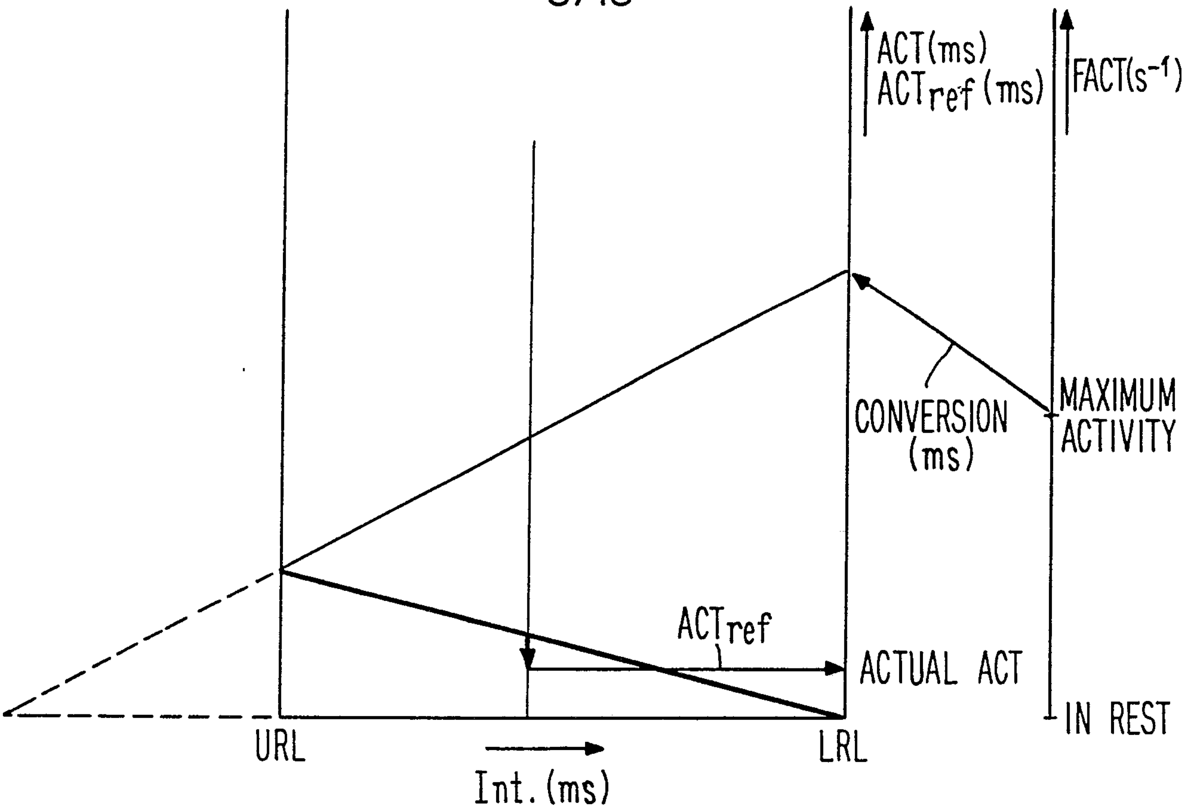
ACT(ms)
ACTref (ms)
FACT(s-1)
CONVERSION (ms)
MAXIMUM ACTIVITY
ACTref
ACTUAL ACT
IN REST
URL
LRL
Int. (ms)

Fig. 9A

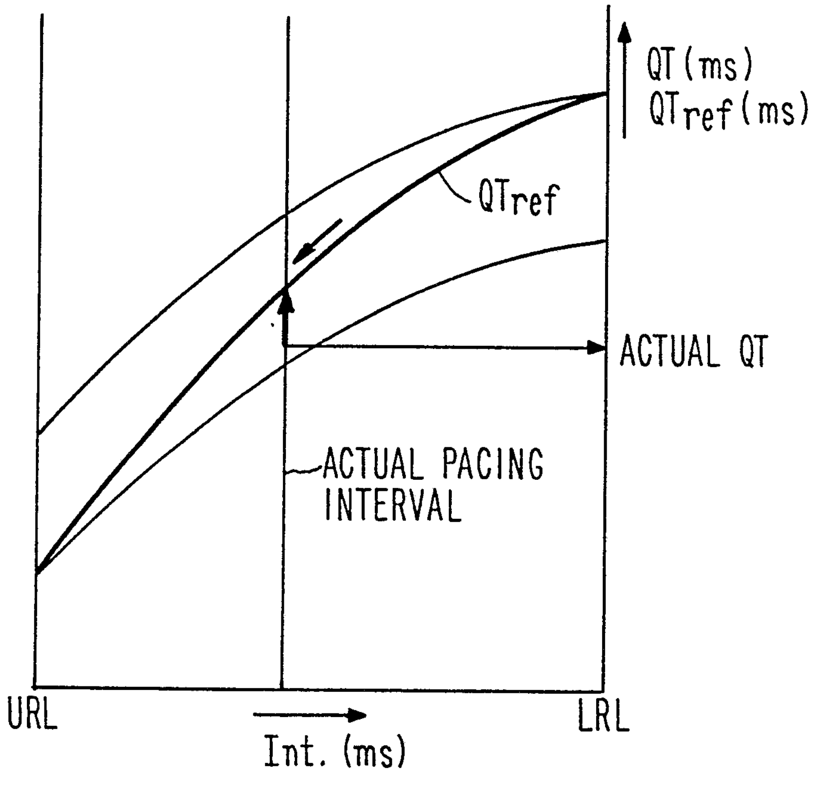
QT (ms)
QTref (ms)
QTref
ACTUAL QT
ACTUAL PACING INTERVAL
URL
LRL
Int. (ms)

Fig. 9B

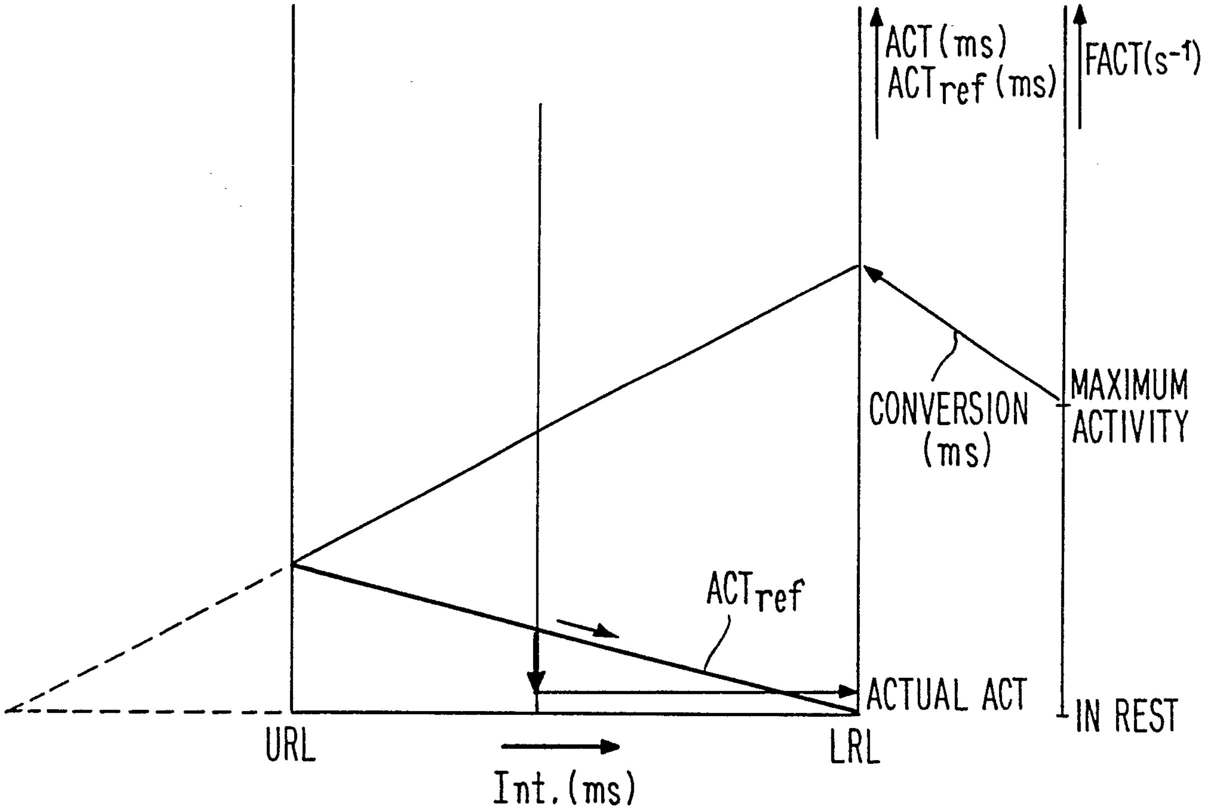

Fig. 10A

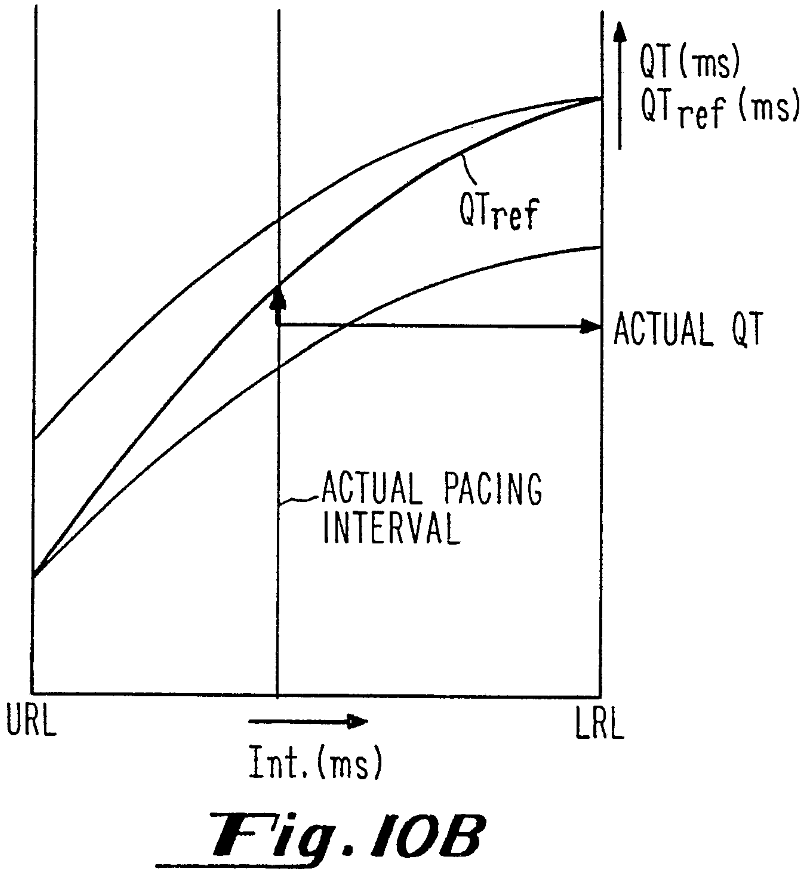

Fig. 10B

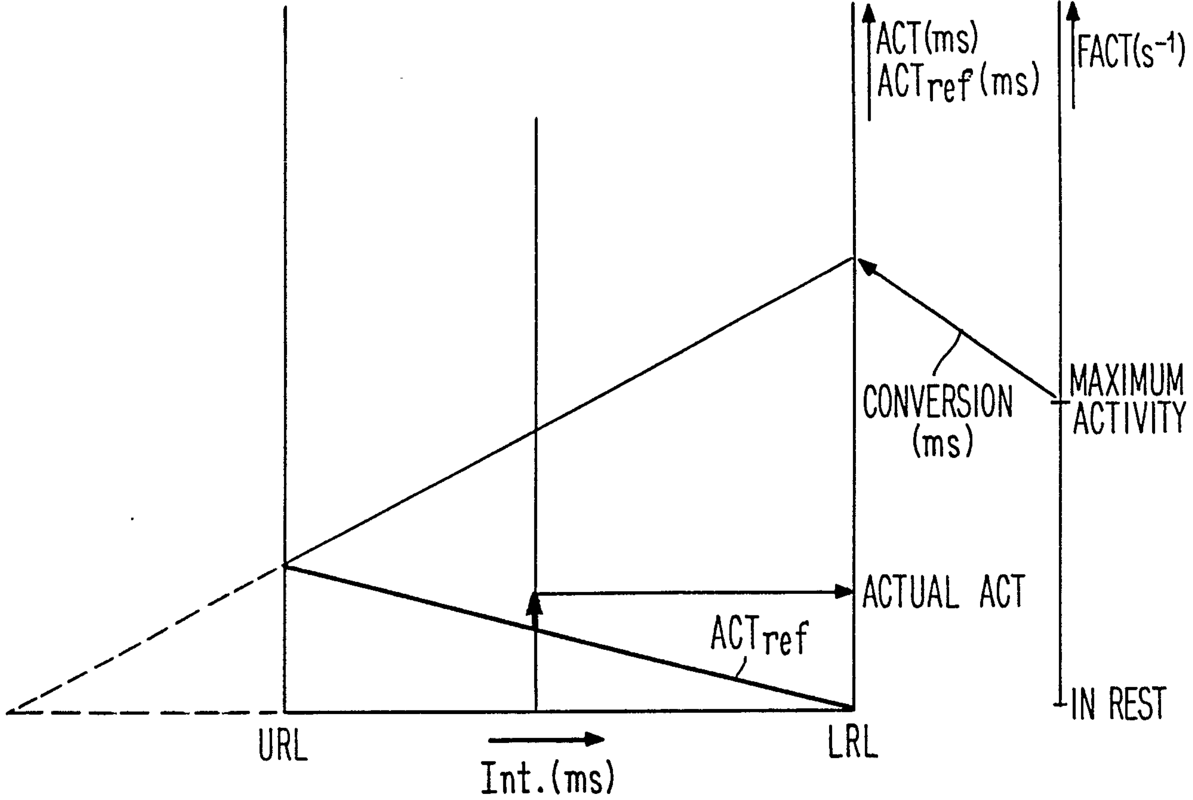

Fig. 11A

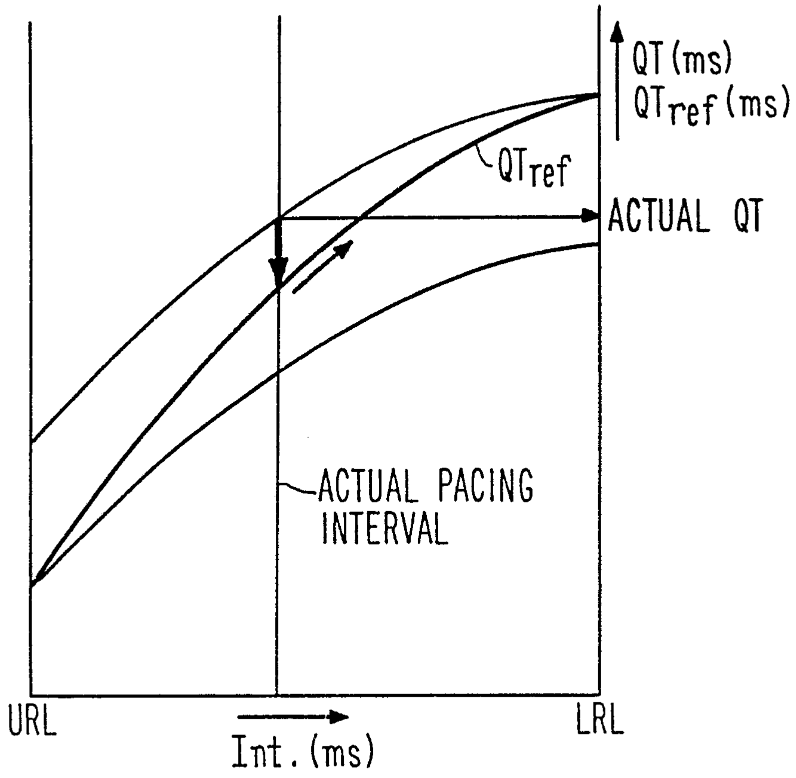

Fig. 11B

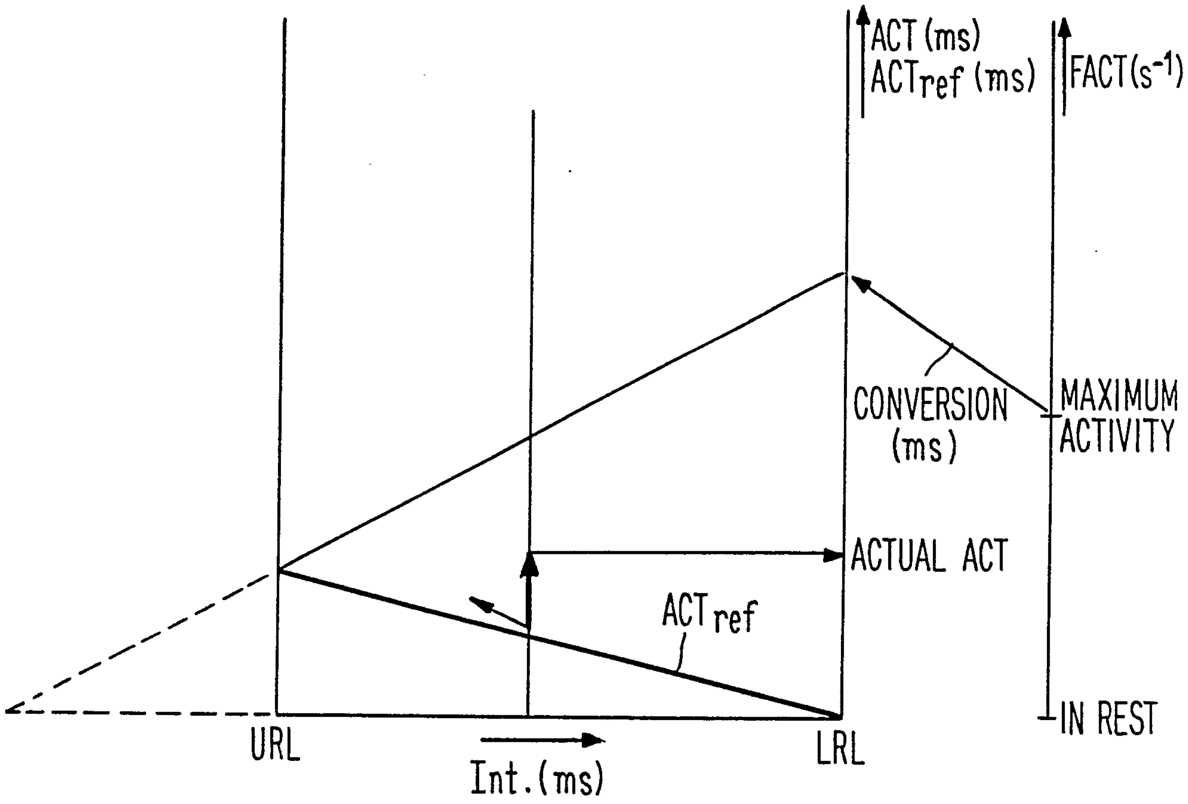

Fig. 12A

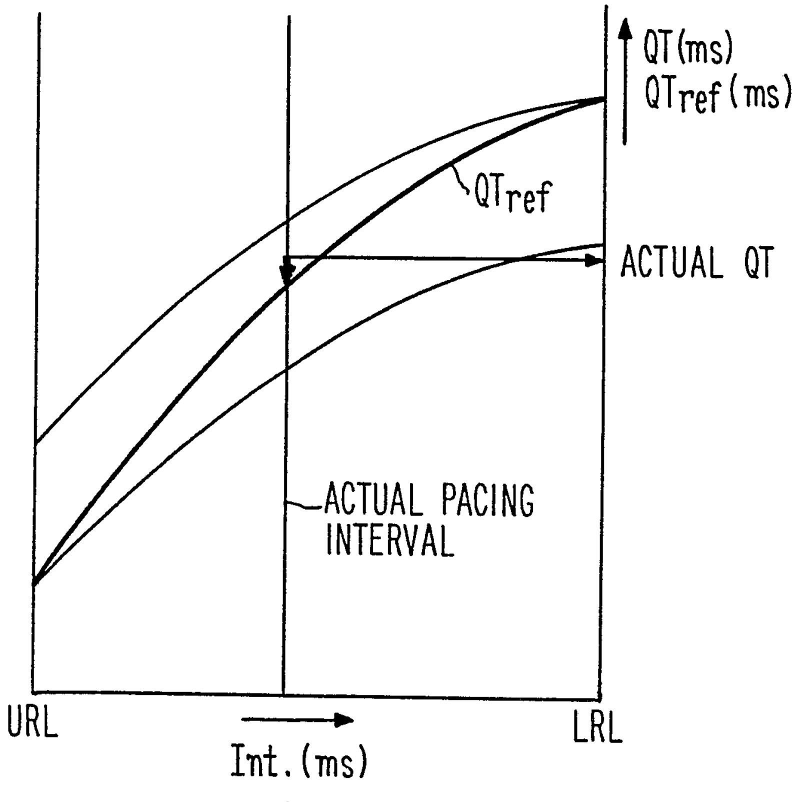

Fig. 12B

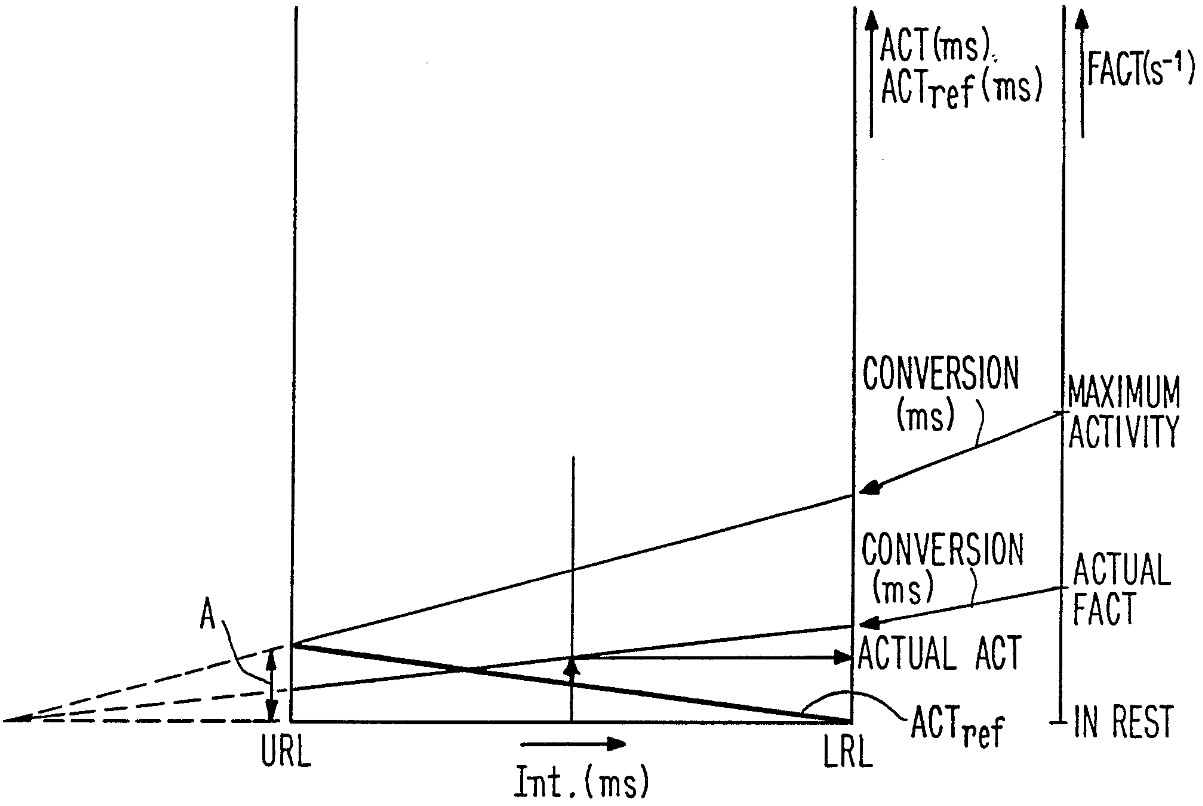

Fig. 13A

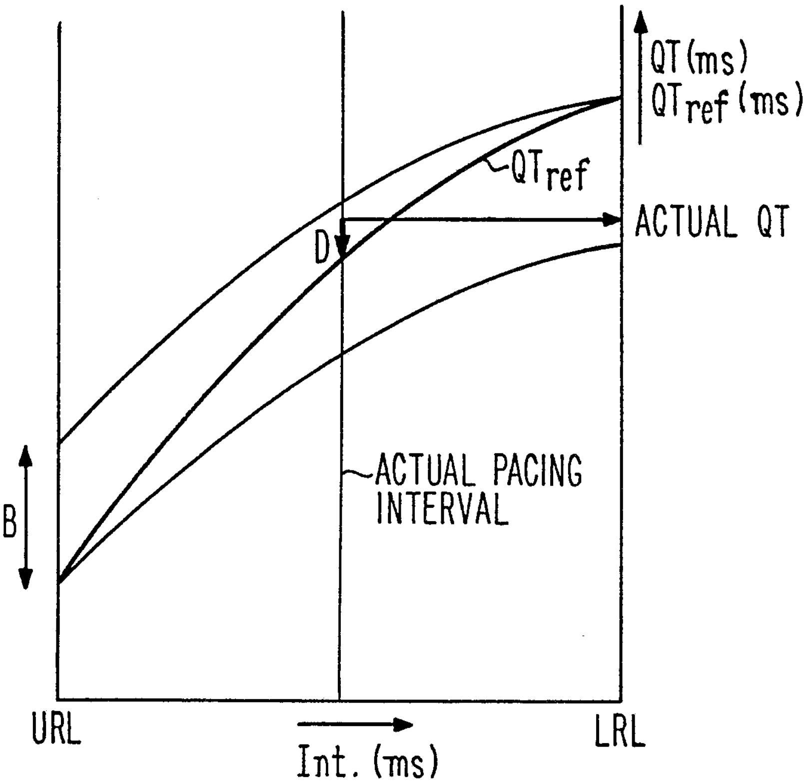

Fig. 13B

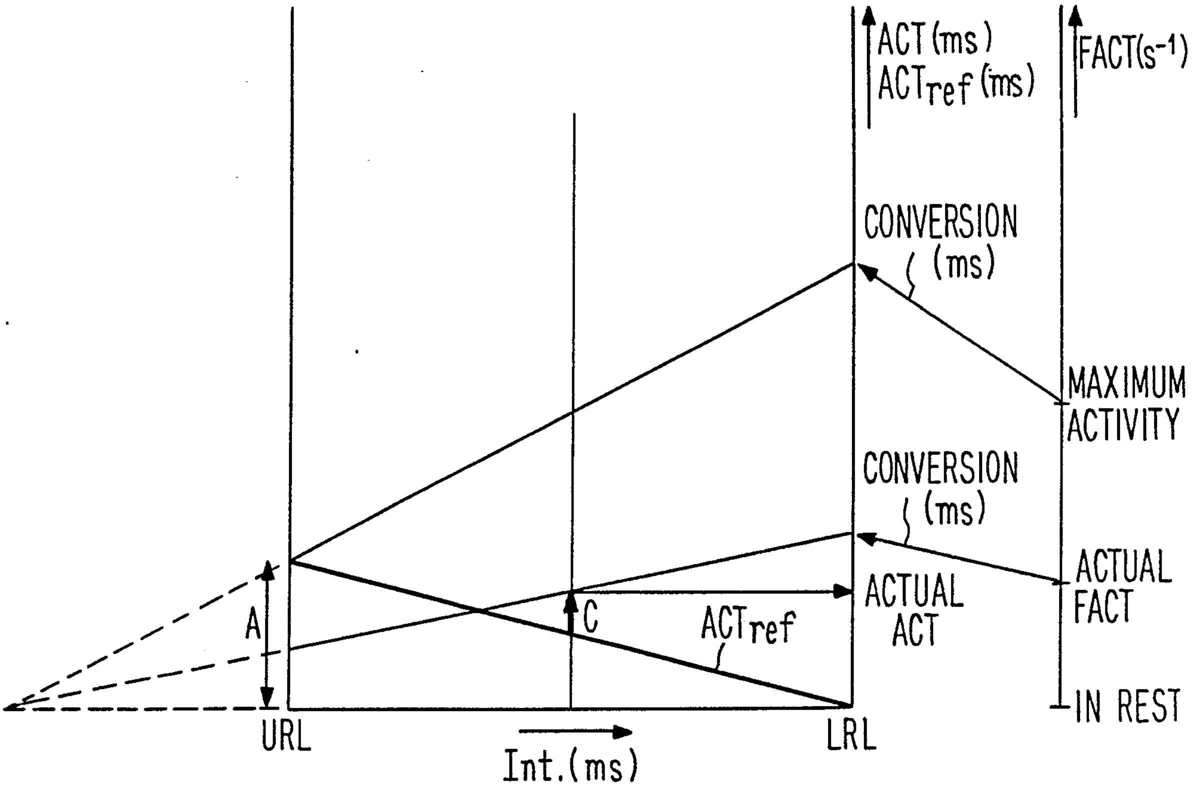

Fig. 14A

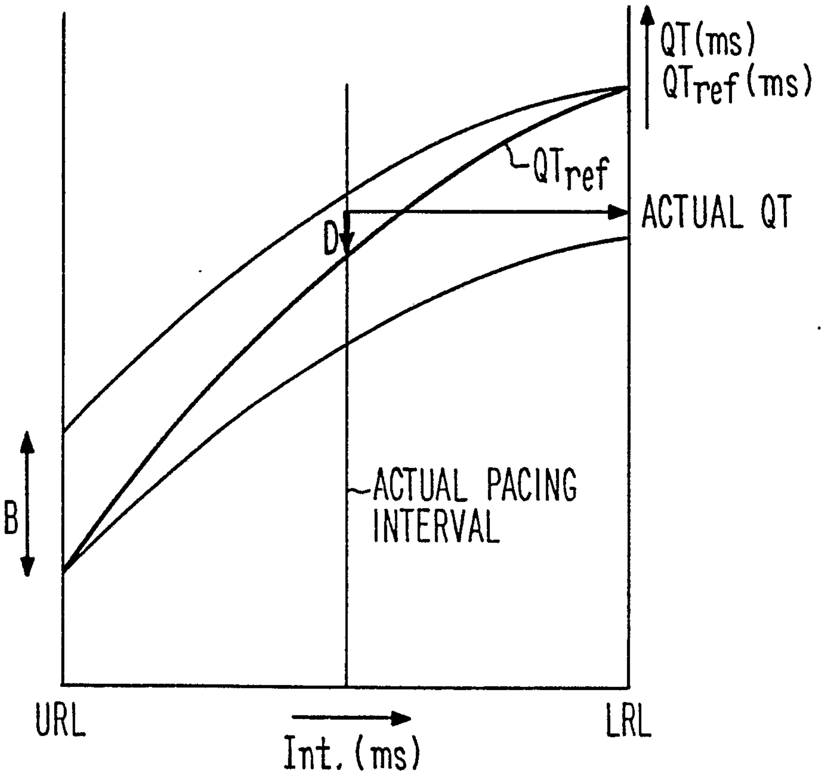

Fig. 14B

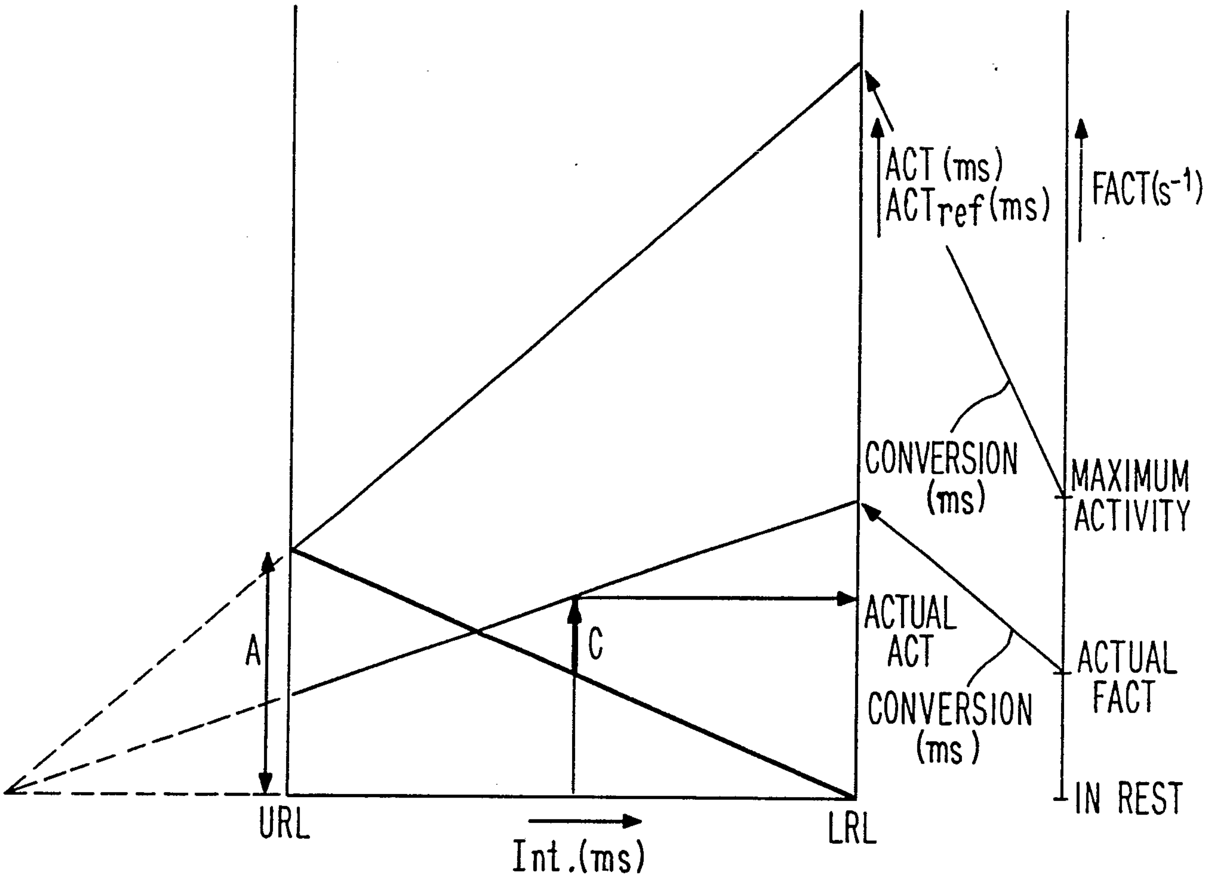

Fig. 15A

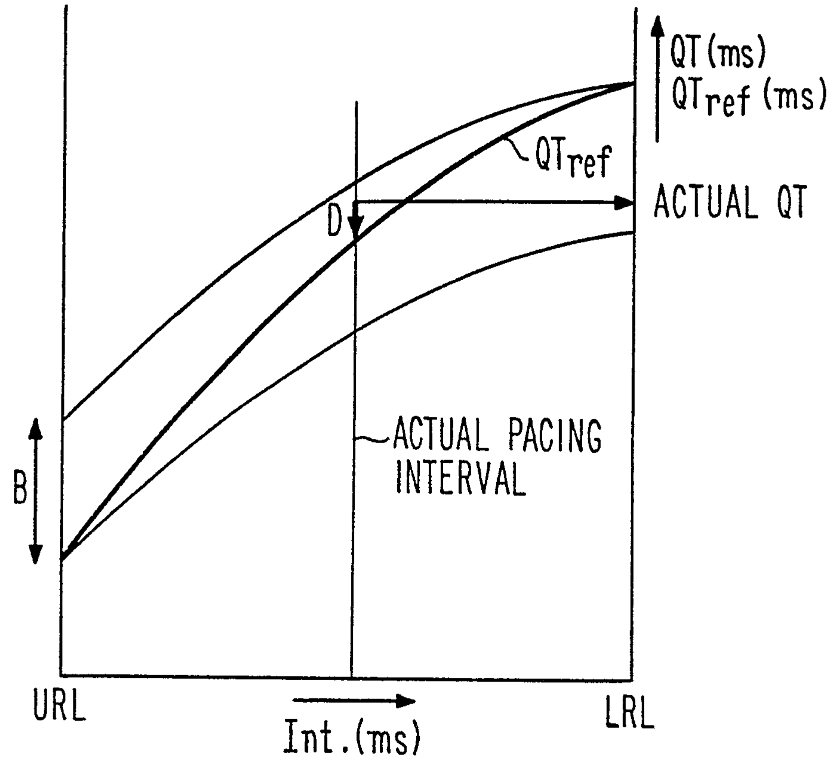

Fig. 15B

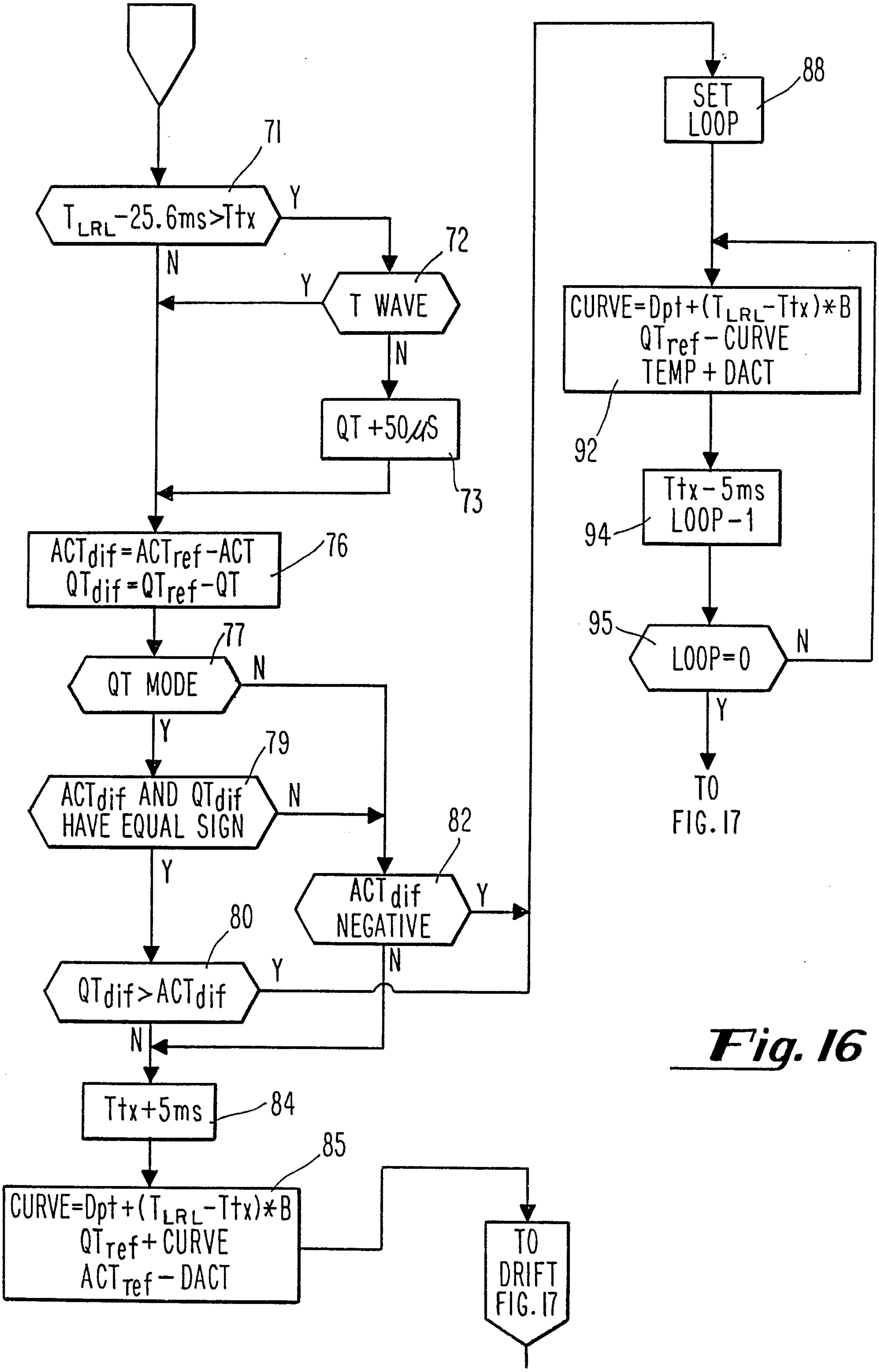
71
T_{LRL}-25.6ms>Ttx
Y
N
72
T WAVE
Y
N
QT +50µS
73
76
ACT_{dif}=ACT_{ref}-ACT
QT_{dif}=QT_{ref}-QT
77
QT MODE
N
Y
79
ACT_{dif} AND QT_{dif} HAVE EQUAL SIGN
N
Y
82
ACT_{dif} NEGATIVE
Y
N
80
QT_{dif}>ACT_{dif}
Y
N
Ttx+5ms
84
85
CURVE=Dpt+(T_{LRL}-Ttx)*B
QT_{ref}+CURVE
ACT_{ref}-DACT
TO DRIFT FIG. 17
SET LOOP
88
CURVE=Dpt+(T_{LRL}-Ttx)*B
QT_{ref}-CURVE
TEMP+DACT
92
Ttx-5ms
LOOP-1
94
95
LOOP=0
N
Y
TO FIG. 17

Fig. 16

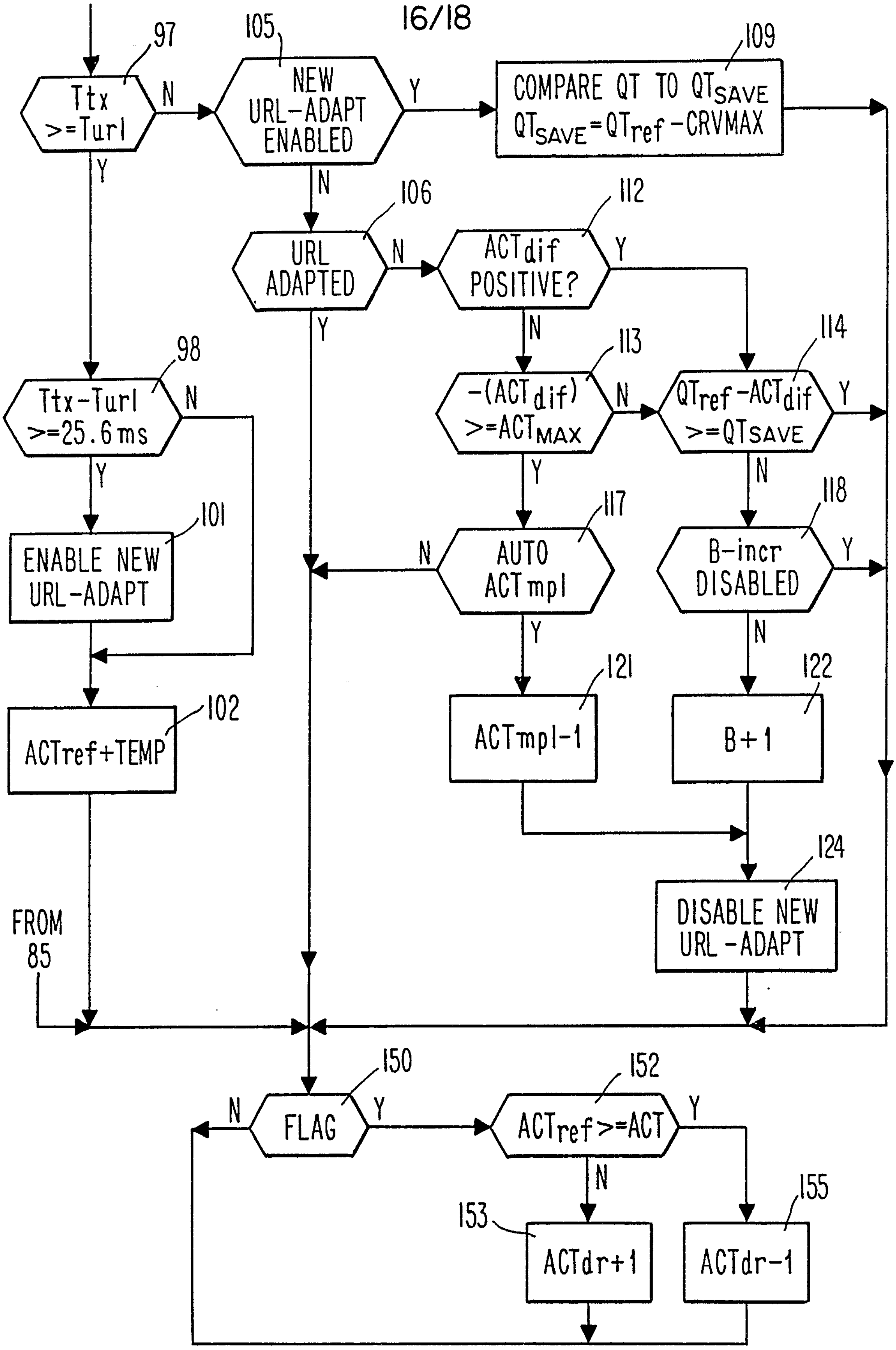
Ttx >=Turl
97
N
Y
105
NEW URL-ADAPT ENABLED
Y
COMPARE QT TO QT_{SAVE}
$QT_{SAVE}=QT_{ref}-CRVMAX$
109
N
106
URL ADAPTED
N
Y
112
ACT_{dif} POSITIVE?
Y
N
98
Ttx-Turl >=25.6 ms
N
Y
113
$-(ACT_{dif}) >= ACT_{MAX}$
N
114
$QT_{ref}-ACT_{dif} >= QT_{SAVE}$
Y
N
Y
101
ENABLE NEW URL-ADAPT
117
AUTO ACTmpl
N
Y
118
B-incr DISABLED
Y
N
102
ACTref+TEMP
121
ACTmpl-1
122
B+1
124
DISABLE NEW URL-ADAPT
FROM 85
150
FLAG
N
Y
152
ACTref>=ACT
Y
N
153
ACTdr+1
155
ACTdr-1

Fig. 17

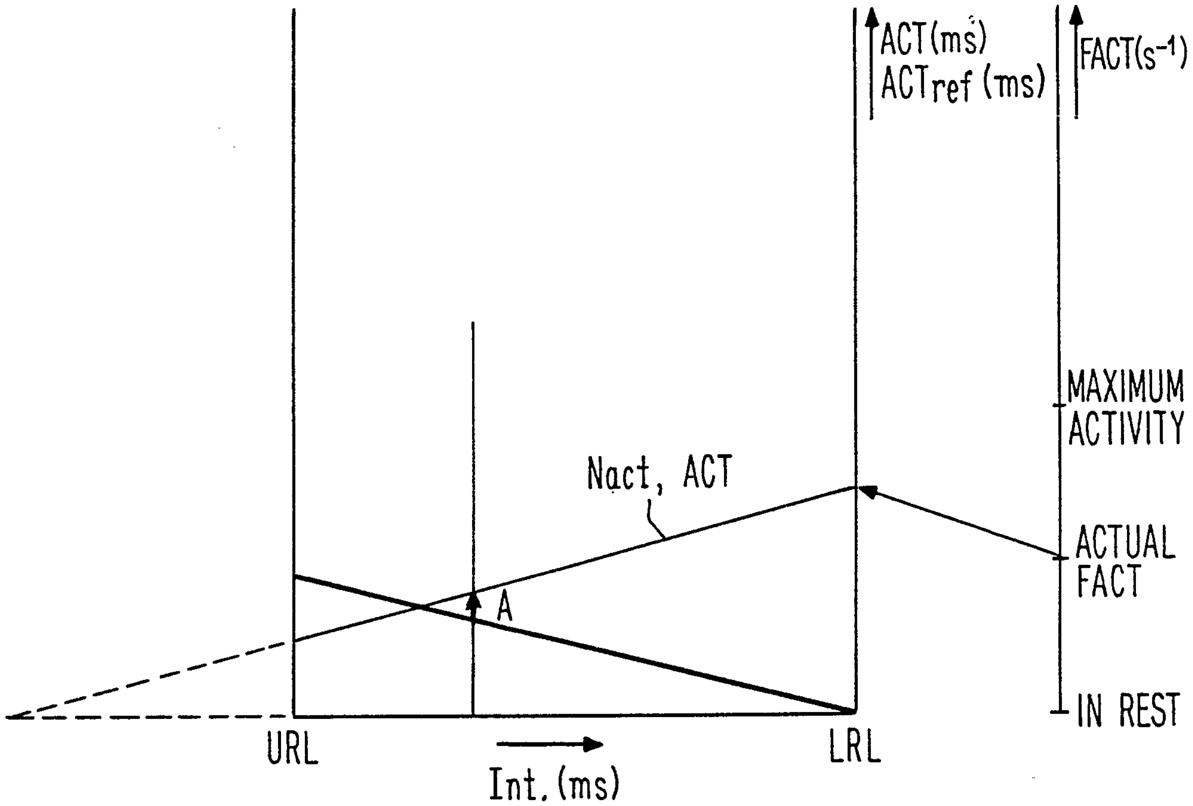

Fig. 18A

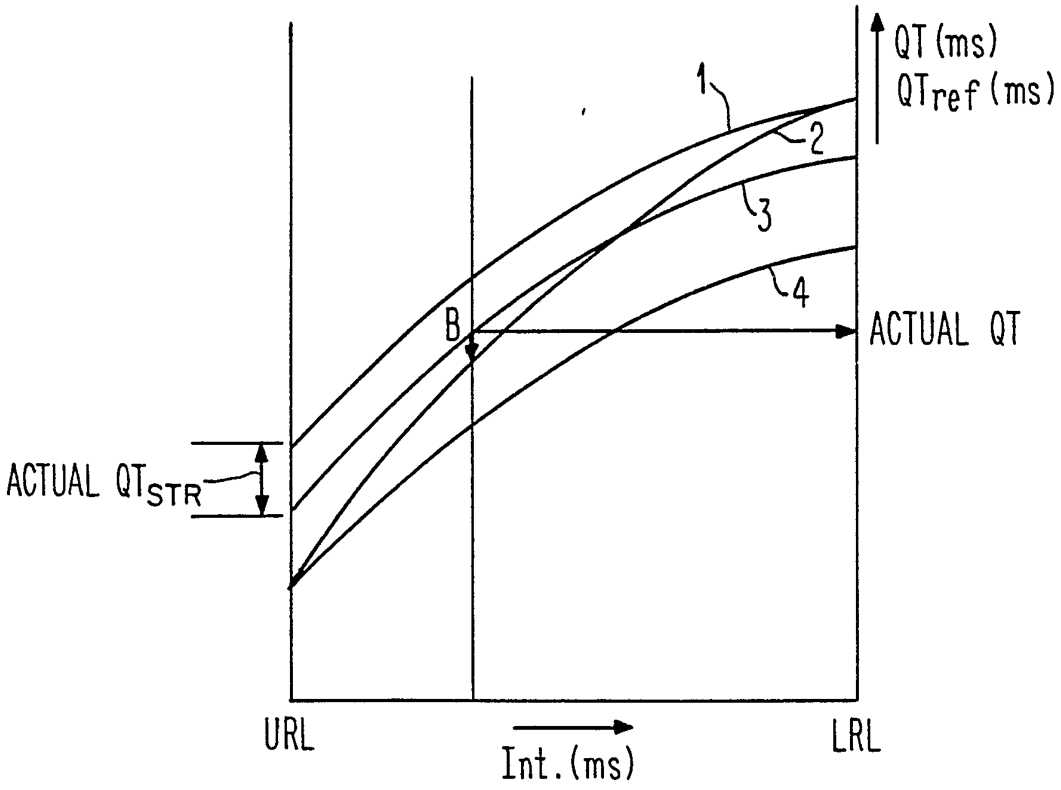

Fig. 18B

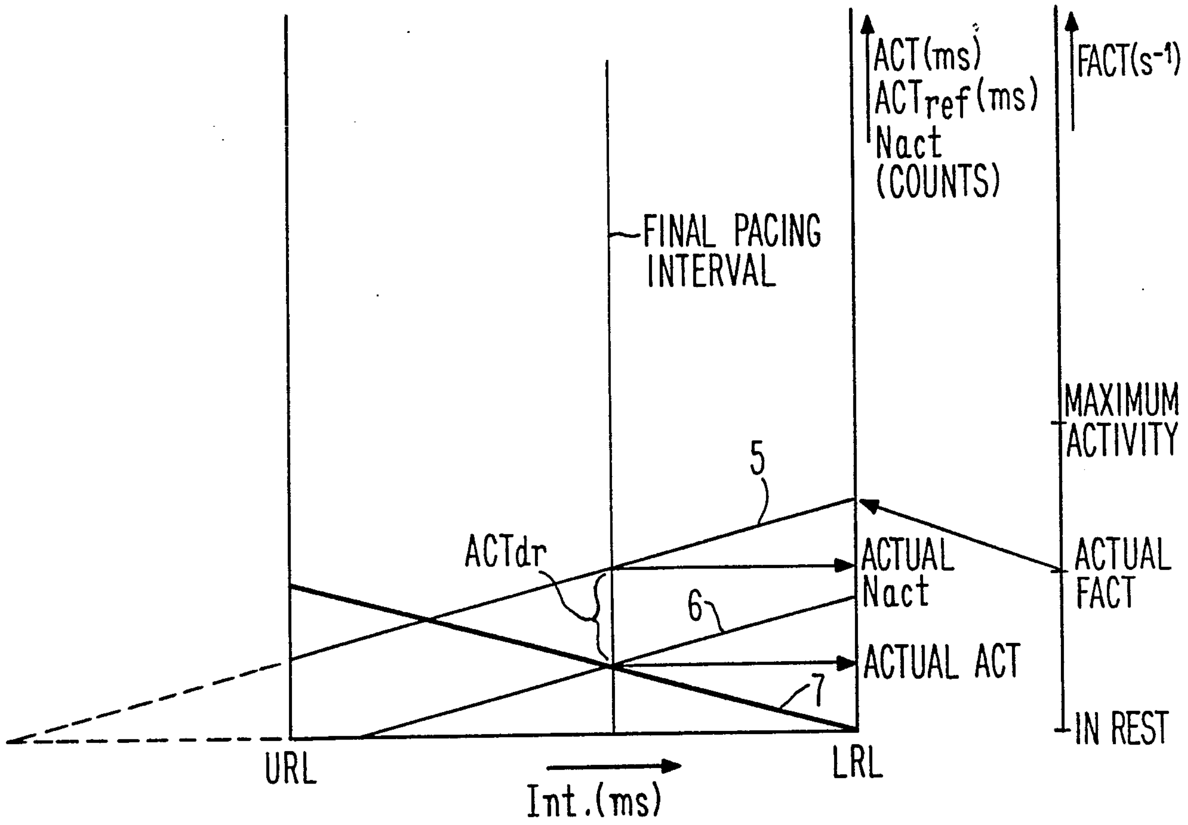

Fig. 19A

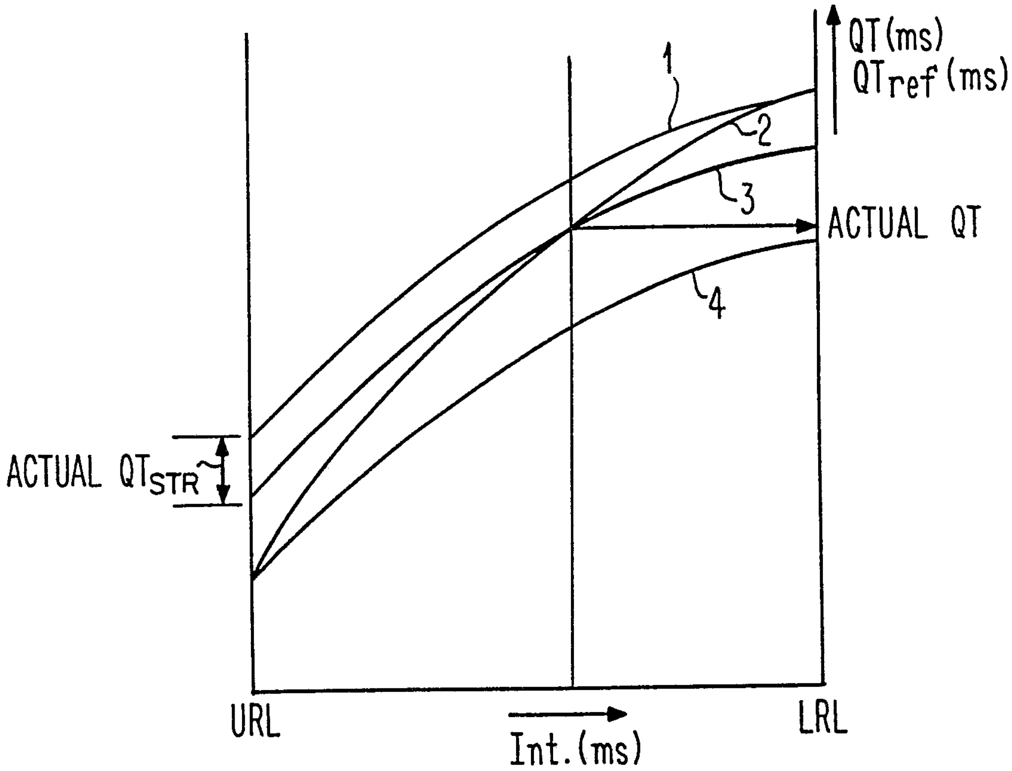

Fig. 19B

INTERNATIONAL SEARCH REPORT

International Application No PCT/EP 91/01512

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 A61N1/365

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	A61N

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
Y	US,A,4 926 863 (E. ALT) 22 May 1990 cited in the application see the whole document	1
A		2-6, 13-19

Y	EP,A,0 215 731 (BIOTRONIK MESS- UND THERAPHIEGERÄTE GMBH & CO) 25 March 1987 see page 38, line 21 - page 57, line 32; figures	1
A		7,9

A	GB,A,2 216 011 (S. C. WEBB ET AL.) 4 October 1989 cited in the application see the whole document	1-19

A	US,A,4 905 697 (K.S. HEGGS ET AL.) 6 March 1990 cited in the application see the whole document	1-19

	-/--	

° Special categories of cited documents : [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search 05 DECEMBER 1991	Date of Mailing of this International Search Report 18. 12. 91
International Searching Authority EUROPEAN PATENT OFFICE	Signature of Authorized Officer FERRIGNO A. A Ferrigno

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	EP,A,0 165 566 (SIEMENS AG) 27 December 1985 see the whole document ---	1,6

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO. EP 9101512 SA 50122

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 05/12/91
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-4926863	22-05-90	DE-A- 3631155	24-03-88
		EP-A- 0259658	16-03-88
		JP-A- 63177872	22-07-88
		US-A- 5044366	03-09-91
		US-A- 5014700	14-05-91
		US-A- 5014704	14-05-91
		US-A- 5014703	14-05-91
		US-A- 5014702	14-05-91
		US-A- 5031615	16-07-91
EP-A-0215731	25-03-87	US-A- 4867162	19-09-89
GB-A-2216011	04-10-89	EP-A- 0331309	06-09-89
		US-A- 5044365	03-09-91
US-A-4905697	06-03-90	None	
EP-A-0165566	27-12-85	DE-A- 3422913	02-01-86
		AU-B- 574193	30-06-88
		AU-A- 4381285	02-01-86
		JP-A- 61013976	22-01-86
		US-A- 4870968	03-10-89

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82