The Measurement of the Q-T Interval of the Electrocardiogram

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The sources of error in determination of the beginning of QRS and the end of T during measurement of the Q-T duration are analyzed. An important error is confusion of an elevated U wave with the T wave, resulting in the diagnosis of a prolonged Q-T. In such cases, some of the precordial leads usually show a notch or kink between T and U which indicates approximately the end of T. If these criteria are used, the true corrected Q-T duration in hypotassiumemia without hypocalcemia is not prolonged, but normal or shortened, corresponding to an earlier appearance of the second heart sound.

The duration of the Q-T interval of the electrocardiogram in its relation to the heart rate (relative or corrected Q-T duration) has been receiving increasing attention during the last decade. It has been found of especially great practical importance in the diagnosis of myocarditis2, 10, 16, 25, 35, 36, 38, 42, 47 and of certain diseases accompanied by electrolyte imbalance (literature quoted in reference 24). It is also of importance in the determination and evaluation of the ventricular gradient.24 The sources of error which may appear in the determination of the corrected Q-T duration are threefold. First, there are difficulties in the exact determination of the points which are to be used for the measurement of the Q-T interval in a given complex. Second, there are difficulties in averaging the Q-T duration of different complexes, which shows physiologic fluctuation even at constant heart rates, but especially when the heart rate varies, as for instance in respiratory arrhythmia and auricular fibrillation. A third group of difficulties arises when the actually measured Q-T duration is corrected for the heart rate and, in some cases, for a prolonged QRS duration. The two last mentioned groups of difficulties were adequately discussed and partly clarified in previous publications2, 3, 10, 16, 25, 35, 36, 38, 42, 47. The first source of error, that of actual measurement, was recognized by some authors,16, 22, 23, 25, 27, 32, 37, 42 but no systematic treatment of this subject was attempted up to the present time. In many cases the difficulties in the definition of the points to be used for measurement are so great that different cardiologists would probably assign widely diverging values to the Q-T interval of the same tracing. The purpose of the present paper is to point out some of these difficulties and to attempt to develop a set of exact rules and methods which could be used in future studies.

There can be no divergence of opinion that the Q-T duration should be measured from the beginning of the QRS complex to the end of the T wave. There are two main sources of error in measuring the Q-T duration. The Q-T duration can appear either shorter or longer than in reality. It can appear shorter if the first or last potentials produced during ventricular systole are directed perpendicular to the lead or, in other words, the initial portion of the QRS group or the terminal portion of the T wave may be isoelectric. It can, furthermore, appear shorter if parts of the T wave have an unusual configuration and are confused with other waves of the electrocardiogram, such as the P or U waves. The Q-T duration can appear longer than it is if other waves (usually the U wave, sometimes the P wave) are mistaken for the T wave proper or for the terminal part of a notched T wave. We shall consider each of

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This investigation was supported by a research grant (H-160) from the National Heart Institute, of the National Institutes of Health, Public Health Service.
the above sources of error systematically in the following paragraphs.

1. **Isoelectric Beginning of QRS**

   It is a well known fact that QRS begins earlier in the chest leads V₁₋₃ than in leads V₄₋₆ or in the limb leads.²⁴,²⁵ The most exact values of Q-T can therefore be obtained in leads V₂₋₃, if the T wave can be adequately measured in these leads (see later). If it is possible to register two or more leads synchronously, the point corresponding to the earliest beginning of QRS in any of these leads must be taken as the beginning of Q-T. If no synchronous registration is possible, the three standard or unipolar limb leads, registered at standard sensitivity, can still be synchronized by moving them horizontally until lead II = I + III or lead aV₈ + aV₄ + aV₆ = 0.²⁴ In most cases the error due to asynchronous beginning of QRS in different leads is small and does not exceed 0.02 second.²⁵

2. **Isoelectric End of the T Wave**

   The end of the T wave, like the beginning of QRS, may have an isolectric course in one or more leads, but because of the long duration of T the differences are much greater than in the case of QRS and may reach 0.04 second (fig. 1). In leads where the T wave is very low, its terminal portion may show such low voltage as to be practically indistinguishable from the slight spontaneous fluctuations of the base line or the U wave. An isolectric terminal portion of T also often precedes a terminal inversion of T.²⁴ It is therefore advisable to measure the Q-T duration in leads showing the highest voltage of T. These are usually the leads V₂₋₄. If it is possible to register synchronous leads or to synchronize the limb leads, it is always the latest point on the T wave in any lead which must be used for measuring Q-T, provided the T wave can be correctly identified.

3. **Notched T Wave Mistaken for U Wave**

   The T wave usually has a smooth, curved form, but in a small number of cases, especially in leads from the transition zones between a positive and a negative T wave, it may show a notch near its summit. In this case the notch can be mistaken for the end of the T wave while the section of T beyond the notch is considered as a U wave. This mistake is especially easy if the notch approaches or reaches the base line. However, other leads, taken synchronously with the doubtful leads or synchronized with them subsequently, usually show T waves of the typical form, whose summits coincide with the notch. As an example, the notched T wave in lead V₂ of figure 2c,d which appeared as a transition between a normal and a terminally inverted T wave during exercise is synchronous with a smooth T wave in lead V₄.

   The situation is more difficult if all the available leads show notched T waves; this occurs in pathologic cases, in some normal dogs²⁴ and usually in children.²⁴ If a distinct U wave is present in addition to the notched T wave, the differentiation is comparatively easy, as in

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Fig. 1. Leads I-III and V₁, registered synchronously in an apparently normal person immediately after two minutes of exercise in the recumbent position. The Q-T duration in lead I is at least 0.04 second shorter than in leads II-III. The first complex of lead V₁ shows a definite kink between the terminal negative phase of a diphasic T wave and the positive U wave, while in the second complex the transition is more gradual.
most of the published cases.\textsuperscript{18, 49} (See also figure 61\textsuperscript{H-J} of reference 22.) If the U wave is so low as to be indistinguishable, the following means of differentiation can be used: The terminal portion of T following the notch is usually of short duration (less than 0.15 second), while a U wave is longer; the slope of the beginning of QRS, while the latter usually exceeds 40 per cent of the distance between the summit of the U wave and the beginning of QRS. The notch in the T wave usually appears at least 0.04 second earlier than the second heart sound while the notch between T and U is usually situated within 0.04 second of this sound; this is discussed at greater length in the next section.

4. U Wave Mistaken for T Wave

If the U wave is separated from the T wave by a distinct isoelectric interval the two waves can be easily differentiated. However, in many of these cases the isoelectric interval is due to an isoelectric terminal portion of T (section 2), and the true end of T can be determined only by comparison with other leads. If the U wave follows the T wave immediately, without an isoelectric interval, it can be confused with the terminal portion of a notched or diphasic T wave. The 16 possible combinations of a positive, diphasic or negative T wave with a positive, diphasic or negative U wave are illustrated in figure 3 (solid parts of the figures).

In 8 of the 16 combinations in which the direction of the terminal limb of the T wave is opposite to that of the initial limb of the U wave, these two parts are separated by a distinct notch. In the other eight combinations where this direction is the same, the T and the U waves are separated by a kink, that is, by an abrupt change in the slope of the curve. This is due to the fact that the return of the T wave to the base line almost always is of a steeper slope than that contained in any part of the U wave. According to tentative measurements, the slope of the U wave usually does not exceed 1 $\mu$V per millisecond while the terminal portion of the T wave usually exceeds this slope. However, in cases where the T wave is depressed and the U wave elevated, the slope of the latter may approach the former. In this case the T wave and the U wave show an apparent merging and the end of the T wave can be determined only indirectly, as described in the following paragraphs, where each of the 16 patterns will be discussed in detail.

The combinations Ia and Ib (fig. 3) occur more often than any other. As long as the positive T and
U waves retain their characteristic shape, the differentiation of these two waves is easy; however, in the presence of a depressed T wave and an elevated U wave, the latter can be mistaken for the second summit of a bifid T wave. The differentiation of such cases has been discussed in section 3. In all cases of this pattern the end of the T wave is determined by the nadir of the notch between T and U.

The combinations Ic and Id, with a positive T wave and a negative initial portion of the U wave, appears sometimes after exercise or in pathologic cases. The inverted U wave in pattern Id can be mistakenly held for the terminal negative part of a diphasic T wave (figure 2 and lead V4 of T as a point halfway between the summits of the T and U wave. A further means of differentiation can be found in the location of the II heart sound, as will be described more fully in section 5.

The patterns IIc and IIId with a diphasic (plus-minus) T wave and a negative initial portion of U are rare. In these patterns the end of the T wave can be easily located at the apex of the notch between T and U (for example, tracing of 9.3.46, in figure 6 of reference 1).

The patterns IIIa and IIIb with a diphasic (minus-plus) T wave and a positive initial section of U usually present little difficulty in the determination of the end of the T wave, which coincides

![Schematic representation of the sixteen possible combinations between T and U waves. Full curves: T and U waves separate. Dotted curves: T and U waves partially merged. The vertical lines indicate the end of the T wave. The arrows point to the notch or kink between T and U.](image)

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a definite kink between the ascending limbs of the T and U waves, which can be used to determine the end of T (lead V₄ in figure 5a of reference 14, chest lead in figure 65 of 18). If no distinct kink is present, the pattern can be mistaken for a diphasic (negative-positive) T wave; however, in such cases the distance between the nadir of the T wave and the summit of the U wave usually exceeds 35 per cent of the distance between the latter and the beginning of QRS, while in the case of a true diphasic T wave the distance between the nadir of the negative phase and the summit of the positive phase usually does not exceed 35 per cent of the distance between the latter and the beginning of QRS.

The patterns IVc and IVd with negative T waves and negative initial portions of the U waves show always a clearly visible notch between T and U, which can be used to determine the end of T (for example, figure 4b, lead V₃).

5. SUPERPOSITION OF THE U WAVE ON THE T WAVE (MERGING OF T AND U)

The greatest difficulty in the determination of the Q-T interval is encountered when the U wave begins earlier than the end of the T wave and the two deflections are superimposed upon each other. The differentiation between the T and U waves in cases where they show merging can be facilitated by the study of the relation of these waves to the second heart sound. In multiple channel electrocardiographs the heart sounds can be recorded synchronously with the electrocardiogram on a separate channel, but even in single channel electrocardiographs which have no provision for heart sounds, the latter can be superimposed on the electrocardiogram by registering lead V₃ through a magnetic microphone (converted radio headphone) placed in the region of the great vessels.

In the great majority of normal cases the second heart sound coincides with the end of the T wave, but it can precede it by 0.02 second or follow it by 0.01 second up to 0.12 second. In a series of 1000 unselected clinical cases the beginning of the second sound occurred within 0.02 second of the end of T in 86 per cent, preceded or followed it 0.02 to 0.04 second in 8 per cent and more than 0.04 second in 6 per cent. However, in this series no adequate differentiation was made between the T and U waves if these showed unusual form. In all illustrated cases where the second sound preceded the end of the T wave by more than 0.07 second, the end of T was not clearly visible and the end of the U wave was used in measuring the Q-T duration. This was emphasized earlier in other illustrated cases where the second heart sound seemed to appear as much as 0.24 second earlier than the end of T (for example, figure 257 of reference 26) the end of the T wave could also not be determined exactly and the end of the U wave was considered as the end of T. In cases with intraventricular conduction disturbances the end of T is caused by the ventricle activated with delay, and must therefore be correlated with the beginning of the second section of a split second sound. However, in right intraventricular conduction disturbances the late closure of the pulmonary valve may not cause any visible vibrations in the phonocardiogram; in this case the difference between the actual QRS duration and the average QRS duration of 0.08 second must be added to the time of appearance of the second sound.

According to our measurements on personal cases and on those published in the literature, the second heart sound always appeared less than 0.10 second (usually less than 0.07 second) before the end of the T wave, when this end could be measured exactly. In all cases without intraventricular conduction disturbances where this interval was ex-
ceeded, a merging of T and U was present and an exact determination of the end of T was not possible. Most of these cases were those of hypopotassiumemia. We therefore suggest consideration of every case in which the beginning of the second heart sound precedes the apparent end of the T wave more than 0.07 second as a possible case of merging of T and U. In such cases as many precordial leads as possible should be taken, since one of these leads usually reveals a clear-cut boundary (a notch or a kink) between the true T wave and the U wave. This boundary must be sought at a point in the neighborhood of the second heart sound. The repetition of electrocardiographic tracings at short intervals (sometimes as often as every few hours or even minutes) during the course of treatment usually reveals a stage where a precise separation of T and U can be made.

Each of the 16 patterns described in the preceding section can be modified by an earlier occurrence of the U wave with respect to the T wave. In figure 3 the patterns which can theoretically result from such a modification are represented by interrupted lines. A slight degree of merging may have been present in most of the examples used to illustrate the figures in the preceding section, but the point of junction between T and U was very near the base line and caused no measurable error in the location of the notch or kink in respect to the end of T.

It would lead too far to describe in detail the modifications of the 16 patterns caused by different degrees of merging of the T and U waves. In the following we shall confine ourselves to a description of some of the most commonly found patterns of merging between T and U. In the first pattern, which originates from pattern 1a of figure 3, the T wave shows only insignificant changes while the U wave shows a progressively earlier beginning, climbing onto the descending limb of the T wave. This pattern is observed especially under the influence of epinephrine and during and after physical exercise (see figure 57 of reference 24). In this pattern there is always a notch between the T and U waves; this notch can be easily recognized because of the great difference in the slope of these waves.

In order to visualize the relation of the notch between T and U in the above pattern to the end of the T wave, an enlarged tracing of the T and U waves of a normal person was made, and the U wave gradually moved to the left toward the QRS complex (see legend to figure 5). An attempt to determine the true end of the T wave in cases of partial merging of T and U can be made by drawing a tangent to the steepest descending slope of T between its summit and the notch, and by determining the point of intersection of this tangent with the base line. In figure 5b, this point is situated before the true end of T, which is indicated better by the nadir of the notch. In figure 5c, the point of intersection lies between the notch and the true end of T and designates the end of T more exactly than the nadir of the notch. In figure 5d, it is beyond the true end of T, but still gives a better approximation than the nadir of the notch. In figure 5e, the intersection of the tangent with the base line is situated far beyond the true end of the T wave, and the best approximation to the end of T will be a point halfway between the nadir of the notch and the point of intersection.

In the patterns of merged T and U waves described in the preceding pages, the T wave retained the characteristic steep slope of its descent, and a notch between T and U was always present. The only difficulty in these cases was the exact determination of the end of the T wave, whereas the presence of merging was easily recognized. In the pattern to be described in the following paragraphs, the T wave usually becomes very flat and finally inverted, while the U wave shows an extreme increase in voltage, assuming a configuration resembling that of the normal T wave and exceeding the latter in amplitude. In this pattern, which appears in its most characteristic form in cases of hypopotassemia, the U wave was very often mistaken for the T wave.

Several patterns of merging between T and U may be observed in hypopotassemia. In many cases these patterns appeared in regular sequence during the development or regression of hypopotassemia; however, due to the rapidity of these changes, only very few cases have been published in which all these patterns appeared in the same patient. In the pattern of figure 6b, the U wave shows elevation and the T wave is depressed, but still shows a normal
configuration and is higher than the U wave, so that no question can be raised as to the identity of the waves. This pattern corresponds to patterns IV and V of Bellet and co-workers,\textsuperscript{4, 6, 7} who found these patterns in about 9 per cent of the cases with hypopotassemia, especially in those due to vomiting. The pattern of figure 6c T wave (section 3). Such cases are illustrated in the following published cases: lead CF4 in figure 20 of reference 33; figures 4A and 5 of reference 8; figure 4B of reference 5; figure 3 of reference 27; figure 35a of reference 18.

In the pattern shown in figure 6d, the T wave has become so low that it forms only an

is characterized by a further depression of the T wave and elevation of the U wave, which leads to a reversal of the normal relation between the voltage of these waves. A notch between T and U can be clearly seen, but because of the high voltage of U this wave can be mistaken for the second summit of a notched insignificant notch in the ascending limb of the U wave, which has become very tall and assumed the typical form of a T wave. In other published cases no notch whatsoever is visible and the pattern, taken alone, cannot be distinguished from an unusually long T wave. In some of these cases, the pattern of figure 6c,
with a distinct notch, or pattern e with a kink between T and U could be found in other leads (figure 2 of reference 12; figure 1A of reference 7; figure 2D of reference 39; figure 8 of reference 40; figure 2 of reference 29; figures 40, 42b, 46a, 63 of reference 18) but in others no such leads were registered (tracing 1 in figure 8 of reference 30; figure 37a of reference 18). If this pattern appears in the same patient as a transition between the patterns c and e, where T and U can be differentiated, and if the peak of this apparent T wave corresponds to the peak of the U wave in electrocardiograms taken within a short interval of time, without a major change in the heart rate (cases of figure 3 of reference 7, figure 2 of reference 5), it is almost certain that the wave in question is the U wave and not the T wave. This also becomes probable if the second heart sound begins more than 0.07 second before the end of the questionable wave (figure 91b of reference 19, figures 35a, 36, 57 of reference 18). At any rate, appearance of similar questionable TU waves in all the registered leads would require repetition of the electrocardiogram at short intervals during treatment, with registration of heart sounds and supplementary chest leads.

The pattern of figure 6e can be easily taken to represent a diphasic (negative-positive) T wave with a greatly prolonged Q-T interval. In most cases there is a definite kink (sudden change in the slope of the curve) between T and U, such as in the cases of figure 6e and figure 1 of references 11, 33, figure 1 of reference 44, figure 2 of reference 15, figure 2 of reference 21, figure 2 of reference 9, figure 38a of reference 18, but in other cases the transition between the negative T and U was smooth, corresponding to pattern IIb of Bellet (figure 2 of reference 33, figure 3 of reference 43, figure 93b of reference 19, figure 25e of reference 18). In these cases it is natural to consider the elevated U wave as a T wave, and a differentiation can be made only if a definite kink between T and U is present in another lead, in another complex of the same lead (figure 7 of reference 4) or at a different time (figures 2 and 6 of reference 12, figure 1 of reference 33, figure 40a of references 18, 34), or if the distance between the nadir of the negative T wave and the summit of the U wave exceeds that usually found between the peaks of a diphasic T wave, as discussed for patterns IVa and IB in section 4. In our own cases as well as in those from the literature (figures 21, 25e, 26a, c, 31, 37a, c, 38a, 40a, 42b, 46a of reference 18) where the heart sounds were registered, the second heart sound actually coincided with the kink between T and U, so that assuming this point to represent the end of the T wave would certainly entail a smaller error than if the end of the elevated U wave were used to measure the Q-T duration.

As mentioned above, the elevated U wave in hypopotassemia was usually considered as a very long T wave, and this led to the widespread belief that prolongation of the relative Q-T duration is one of the most characteristic criteria of hypopotassemia. It was recognized early by one of us32 as well as by Ljung27 that in many published cases where such a prolongation was found, the Q-U interval was measured instead of the Q-T interval. Bellet
and his group, (6-7, 20) who must be credited with the most comprehensive study of the ECG in hypopotassemia, saw many cases in which consecutive cycles of the same lead showed transitions between an apparently long Q-T interval and a T wave of normal duration accompanied by an elevated U wave. That the elevation of the U wave is a more specific sign of hypopotassemia than changes of the T was shown by the observation of Bellet and co-workers that after medication with potassium salts the U wave disappeared with but little change of the T wave. McAllen28 pointed out that the broad and deformed T waves seen in cases of hypopotassemia are similar in form and position to well defined U waves which appeared in the same patients and in the same leads within short intervals of time; he therefore came to the conclusion that the Q-T interval proper is not characteristically prolonged in hypopotassemia. If the inverted waves which precede the elevated U waves in cases of marked hypopotassemia are to be considered as T waves, a definite shortening of the relative Q-T duration must be postulated. This agrees with the shortening of the interval between the Q wave and the beginning of the second sound.

Bellet and co-workers recommended that the Q-T duration and the Q-U duration should be used interchangeably in the diagnosis of hypopotassemia, since they considered the U wave as well as the T wave as part of the electrical systole. This seems to us not justified as the U wave occurs in all cases after the end of the second heart sound and therefore during hemodynamic diastole. If Q-T and Q-U were used interchangeably, the corrected Q-T duration would appear prolonged even when hypopotassemia is not present, as a U wave is present in at least one lead in almost all cases. At any rate, the designation of "relative Q-T duration" implies explicitly that it is the T wave and not the U wave which is being measured. It seems imperative to us that in any evaluation of the relative Q-T duration it should always be stated explicitly whether the Q-T duration or Q-U duration was being measured, and that cases where an adequate separation of the two waves could not be made should be clearly indicated as such. According to our experience, the error entailed when a notch or kink between the T and U waves is considered as the end of the T wave is much smaller than when the end of the U wave is used to measure the Q-T duration; this error is the smaller, the nearer the base line and the further away from the apex of T these notches or kinks are situated.

6. Superposition of Auricular Complexes on the T Wave

Fusion of the T wave with the P wave is common in A-V conduction disturbances, in A-V dissociation and in supraventricular extrasystoles. In cases where all T waves are merged with P waves there may be a considerable difficulty in the determination of the Q-T interval. In the cases where the shape of the P wave is known (for example, in 2:1 A-V block), it can be geometrically subtracted from the area of the merged T and P wave; this would give us the true shape of the T wave. In many cases of supraventricular tachycardia T and P cannot be properly separated as the transition between these waves is continuous. In all these cases the left precordial leads V4-6 can be best used for the determination of the end of T, as the voltage of P in these leads is usually very small. This applies also to superposition of auricular fibrillation and flutter waves on the T wave.

Summary

1. The difficulties and sources of error in determination of the beginning of QRS and the end of the T wave are classified and analyzed.

2. The beginning of the QRS complex and/or the end of the T wave may be isoelectric in some of the leads. If a number of leads can be registered synchronously, the Q-T duration should be measured from the earliest point of QRS to the latest point of the T wave; curves of the three standard or of unipolar limb leads can be synchronized even if they were not registered synchronously.

3. In fusion or merging of the end of T with an elevated U wave, the merged T + U complex is usually mistaken for a notched or diphase T wave of bizarre configuration. A simple method of differentiation between these two
forms is based on the fact that the distance between the summits of a notched or diphasic T wave almost never exceeds 35 to 40 per cent of the distance between the beginning of QRS and the second summit, while the distance between the summits of T and U exceeds this percentage of the distance between QRS and the summit of U. In most cases a notch or a kink is present between T and U, especially in the precordial leads V2 and V3. This point is usually situated within 0.04 second of the beginning of the second heart sound; it indicates the end of T the more precisely, the nearer to the base line and the further away from the summit of the T wave it is situated.

4. The measurement of the end of an elevated U wave instead of the end of T has caused the erroneous conclusion that the corrected Q-T duration is prolonged in many published cases of hypopotassemia and in some cases after physical exercise. If the criteria outlined in this paper are applied, the true corrected Q-T duration is not increased or is even shortened in typical cases of hypopotassemia without hypocalcemia.

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Circulation. 1952;6:378-388
doi: 10.1161/01.CIR.6.3.378
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on
the World Wide Web at:
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