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Citation/Reference	Moeyersons J., Goovaerts G., Huijghebaert S., Vandenberk B., Willems R., Van Huffel S. (2017), **Automated T Wave End Detection Methods: Comparison of Four Different Methods for T Wave End Detection** In Proceedings of the 10th International Joint Conference on Biomedical Engineering Systems and Technologies - Volume 4: BIOSIGNALS, 92-98, 2017, Porto, Portugal
Archived version	Author manuscript: the content is identical to the content of the published paper, but without the final typesetting by the publisher
Published version	http://www.scitepress.org/DigitalLibrary/PublicationsDetail.aspx?ID=6p1vT7HJUzE=&t=1
Journal homepage	http://www.biosignals.biostec.org/?y=2017
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Abstract	
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Automated T Wave End Detection Methods
Comparison of Four Different Methods for T Wave End Detection

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Keywords: T wave end detection, electrocardiogram (ECG)

Abstract: T wave end detection is essential for electrocardiogram (ECG) processing and analysis. Several methods have been proposed and tested, but an objective comparison is lacking. In this paper, four different (semi-)automated methods are compared with the manually annotated T wave ends of the PhysioNet QT database. The first method is a semi-automatic method, based on a template matching algorithm. The second method uses the tangent of the steepest point of the descending limb of the T wave. The third and fourth method perform a maximum area search of, respectively, a trapezium and the area under the curve. In order to evaluate the accuracy and repeatability of the proposed algorithms, the mean and standard deviation (sd) of the detection errors were computed. This was performed for leads I and II separately, after selection of the best annotated T wave end per beat and after selection of the best lead. We demonstrated that the trapezium method is the least repeatable of all methods tested (sd=29.7ms), whilst the integral method scores best in terms of accuracy (mean=2.2ms). These findings were strengthened by the analysis of the generated Bland-Altman plots, where the smallest bias was observed for the integral method (-1.89ms).

1 INTRODUCTION

The QT interval is an indirect measurement of the time of the depolarization and repolarization of the ventricular cells. Prolongation of this interval is associated with the occurrence of lethal ventricular arrhythmias in patients with the congenital long QT syndrome (Schwartz & Wolf 1978)(Goldenberg et al. 2008), in patients taking QT-prolonging non-antiarrhythmic medication (De Ponti et al. 2002) and even in the general population (Goldenberg et al. 2006). Therefore, accurate measurement of the QT interval is of major importance.

Manual detection of the T wave end requires a time consuming effort of the clinician. Unfortunately, the great morphological variation in ECG signals makes it hard to design an automated and widely applicable algorithm (Manriquez & Zhang 2007). Whereas the QRS onset is easily detected, because of its sharpness, it can be quite challenging to determine the end of the T wave, since it gradually merges with the baseline (Couderc & Zareba 2005). Furthermore, the presence of U waves might cause additional difficulties. Large U waves, fused with the T wave, should be included in the measurement, in contrast to small and/or separate U waves which should not be included (Vohra 2007). During exercise, the problems with T wave end detection are even more distinct, since at fast heart rates, the T wave might fuse with the following P wave (Chauhan et al. 2002). These facts make it difficult to automatically detect the end of the T wave.

Despite all these challenges, several algorithms have been developed using different methodologies. Since these different algorithms can differ in QT interval measurement by 10 to 20ms it is important that a correct detection method is selected (Panicker, Karnad, Joshi, et al. 2009). This paper is the first to compare four different (semi-)automated methods on

the same manually appointed T wave ends of the PhysioNet QT database.

The first method is a semi-automatic method, based on a template matching algorithm in which the user manually selects, hence the semi, the beginning and the end of the QT interval on a template beat (Berger et al. 1997). The second method determines the end of the T wave using the tangent of the steepest point of the descending limb of the T wave. The third and fourth method perform a maximum area search of, respectively, a trapezium (Vázquez-Seisdedos et al. 2011) and the area under the curve (Qinghua Zhang et al. 2006). In the following, we will briefly summarize the four methods mentioned.

2 METHODS

2.1 Method 1: Semi-automatic (SEMI) T Wave End Detection

The first step of this algorithm is the storage of all beats, 0.35s before and 0.75s after each R peak. Hereof the trimmed mean is calculated, excluding the upper and lower 10% percent of the data, to create a template representing the average beat. In order to calculate the QT interval, the distinct features of the template have to be detected. The template's R peak is known, since we segmented the signal based hereon. The time location of the R peak is denoted T_k. Hereafter, the user manually selects the beginning and the end of the QT interval. This segment is denoted $\varphi(\mathrm{n})$, where n is the sample number. Thus,

$$\varphi(\mathrm{n}) = x(n)\ for\ n = n_0 : n_1 \qquad (1)$$

where $x(n)$ is the ECG signal and n_0 and n_1 are the manually selected beginning and end points of the QT interval. The duration of the interval is N samples. For the purpose of matching all other beats to the template, only the region of the template from $n = T_k + n_\nabla\ to\ n = n_1$ is used, with n_∇ equal to 50ms. Per beat, an error function $\varepsilon_i(a)$ is defined:

$$\varepsilon_i(a) = \sum_{j=n_\nabla}^{n_1 - T_k} [\,\varphi(T_k + j) - x(T_i + aj)]^2 \qquad (2)$$

where a is the time-stretching factor and T_i is the R peak under investigation. The result is the sum of squared differences between the template T wave and the stretched or compressed T wave for beat i. A progressive search in the interval $[0.9\ 1.1]$ is conducted in order to find the value of a that minimizes $\varepsilon_i(a)$. The best value of a is denoted $\hat{a}_i$ and the QT interval of the ith beat is defined as

$$QT_i = \hat{a}_i N \qquad (3)$$

with, as stated before, N equal to the duration of the template QT interval. The ith T wave end is defined by the sum of the ith QT interval and the location of the according R peak, minus the length of the template's QR interval. In summary, the algorithm finds the QT interval for each beat such that the T wave shape best matches the template T wave under the time-stretch model.

The working principle of this method is demonstrated graphically in Figure 1. The top panel presents the template beat. Here, the manually selected beginning and end of the QT interval are indicated. The region highlighted in bold is the segment used to compute the error function. In the next panel, several time-compressed versions of a new beat's T wave are superimposed on the template. The area of difference between the template T wave and the uncompressed T wave of the beat is then calculated and the optimal value of a is determined.

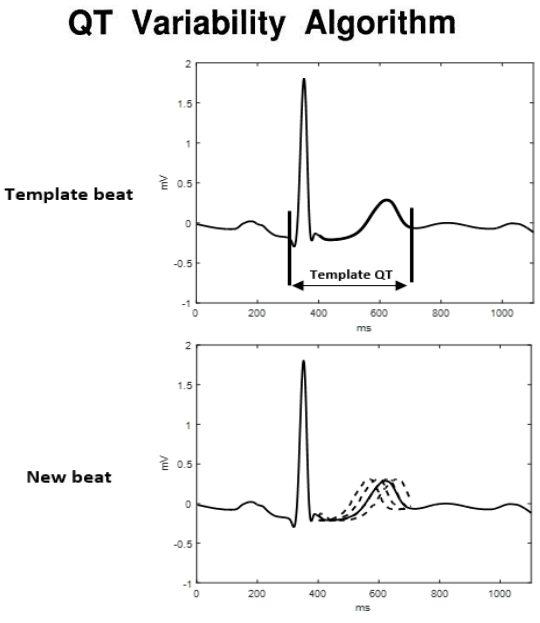


Figure 1: Operator selects beginning and end points of the QT interval from the template (top panel). For each of the other beats in the epoch, multiple time-compressed or time-stretched versions of the QT interval are generated (second panel). These will be used for comparison with the template QT interval to derive the optimal time-stretching factor $\hat{a}$.

2.2 Method 2: Tangent Method (TAN)

The first step of this algorithm is again the segmentation of all beats, 0.35s before and 0.75s after each R peak. Every beat will be processed and analysed separately. The second step is an additional cleaning of each beat using a cubic Savitzky-Golay filter in order to remove high frequency noise. Afterwards, the isoelectric baseline of the beat is aligned with the zero line by subtracting the median of the first 320ms of the studied beat.

In the third step, a search window is defined in which the T wave peak is selected. The left bound is set at 60ms after the R peak, in order to exclude the QRS complex, but to include the whole T wave. The right bound is set in the interval between the suspected end of the T wave and the next R peak. In this search window the derivative is calculated, followed by a detection of all sign changes. This operation results in the location of all peaks and valleys in the selection window. Subsequently, the T peak is defined as the peak or valley with the maximal absolute amplitude in the selection window, but located maximally 850ms from the start of the beat.

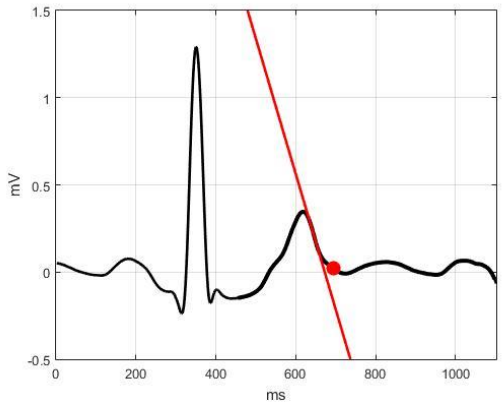


Figure 2: Tangent Method. The red line represents the tangent of the steepest point of the descending limb of the T wave and the red dot represents the T wave end.

The fourth step is the selection of the T wave end. First the steepest point of the descending or ascending limb of the T wave is defined. Secondly, the tangent through this point is calculated and the cross point between this line and the zero baseline is searched. Finally, since this cross point does not exactly align with the T end, the point 20ms after the cross point is selected to be the T end. The working principle of this method is demonstrated graphically in Figure 2.

2.3 Method 3: Trapezium's Area (TRA) Method

The TRA method assumes that T peaks are previously detected, following the described steps. First, a search window is defined, which encloses the whole T wave. Second, the search window is narrowed. The left and right bound are replaced by the samples with the maximal and minimal slope in the search window. Finally, the first point with an absolute slope smaller than 0.1 is selected and a maximum search of the absolute values around this point is conducted. The maximal is referred to as the T peak.

This T wave end detection method is based on the calculation of consecutive areas of a rectangular trapezium defined by three fixed and one variable vertex.

The first fixed point is located 100ms past the T peak in order to ensure the inclusion of the T wave end (x_r, y_r). The second fixed point is defined by subtracting each value of a search window in between the T peak and the first fixed point. A maximum search is performed and the steepest point of the descending limb of the T wave is selected (x_m, y_m). The third fixed point is the cross point between a vertical line through the first and a horizontal line through the second fixed point (x_r, y_m). The variable point starts at the second fixed point and follows the graph, until it reaches the first fixed point (x_i, y_i). This is demonstrated graphically in Figure 3. The T wave end is defined as the point where the area A of the trapezium is maximal. A is calculated by the following formula:

$$A = 0.5 * (y_m - y_i) * (2x_r - x_i - x_m) \qquad (4)$$

This means that the area A will be zero when the variable point equals the second fixed point and maximum when it is located at the end of the T wave.

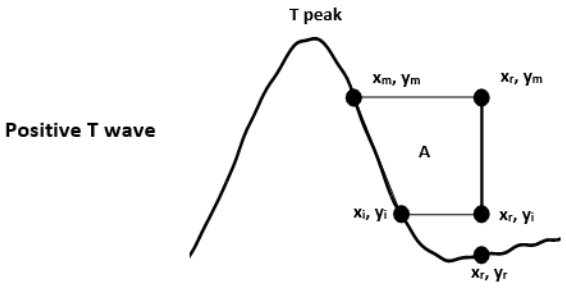


Figure 3: Determination of the T wave end by the computation of the area A of several trapezes. T end denotes the maximum area.

2.4 Method 4: Integration (INT) Operation

Based on the R peak detection for each beat, an interval, $[k_a\ k_b]$, is delimited so that the T wave end is inside this interval, with no overlap with the other wave forms. The proposed algorithm mainly consists of the computation of an indicator A_k which reaches its maximal value when the T end is detected. It is computed through an integration operation in a sliding window, with the window size smaller than the length of the whole T wave. A_k is computed by the following formula:

$$A_k = \sum_{j=k-w+1}^{k} s_j - \bar{s}_k \qquad (5)$$

where w is the sliding window size in discrete time, s_j is the signal value at time point j and $\bar{s}_k$ is the mean value of the signal in a small window around k. For each instance k inside the earlier defined interval, the value of A_k is computed and the T wave end is located at the value of k maximizing A_k.

3. EVALUATION WITH MANUALLY ANNOTATED ECG SIGNALS

The performance of the presented algorithms is evaluated on the PhysioNet QT database. We compared the performance of the different detection methods with the manually annotated T wave ends in this database.

3.1 The PhysioNet QT Database

The PhysioNet QT database has been designed to serve as a reference for the validation and comparison of T wave end detecting algorithms (Laguna et al. 1997). It contains 105 records of 15min two-lead ECG signals and a total of 3944 T wave end annotations. The annotations were performed manually by two expert cardiologists. 3542 T wave ends were annotated by the first cardiologist and 402 were annotated by the second cardiologist, in 11 recordings. At least 30 beats per record were annotated, except for 2 records in which no T wave ends were annotated. The signals are sampled at 250Hz.

Since each detection method uses different types of filtering, their performance could depend on the characteristics of the filters. To homogenize this dependence, the pre-processing was generalized. All signals were filtered with a zero-phase bandpass filter between 1 and 40Hz, to correct for baseline drift and high frequency noise.

3.2 Performance Comparison

In order to evaluate the accuracy and repeatability of the proposed algorithms, the mean and standard deviation (sd) of the detection errors, that is the time difference in ms, between the manually and automatically detected T wave ends, were computed for the four different methods in the two ECG leads.

The mean and standard deviation of the errors were computed as follows. First, the four algorithms were applied to each of the two leads of an ECG record in the QT database. Each T wave end is annotated once by the cardiologists and located twice by the four algorithms, once per ECG lead. Second, the detection error is computed. Each manually annotated T wave end was compared with the corresponding four automatically annotated T wave ends. For each lead, the mean detection error and standard deviation per algorithm was computed. Finally, the overall mean and standard deviation for all ECG records were computed.

In Table 1 the results of the validation of the four proposed algorithms are presented. In row 1 and 2 the overall mean and sd of lead I and II are presented. The mean value expresses how close the algorithms are to the manually annotated markers (accuracy), and the sd value provides information about the stability (repeatability) of the detection criteria. The mean values have to be interpreted with caution, since over- and underestimation of the manually annotated T wave ends cancel each other out. This might result in a lower overall mean value.

Table 1: Comparison of the overall mean and standard deviation (sd) of the differences, in ms, between the automatic and manually annotated T wave ends for all methods in both leads separately.

	SEMI		TAN		TRA		INT	
Lead	mean	sd	mean	sd	mean	sd	mean	sd
I	-6.2	15.4	-18.0	17.8	25.7	37.2	10.1	21.4
II	-2.1	15.9	-5.4	18.0	19.7	36.1	14.9	29.1

The results of Table 1 show that, in terms of the overall mean error and standard deviation, the TRA method is outperformed by the other three algorithms, when evaluated on the PhysioNet QT database. Although obtained on the same database, this method

showed worse results, compared to the original paper (Vázquez-Seisdedos et al. 2011). A first explanation might be the exclusion of some beats in the original paper due to poor quality of T wave end detection. Eliminating cardiac cycles of poor quality generally improves the results. Therefore, evaluating the detection errors without removing the bad cardiac cycles puts the proposed algorithms in the least favourable evaluation condition, which might explain the difference. The second explanation is the choice of lead. In this paper, the algorithm is applied on both leads separately, whilst in the original paper the a posteriori best result among two computed positions was chosen for error evaluation (best beat per record (BB)). In clinical practice, the human operator could choose the best lead for each patient individually (best lead per record (BL)), but it is less reasonable to switch leads per cardiac cycle (Zhang et al. 2005). In order to take this difference in lead selection into account, the BB and BL values were also calculated.

The BB values were computed according to the method adopted first in (Martínez et al. 2004) and later in (Zhang et al. 2005; Vázquez-Seisdedos et al. 2011). This method defines the T wave end per beat by selecting the lead in which the detection error, between the automatically and manually annotated T wave end, is minimal. The BL method selects the ECG lead which contains the most T wave ends, appointed by the previously described method. If an equal amount of T wave ends were appointed in both leads, the first lead was selected. From the viewpoint of a human operator, this is a more realistic procedure. The results of both methods can be found in Table 2.

Table 2: Comparison of the overall mean and standard deviation (sd) of the differences, in ms, between the automatic and manually annotated T wave ends for all methods with the supplementary BB and BL protocol.

	SEMI		TAN		TRA		INT	
Lead	mean	sd	mean	sd	mean	sd	mean	sd
BB	-4.9	15.1	-8.0	16.3	11.8	29.7	2.2	20.0
BL	-6.2	17.6	-7.6	19.0	14.3	37.5	3.9	22.9

When applying the BB protocol, it was observed that the overall sd, obtained by each of the methods, was lower compared to the sd obtained for lead I and II. This was expected, since the lead in which the detection error is minimal was selected per beat. This protocol is most in accordance with the annotation method of the cardiologists, since they made their annotation by examining both leads and based their decision on the best lead (Martínez et al. 2004).

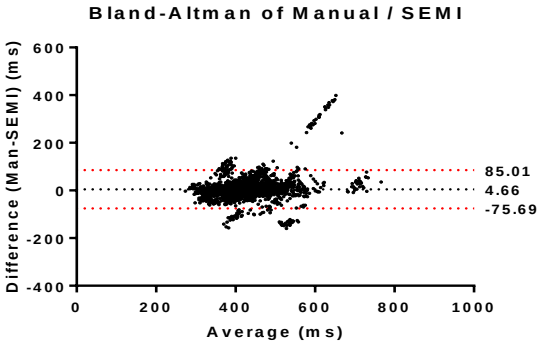
In clinical practice, the best lead can be selected after the ECG recorder is set up. Hence, the BL results are clinically the most relevant, concerning everyday T wave end detection. We demonstrated that the TRA method is the least repeatable of all methods tested (sd=37.5ms), whilst the SEMI method is the most repeatable one (sd=17.6ms). The integral method scores best in terms of accuracy (mean=3.9ms).

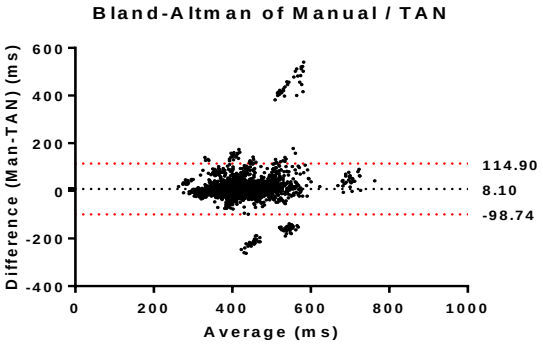
It might be noted that the mean and sd calculation was simplified. One value was computed per record and the overall mean and sd were computed as the average of these values. This method does not take the number of annotated T wave ends in each record into account. Therefore, we opted to generate Bland-Altman plots. These allow a direct comparison between all manual annotations and the T wave end selections of the four algorithms. Only the BB values were taken into account, since this protocol is most in accordance with the annotation method of the cardiologists. Based on the Bland-Altman plots of the respective QT intervals, Q being manually annotated by the cardiologists, an evaluation of the agreement of the methods was performed. The results of the evaluation are depicted in Figure 4.

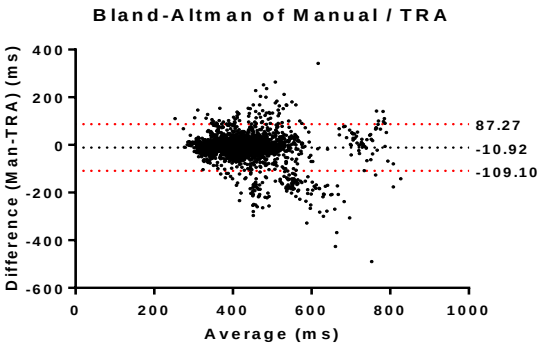
The comparison of the TRA method shows the largest limits of agreement (-109.10/87.27ms). These results strengthen the previous findings. In accordance, the best agreement was determined for the SEMI method (-75.69/85.01ms), although the agreement of the INT method was only slightly worse (-84.48/80.70ms). The obtained biases are in the range of the ones earlier reported (Panicker, Karnad, Natekar, et al. 2009; Vázquez-Seisdedos et al. 2011).

The results of the SEMI method could be explained by the small influence of baseline wander and U waves on the detection of the T wave end. Because of their low amplitude, U waves have significantly less influence on the sum of the squared differences compared to the T waves. However, it should be noted that the method is very operator dependent. This is highlighted by the cluster forming of the difference points in the Bland-Altman plot. All QT intervals computed per record will be biased in accordance to the difference in end point selection of the template T wave end, compared to the manually annotated T wave end. This results in a relatively unaffected QT variability, but alters the QT lengths. This operator dependency should be taken into account when using this method in QT interval analysis.

Besides the agreement intervals, the biggest difference between the algorithms could be observed for the cloud on the right. This cloud contains the longest QT intervals, including biphasic T waves and fusions with the U wave. Both the TAN and TRA method were outperformed by the INT method for the detection of the actual ends of these QT intervals. Probably, this is due to the fact that the TAN and TRA method rely on the detection of the T wave peak, making it harder to detect more complex biphasic T waves or fused T and U waves.







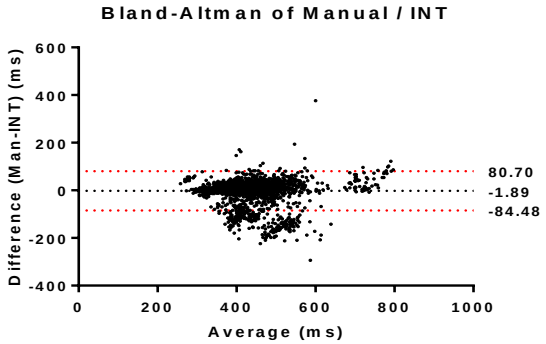


Figure 4: Bland-Altman plots of the four T wave end detection algorithms, compared to the manual annotated beats. The dotted black line indicates the average bias, or the average of the differences. The dotted red lines represent the 95% limits of agreement.

3.3 Limitations

We annotated the T wave ends on the template beats for the SEMI method ourselves. Better results could have been obtained by annotation of the template by a cardiologist. Also, the tangent and trapezium method heavily rely on an accurate T peak detection. This could not be fully guaranteed and might be an additional cause for the large limits of agreement of the TRA method. Finally, although the PhysioNet QT database provides a large database of annotated beats, it should be noted that it is not known which lead was annotated. In this paper the BB approach is further investigated, but it should be noted that this approach cannot be applied in a clinical setting.

4. CONCLUSION

This paper is the first to compare four different (semi-)automated methods on the same manually appointed T wave ends of the PhysioNet QT database. We demonstrated that, in terms of overall mean error and standard deviation, the TRA method is outperformed by the other algorithms. The SEMI and INT methods perform approximately equivalent, but the SEMI method is very operator dependent. Therefore, the INT method is the preferred method. As presented, an important difference remains between automatically and manually annotated T wave ends. This is probably due to the previously mentioned morphological variation, U wave fusion and omnipresent noise, which also impede manual annotation.

ACKNOWLEDGEMENTS

RW is supported as a clinical researcher by the Fund for Scientific Research Flanders (FWO).
SV: BOF KU Leuven: CoE #: PFV/10/002 (OPTEC), SPARKLE #: IDO-10-0358, The effect of perinatal stress on the later outcome in preterm babies #: C24/15/036; FWO: project #: G.0869.12N (Tumor imaging), G.0A5513N (Deep brain stimulation); IWT: project #: TBM 110697-NeoGuard, SWT 150466-OSA+; iMinds Medical Information Technologies: SBO2016; Belgian Federal Science Policy Office: IUAP P7/19/ (DYSCO, 'Dynamical systems, control and optimization', 2012-2017); Belgian Foreign Affairs-Development Cooperation: VLIR UOS programs (2013-2019); EU: European Union's Seventh Framework Programme (FP7/2007-2013): EU MC ITN TRANSACT 2012, #316679, ERASMUS EQR: Community service engineer , #539642-LLP-1-2013; The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013) / ERC Advanced Grant: BIOTENSORS (n° 339804). This paper reflects only the authors' views and the Union is not liable for any use that may be made of the contained information. (Tumor imaging) G.0A5513N (Deep brain stimulation);

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