A Quantitative Comparison of Unipolar and Augmented Unipolar Limb Leads

By Ernst Simonson, M.D., and Ancel Keys, Ph.D.

Goldberger has claimed that his augmented unipolar limb leads (aV) are identical—except for a 50 per cent larger amplitude—and interchangeable with Wilson’s original V leads, but this claim was not supported by quantitative evidence. The advantage of larger amplitudes explains the increasing preference for the aV leads. A quantitative comparison between V and aV leads revealed such tremendous variability of the augmentation ratio, both interindividual and between leads in the same individual, that standards obtained with V leads are not applicable to aV leads and vice versa. V leads and aV leads are not interchangeable.

PROCEEDING from the Einthoven triangle theory of the electrocardiogram, Wilson and his collaborators suggested that a relatively neutral reference electrode (T) could be obtained by pooling the three limb electrodes in a common terminal. Though the potential of such a terminal electrode is not zero, it is definitely smaller than the potential variations in any single limb electrode. In spite of the theoretic merit of Wilson’s V lead, it has the disadvantage of occasional small magnitude of the deflections in the unipolar limb leads VR, VL, and VF. In order to increase the amplitude of deflections, while still retaining the advantage of an “indifferent” reference electrode, Goldberger modified Wilson’s procedure by disconnecting the central terminal from the limb to which the exploring electrode was attached. Thus, Goldberger pools only two instead of three leads. By mathematical deduction he concluded that this procedure would augment the deflections by 50 per cent. This was expressed in the nomenclature “aV” leads, “a” indicating augmented. Expressed on a percentage basis, the unipolar aV limb leads would equal 150 per cent of the amplitudes in the unipolar V leads. Except for the larger amplitude, Goldberger claimed that the V and aV leads are identical and interchangeable. Goldberger also omitted the 5,000-ohm resistors placed between the extremity electrodes and Wilson’s terminal (T); this, however, does not essentially affect the basic principle of augmentation.

The advantage of having larger amplitudes in the unipolar limb leads explains the recent tendency of electrocardiographers to use Goldberger’s aV leads. The preference for aV rather than V unipolar leads is, however, not uniform. While Myers and Klein prefer the Goldberger leads, Kossmann and his associates discarded Goldberger’s electrode because they sometimes observed considerable distortions compared with Wilson’s three-lead terminal electrode. At times, however, Kossmann and his co-workers used Goldberger’s two-lead pooling with Wilson’s resistors; detailed comparisons were not reported for any of these arrangements. Although no objection can be made against the mathematical basis of the aV leads, the question of possible distortion can only be decided experimentally. Kisch reported a case with grossly different augmentation in aVR (162 per cent), aVL (143 per cent) and aVF (108 per cent) and implied that this is not unusual. In the absence of a quantitative comparison between the aV and V leads, the choice between them has been left mainly to subjective preference. This article reports a quantitative analysis of the augmentation obtained with aV limb leads.

METHOD

In a group of 20 normal men aged 20 to 53 years, in 2 patients with abnormal right axis deviation, and in 4 patients with abnormal left axis deviation, the standard leads, the
VR, VL, VF leads (Wilson leads), and the aVR, aVL, and aVF leads (Goldberger leads) were taken with the Sanborn Viso-Cardiette. The exploring electrode was placed several inches from the nearest terminal of the "T" electrode. Previous to this work, a quantitative comparison of electrocardiograms obtained with a string galvanometer (Cambridge), an amplifier instrument (Sanborn), and the Viso-Cardiette was made. There was good agreement between the various instruments in regard to the recorded amplitudes of the deviations. In the Viso-Cardiette, the three limbs RA, LA and LL are connected to the V terminal each through a separate 5,000-ohm resistance. The Sanborn Company states that this arrangement in connection with the high-impedance amplifier input (around 500,000 ohms) reduces the error due to variable skin resistance to 0.2 per cent. It seemed therefore, that the Viso-Cardiette was well suited for this experimental study.

In each tracing, the amplitudes of the QRS complex and the T wave were averaged from at least five beats. The measurements were made as carefully as possible and were independently checked. In 10 of the subjects the aV leads were compared with and without 5,000 ohms in each branch of the central terminal; for this purpose shielded cables were used to pool the leads. In another group of 22 subjects (13 men, 9 women), the repeat variability of the RS amplitude in VF was investigated with both Wilson and Goldberger leads. Finally, in 15 subjects, VR and aVR leads were also taken with the Cambridge electrocardiograph (string galvanometer).

**Results**

The amplitudes (positive or negative) of the QRS complex and of the T wave were plotted for all unipolar limb leads with the amplitudes in the V leads as abscissa (positive right, negative left) and the amplitudes in the aV leads (positive up, negative down) as ordinates. Thus, in figure 1, the right upper quadrant shows the R wave, the left lower quadrant shows the S wave.

The scatter diagrams for the various leads and deflections were similar, so that it is sufficient to show three diagrams (figs. 1–3) for illustration: the R and S waves for the left leg lead (fig. 1), the T wave for right arm lead (fig. 2), and the QS deflection for the right arm lead (fig. 3). Since the R wave in this lead is small or absent, only the negative deflection, Q or S, was plotted, with abscissa and ordinate increasing from left to right and upward. The 150 per cent slope, which corresponds to Goldberger's predicted augmentation over the Wilson leads, is indicated by a solid line. The figures show that the predicted slope agrees roughly with the general trend observed. However, the individual scatter is great. Theoretically, there is no reason to expect an effect of the axis or the direction of potentials on the augmentation in the aV leads, but nevertheless it should be investigated whether these factors determine the individual scatter and trend. It seems that the scatter or trend is not affected by the QRS axis within the normal limits. In figure 1, the values of the S wave in the 4 patients with abnormal left axis deviation are below the 150 per cent slope, and the R waves of the 2 patients with abnormal right axis deviation are above the 150 per cent slope. However, the scatter of the values of patients is within the range of normal scatter. In figure 2, the augmentation for two positive T waves, one of a patient with abnormal left axis deviation, and the other of a patient with abnormal right axis deviation, fall below the 150 per cent slope. In the VL leads, the values of the patients were within the normal scatter (not included in figs. 1–3). The QS waves of the right arm lead (fig. 3), representing mostly right ventricular cavity potentials, and the R wave in the left leg lead (fig. 1), mostly representing left ventricular epicardial potentials, show about the same general trend, and the same is true also for the R and S waves of the left arm lead (not included in figs. 1–3). Thus, it is our impression that trend and scatter are largely independent of QRS axis and the direction of deflections. This is of interest since the potential of the left ventricle (R wave as major deflection) might be recorded in the VF or VL lead, de-
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pending on the position of the heart. The S wave was the major deflection in the VL or aVL leads in all cases with a QRS axis exceeding 64 degrees, and in the VF or aVF leads in all cases with a QRS axis less than 39 degrees. Since the augmentation does not depend on the direction of the potential, it seemed to be justifiable to take the major QRS deflection in any given lead, whether R or S wave, as the basis for statistical evaluation. Small amplitudes involve a comparatively large error of measurement, which has been recently demonstrated in a quantitative way, and the error in calculating percentages of augmentation with small amplitudes is so great that we discarded all amplitudes lower than 1 standardized mm. (= 0.1 mv) in the Wilson leads or 1.5 mm. in the Goldberger leads.

Fig. 1.—Amplitude of R S deflection in V (abscissa: positive right, negative left) versus aVF (ordinata: positive up, negative down). The right upper quadrant shows the R wave; the left lower quadrant shows the S wave. The solid line corresponds to an augmentation factor for aVF = 150 per cent of V. The individual QRS axis is indicated by symbols.

\[
\begin{align*}
\text{QRS AXIS} & \geq +10 & \text{V}_{F} \\
\text{QRS AXIS} & = -9^\circ \text{ to } +10^\circ & \text{aV}_{F} \\
\text{QRS AXIS} & = +11^\circ \text{ to } +25^\circ & \\
\text{QRS AXIS} & = -26^\circ \text{ to } +45^\circ & \\
\text{QRS AXIS} & = +46^\circ \text{ to } +70^\circ & \\
\text{QRS AXIS} & = +71^\circ \text{ to } +90^\circ & \\
\text{QRS AXIS} & > +90^\circ & \\
\end{align*}
\]
While figures 1–3 show that the slope agrees roughly with the predicted augmentation of 150 per cent, the validity of the aV leads as a clinical method must be determined by analysis of interindividual variability. Clinical electrocardiography is concerned with individual patients and not with groups.

Table 1 shows the means, interindividual variability of the augmentation expressed as standard deviation (S.D.), the expected normal range for 90 per cent population (calculated from the S.D.), and the number of values. In the QRS deflections the number of available values (those exceeding 1 mm. in the Wilson leads) equals or approaches 26 (the total number of subjects), while it is substantially smaller for the T wave in Leads V_L and V_F.

In agreement with the impression gained from figures 1–3, the mean is fairly close to 150, except for Lead V_F (aV_F) in which there were
Fig. 3.—Amplitude of QS deflection in $V_R$ (abscissa) versus $aV_R$ (ordinate). The solid line corresponds to an augmentation factor of $aVF = 150$ per cent of $V_F$. The individual QRS axis is indicated by symbols.

TABLE 1.—Augmentation of Amplitudes in the Goldberger Leads (aV) Expressed as a Percentage of the Wilson Leads

<table>
<thead>
<tr>
<th></th>
<th>$\frac{aV_R}{V_R} \times 100$</th>
<th>$\frac{aV_L}{V_L} \times 100$</th>
<th>$\frac{aV_F}{V_F} \times 100$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>QRS T</td>
<td>QRS T</td>
<td>QRS T</td>
</tr>
<tr>
<td>Mean</td>
<td>156 147</td>
<td>165 157</td>
<td>184 187</td>
</tr>
<tr>
<td>S.D.±</td>
<td>29.8 48.3</td>
<td>41.4 39.0</td>
<td>77.0 62.7</td>
</tr>
<tr>
<td>Expected upper limit†</td>
<td>205 220</td>
<td>233 221</td>
<td>311 290</td>
</tr>
<tr>
<td>Expected lower limit‡</td>
<td>107 100‡</td>
<td>100‡ 100‡</td>
<td>100‡ 100‡</td>
</tr>
<tr>
<td>Number of values</td>
<td>26 24</td>
<td>22 13</td>
<td>25 15</td>
</tr>
</tbody>
</table>

* The QRS or T deflection is compared in the same unipolar limb lead. Means and standard deviations for twenty-six subjects.
† The expected range refers to 90 per cent of the population.
‡ The lower limit of 100 is assumed where, according to the variability, the aV leads may show a smaller amplitude than the V leads.
means of 184 and 187 per cent, respectively, for the QRS complex and the T wave.

The variability, expressed by the standard deviation (S.D.) is very large. A predicted range was calculated for the accepted limit of statistical significance of \( P = \pm 5 \) per cent, which indicates the variability limits for 90 per cent of the population. A lower limit of 100 (equality of amplitude in the V and aV leads) was assumed when a lower value would have been obtained on the basis of the statistical calculation. It is not probable that the aV leads would show a smaller amplitude than the V leads; it must be assumed that the distribution curve is asymmetrical to the left.

Table 2.—Comparison of Augmentation with the Goldberger Leads (aV) in the Three Unipolar Limb Leads in the Same Subjects*

<table>
<thead>
<tr>
<th>Largest QRS Deflection</th>
<th>T wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>aVR ( \times 100 )</td>
<td>aVR ( \times 100 )</td>
</tr>
<tr>
<td>VR ( V_L )</td>
<td>VR ( V_F )</td>
</tr>
<tr>
<td>Mean</td>
<td>98</td>
</tr>
<tr>
<td>S.D.±</td>
<td>26.5</td>
</tr>
<tr>
<td>Number of values</td>
<td>25</td>
</tr>
<tr>
<td>Expected upper limit†</td>
<td>142</td>
</tr>
<tr>
<td>Expected lower limit†</td>
<td>54</td>
</tr>
</tbody>
</table>

* Expressed as the ratio between leads on a percentage basis. A value of 100 would mean identical augmentation in the two leads compared.
† The expected range refers to 90 per cent of the population.

The expected range extends from 100 to 200 per cent augmentation or more. In other words, the augmentation obtained with the aV leads in any individual may lie anywhere between no augmentation at all and twofold or even threefold augmentation. In the remaining 10 per cent of the population the expected range would even be greater. This tremendous variability is not explained by or correlated with the mean amplitude of deflections; this means, indirectly, that it is not due to the error of measurement. The mean amplitude of the QRS deflections in VR, VL, and VF was 4.3, 3.3, and 4.8 mm., respectively, and even larger in the aV leads. This is a magnitude which can be measured with reasonable accuracy. The mean amplitude of the T waves is much smaller (1.5, 1.2, and 1.3 for VR, VL, and VF, respectively), but in the left arm and left leg leads the S.D. of the augmentation of the T waves is the same as or even somewhat smaller than the S.D. of the QRS complex.

Another criterion for the use of Goldberger's method is the consistency of the augmentation between the various leads. This is expressed as the ratio of augmentation between two (aV) leads, again compared on a percentage basis. Equal augmentation between two leads would be indicated by a percentage of 100.

Table 2 shows that the mean percentage is close to 100, but the variability (S.D.) is as large as the interindividual variability of the augmentation in any single lead (table 1).

In any single individual (in 90 per cent of the population), the ratios of the augmentation between the various leads may vary from 0.2 to 1.8. In other words, the relative augmentation in the different limb leads is completely erratic.

In our first series the leads were taken in the following sequence: VR, aVR; VL, aVL; VF, aVF. This might exaggerate the scatter of the augmentation ratio if there was spontaneous variability of electrocardiographic potentials within the short intervals between two successive leads. This seemed improbable, but it could not be excluded without test. In a former study it was observed that considerable day-to-day variability of several electrocardiographic items was observed. Ideally, the V and aV leads should have been recorded simultaneously. Since this is
technically impossible, the repeat variability of the RS wave in the $V_F$ and $aVF_F$ leads was studied in the second series in the following sequence: $V_F, aVF_F, V_F, aVF_F$. The time intervals between the first and second $V_F$ (or $aVF_F$) lead corresponded closely to the time interval between the $V$ and $aV$ leads in our original procedure.

Twenty-two normal subjects were used for this second series (13 men and 9 women); ten of them had also served as subjects in the first series (Tables 1 and 2). The largest deflection (R or S) was taken as the basis for the calculation; this exceeded 1 mm. in the $V_F$ leads and 1.5 mm. in the $aVF_F$ leads in all 22 subjects. The average amplitude of the RS deflection in the first $V_F$ sample was 3.8 millimeters. The mean value of $RS$ in the second recording of the $V_F$ lead, expressed as a percentage of the first record, was 100.6, with a standard deviation of ±5.8; the second recording of the $aVF_F$ lead averaged 98.9 per cent of the value in the first record of $aVF_F$, with a standard deviation of ±2.6. The variability is small and corresponds roughly to the magnitude of the error of linear measurement of the record. This means that the variability of the augmentation in the $aVF_F$ leads cannot be explained by spontaneous physiologic variability of the amplitude in the time interval between two leads or by intrainstrumental variability.

We chose the $V_F$ leads for this second comparison for two reasons: The standard deviation was higher than in the other leads (table 1), and the mean augmentation (184 per cent of the RS deflection and 187 per cent for the T wave) was substantially higher than Goldberger’s predicted augmentation of 150 per cent. The additional series gave the opportunity to check this result.

In this second series the mean augmentation of the RS deflection in the $aVF_F$ lead was 193 per cent with a standard deviation of ±57.1. The results are in good agreement with those shown in table 1. In order to test the statistical significance of the difference between actual and predicted augmentations, the F test was used for the total of 39 different subjects of both groups. For each subject only one determination was used. The mean difference between actual and predicted augmentation was +34.5 per cent (of $V_F$) practically identical with the value in table 1. The F value was 15.2, that is, above the level of 0.1 per cent chance probability. The difference between actual and predicted augmentation ratio in the $aVF_F$ leads is statistically highly significant.

Comparison of the $aV$ leads with and without the 5,000-ohm resistance in ten subjects showed close agreement in the majority but occasionally larger differences were observed. Out of twenty-nine pairs of comparisons of the QRS complex for the three unipolar limb leads (the deflection in one subject in $V_L$ was less than 1 mm. and was omitted for this reason), the agreement was within 10 per cent in eighteen, between 10 and 20 per cent in seven; the deviation exceeded 20 per cent in four comparisons. This distribution agrees fairly well with the recent observations of Bryant and associates.9

In 15 subjects, the $V_k$ and $aV_k$ leads were taken with the Cambridge Electrocardiograph (string galvanometer). The results obtained for the QS deflection (mean augmentation 157 per cent with a standard deviation of ±24.9) were very similar to those obtained with the Viso-Cardiette (156 per cent ±29.8, see table 1). This result agrees also with Rappaport and Williams’10 conclusions that the unipolar limb leads will be accurately recorded by a string galvanometer if the contact resistances at the right arm, left arm, left leg, and exploring electrode do not exceed approximately 9,000 ohms. The variability of the augmentation ratio was about the same with and without the resistance.

**DISCUSSION**

The results show such a degree of interindividual variability of the augmentation factor in the $aV$ leads, both in single leads and between leads, that Goldberger’s method appears to be unsuitable for any purpose in which comparison with the Wilson leads is to be made or implied. Clearly, standards obtained with the Wilson leads are not applicable to the Goldberger leads and vice versa, and these leads are not interchangeable.
The predicted range of variability in the augmentation applies, in a strict sense, to a population similar to that represented by our sample. There is no reason to expect essentially different results by enlarging the number of our experimental group, but the variability might be different in another group differently composed. Our group was rather homogeneous compared to the material in average hospitals. Since it is reasonable to expect an even greater variability in more heterogeneous groups, our data and estimates of the variability in augmentation in the Goldberger leads as compared with the Wilson leads are, if anything, conservative.

It is of interest to consider the possible reason for the discrepancy between the Wilson and the Goldberger leads. Since, according to Einthoven's theory, the algebraic sum of the potentials of all three limb leads should be zero, Goldberger\textsuperscript{2-4} suggested that advantage be taken of the fact that the potential in any limb lead should equal the (negative) sum of the potentials of the two other leads. Thus, left arm (LA) potential + left leg (LL) potential = right arm (RA) potential, and a similar relationship would hold for any other lead. The result would be, as Goldberger claims, that it should be possible to obtain a potential, augmented by 50 per cent, without distortion.

The present results show, however, that this expectation is not realized for individuals for any one of the unipolar limb leads and for the leg lead even the mean of a group of normal individuals does not conform to the simple theory. But the theoretical basis for both Wilson's and Goldberger's methods is the same. Obviously, there must be erroneous assumptions in the basic theory. Goldberger\textsuperscript{4} clearly indicated these assumptions but did not offer any real proof of their validity. The crux of the theory is the assumption that the algebraic sum of the true absolute potentials for the recording positions on the three limbs is equal to zero. But if the potential at the V terminal is not actually zero, then Goldberger's calculation as to the augmentation obtained by his arrangement is invalid. Wilson and his collaborators\textsuperscript{11} referred to the work of Eickey and Fröhlich\textsuperscript{12} and of Burger\textsuperscript{13} as showing that the departures from zero of the terminal (three lead) "do not ordinarily exceed 0.3 millivolt." However, Wolferth and Livezey\textsuperscript{14} have criticized the validity of the procedure used by Eickey and Fröhlich and the most that one may say is that the resultant absolute potential at the V terminal is probably rather small in most cases. It should be pointed out, however, that a potential of 0.3 millivolt would be by no means negligible in view of the magnitude of the deflections in the unipolar limb leads.

Substantial arguments have been made for\textsuperscript{12, 13, 15} and against\textsuperscript{16, 17, 18} the validity of the Einthoven triangle theory. The situation seems to be that the Einthoven triangle theory is a useful approximation but that it cannot be applied with absolute rigor. It is necessary also to consider the variability of the skin resistance, as recently discussed by Rappaport and Williams.\textsuperscript{10}

Consideration of the utility and meaning of so-called unipolar leads is impaired by such loose or misleading statements as "unipolar extremity leads are more accurate than the standard leads,"\textsuperscript{14, p. 56} and that Goldberger's two-lead terminal is an "indifferent electrode of zero potential."\textsuperscript{74, p. 28} It is true, for example, that $V_R$, or $aV_R$, is a more accurate estimate of the absolute potential at the right arm than could be obtained from the standard Leads I and II but, conversely, Lead I is a more accurate estimate of the difference between right and left arms than is gained from $V_R$, $aV_R$, $V_L$, or $aV_L$. And it can hardly be maintained that the Goldberger two-lead terminal is actually "indifferent" or has truly a "zero potential." Elsewhere,\textsuperscript{19, p. 273} Goldberger admits the possibility that his "indifferent electrode" may not have a zero potential but goes on to argue that "the algebraic sum of the records obtained from the three extremities will equal zero." We have already noted the absence of experimental support for this statement.

It cannot be denied that there are important advantages in any system in which potentials are recorded so that they reflect primarily a single point of placement of the electrode rather than the difference between two points which may vary independently in potential.
We should, therefore, commend both Wilson's and Goldberger's procedures and should hope to see the older bipolar leads discarded eventually. But as between Wilson's and Goldberger's leads we see little theoretic basis for choice. In Goldberger's papers as well as in much of the present discussion the Wilson leads were used as the criterion for evaluating the Goldberger leads. The reason is mainly historical and stems from the fact that Wilson's leads have preceded those of Goldberger in time.

In view of our results it is surprising that Goldberger attempted to use his method as a means of proving the validity of Einthoven's theory. He determined the greatest maximum and minimum deflections on the body surface with reference to the right arm. For this purpose, a wandering electrode was placed successively on a total of eleven points. The two points with the maximum positive and negative potentials were considered to represent a true indifferent electrode, and comparison was then made with Goldberger's aV leads. Goldberger claimed that these two methods yielded substantially identical results in 10 subjects, but offered only two examples of the electrocardiograms in lieu of numerical data. Unfortunately, the quality of the illustrations is very poor, but there appear to be several discrepancies between the records obtained with the two different electrodes.

More complete information of the results in the 8 other subjects would have been desirable. Goldberger argues that such "constancy" could not be a chance phenomenon, and therefore proves the validity of Einthoven's theory. He actually did not test whether the "agreement" is a coincidence or not. There are valid procedures to do so; for instance, other points with positive and negative potentials could be pooled as "indifferent" electrodes and compared on a quantitative basis.

Our results have no immediate bearing on the clinical usefulness of Goldberger's method. Normal standards could be developed for Wilson's or Goldberger's method, and results obtained on clinical material could be interpreted on the basis of such standards. But, as we have pointed out, standards for the V leads cannot be used for the aV leads. The clinical usefulness of either method can be decided only on the basis of large clinical experience. For the present, there is, in our opinion, no definite evidence for the superiority of the V or the aV leads. However, an agreement is desirable as to whether the V leads or the aV leads should be used. It would be confusing to have two similar, but not identical, procedures in use.

This laboratory is engaged in a long-range study on cardiovascular degeneration involving the periodical investigation of about 400 normal subjects. We wanted to utilize this material for normal standards of the unipolar limb leads. The present study was mainly undertaken in order to arrive, for our own case, at a decision whether the V leads or the aV leads should be used. We have chosen the V leads because the only advantage of the aV leads is the larger amplitude, which can be as well obtained by a standardization of 15 mm. = 1 millivolt.

**Summary**

In 20 normal men and in 6 patients with abnormal axis deviation, the amplitudes of the QRS complex and the T wave in the three unipolar limb leads were taken with Goldberger's two-lead and Wilson's three-lead terminal. The mean augmentation obtained with Goldberger's method agrees fairly well with the predicted 150 per cent of the Wilson leads, except in Lead aVF, where the mean is 184 (QRS complex) or 187 per cent (T wave). The high augmentation rate in aVF was confirmed in another group of 22 subjects and was found to be highly significant.

The individual variability is so large that in 90 per cent of the population the augmentation...
may range from zero to two or even three times. The variability of the augmentation between the three unipolar limb leads in an average individual is about as large as the interindividual variability in any of the unipolar leads. The individual variability of the augmentation of aVR was about the same when taken with the Viso-Cardiette or the Cambridge string galvanometer. The results show that Wilson’s three-lead terminal and Goldberger’s two-lead terminal are not interchangeable, and that standards obtained with one method are not applicable to the other method. The results have some bearing on the degree of validity of Einthoven’s triangle hypothesis.

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