Analysis of the Normal and Abnormal Vectorcardiogram in Its Own Reference Frame

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In common vectorcardiographic practice, vector loops are recorded in three plane projections that are perpendicular to one another (frontal, sagittal, and horizontal planes). The arbitrary choice of these planes has been derived from body axes rather than from the spatial orientation of the vectorcardiogram or the heart itself. Several investigators have or the cardiogram place the orientation of the subjects form the plane. Investigators have reported in 1936 the subjects form the plane. The investigators have reported in 1936 the subjects form the plane. Schellong reported in 1936 that spatial QRS loops of normal subjects form almost a perfect plane, the "QRS plane." A reference frame based on the "QRS plane" becomes independent of variability in QRS direction because any QRS shift or rotation will always lead to a concomitant shift of the reference system. The spatial orientation of such a reference frame can be completely described by one term, an axis perpendicular to the QRS plane. Burger and Vaane introduced the term "polar vector" for this axis. The orientation of the QRS plane represents the spatial equivalent of Einthoven’s manifest QRS axis of the frontal plane whose diagnostic significance is well documented.

Several investigators reported that in normal subjects QRS loops viewed in the QRS plane are more uniform in configuration than in conventional plane projections. Consequently, it can be expected that analysis of abnormalities, both in direction and configuration, could be improved through comparison with such a relatively uniform normal standard.

Normal ranges for the spatial orientation of QRS loops and their configuration have been reported by several authors. Only a relatively small number of abnormal records have been published, however, mainly for illustrative purposes. Milnor proposed criteria for the analysis of VCG abnormalities based on QRS plane projections but no systematic studies of VCG abnormalities in such a reference system have been reported. In the present study an attempt was made, therefore, to evaluate statistically the diagnostic usefulness of various VCG parameters derived from a reference frame which was based on the QRS plane. Records from 295 patients with a variety of electrocardiographic (ECG) abnormalities were compared with normal standards obtained from a group of 249 "normal" subjects. A VCG lead resolver of the Schmitt-type was used for spatial rotation of QRS loops into their reference frame.

Materials and Methods

The age distribution of the "normal" control group of 249 cases is shown in table 1. These patients were admitted to the Veterans Administration Hospital, Mt. Alto, for reasons other than heart disease. They had complete physical examinations, 12-lead electrocardiograms, and chest x-rays, which were considered normal. All cases admitted for diseases that might secondarily affect the cardiovascular system such as hyperthyroidism, chronic lung disease, diabetes mellitus, etc., were excluded from the control group.

The 295 abnormal cases were chosen on the basis of their VCG and ECG diagnosis by normal standards published previously. Cases with myo-

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cardiac infarctions and hypertrophies were selected only when supportive historical or clinical evidence for the diagnosis existed. The distribution of the ECG diagnoses is given in table 2.

Orthogonal ECG records of 47 per cent of both the normal and abnormal group were taken with Schmitt's SVEC III lead system. For the remainder of the cases, Frank's lead system was used. As previously reported two lead systems have essentially identical performance characteristics. In order to obtain an additional evaluation of their conformity, results obtained by each lead system were compared with those of the other. Data were pooled only when no significant differences were encountered.

All tracings were recorded first on magnetic tape using FM channels as previously reported. The over-all frequency response of the recording system was flat from 0.1 to 1,250 cps. The playback mechanism of the tape recorder was used for the reproduction and display of the vector loops on an oscilloscope screen. A lead resolver of the Schmitt-type was available for spatial rotations of the vectocardiograms. Loop projections onto any desired plane can so be obtained. The reference frame for the spherical coordinates of the lead resolver is shown in figure 1. Azimuth and elevation angles indicate the "viewpoints" used to observe the vectocardiogram.

The following procedure was used to rotate the QRS loop into the QRS plane (fig. 2). Starting from the frontal plane projection the loop was rotated with the azimuth dial until an "edgewise" view of the loop was obtained. The search for this view was limited to 90° rotation in leftward or rightward direction, i.e., the search was not extended beyond the left or right sagittal plane projections. Consequently, the azimuth dial was rotated by 90° to the left. This leads to the most open projection of QRS obtainable without operation of the elevation dial. This latter dial was then rotated until a second "edgewise" projection of QRS was obtained. This projection is typically a nearly horizontal line as shown in figure 2. The horizontal position is important because the following procedure is based on this position. The last step consisted in a rotation of the elevation dial by 90°, which results in the most open view of the QRS loop. The direction of rotation for this last step was always such that a counter-clockwise rotation of QRS in its open or "broadside" projection was obtained. The "viewpoint" for this projection can then be read directly from the dials in terms of azimuth and elevation angles. The axis connecting this "viewpoint" and the point of origin of QRS is perpendicular to the QRS plane (fig. 2). Its direction is identical with the "polar vector" as described by Burger and Vaan.

Figure 3 shows the measurements that were analyzed in edgewise and broadside QRS loop projections. The selection of parameters was based to a large extent on Milnor's suggestions. The choice was also guided by considerations of simplicity in order to arrive at a practical method of analysis. The measurements were the following.

1. Direction of polar vectors (perpendicular to the QRS plane as indicator for the spatial orientation of QRS).

2. Ratios between major and minor axes of edgewise projections. These ratios indicate the degree of planarity of the QRS loop.

3. Ratios between major and minor axes in broadside QRS projections in order to evaluate the configuration of the open projection. A "half-area" axis was used as major QRS axis, obtained by planimetric division of the loop as described previously.

4. Number and duration of QRS loop deformities in broadside projections. These deformities represent indentations into the smooth outline of

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*The fourth intercostal space was used for Frank's lead system as recommended for the supine position. The original description of this lead system was given for sitting or standing subjects where the fifth intercostal space is more correct.

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Figure 1

Spherical coordinates used for the determination of polar vector directions. In this and the following figures a "polar projection" of a globe has been used in order to obtain a two-dimensional display. The cephalad pole, indicating the head of the patient, is shown in the center with an elevation angle of $-90^\circ$. The opposite pole is not represented by a point but by the outer circle of the diagram with an elevation angle of $+90^\circ$. The "equator" of the globe is indicated by the heavy line with $0^\circ$ elevation. Azimuth angles are shown in the periphery with their respective body directions. Note that this two-dimensional display leads to a disproportionate spread of the caudal half of the globe.

5. The QRS-T angle in broadside projections. A tangent to the loop from the beginning to the end of the deformity was drawn as shown in figure 3. The duration of the indentation can then be determined by counting the time markings (400 per second) from beginning to end. The smallest deformities measurable by this method have a duration of 5 msec., indicating frequency components of up to 200 cps.

Results

Polar Vectors

The directions of polar vectors were plotted on the surface of a globe. Figure 4 shows their distribution for the series of normals for both the 116 cases recorded with Schmitt's SVEC III system and the 133 cases with Frank's lead system. In this and the following illustrations a polar projection of the globe has available from records of scalar orthogonal leads. The study was, therefore, limited to those measurements that can be obtained only through spatial rotation of QRS loops.

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Procedure for obtaining "edgewise" and "broadside" QRS loop projections by means of a lead resolver of the Schmitt-type. Scalar orthogonal leads are shown in the upper left corner. Positive polarity of these leads was chosen in leftward, downward, and posterior direction. Loop number 1 represents the frontal plane projection, which was used as basis for spatial loop rotations. The "viewpoints" for the projections 2 to 5 are shown on the polar projection of the globe, which corresponds to the reference frame in figure 1 (left lower corner). For the method used for rotations see text. Projections 4 and 5 represent the edgewise and broadside projections used for measurements. The direction of the polar vector is indicated on the polar projection of the globe by point 5. Leads a, b, and c on the right are scalar components of edgewise and broadside projections. In order to obtain the former the amplitude of lead a has to be minimized. Lead b indicates the longitudinal and lead c the left-to-right scalar component of the broadside projection.

been used in order to arrive at a complete display of the globe's surface in two dimensions. The mean direction of normal polar vectors for the SVEC III system in terms of azimuth and elevation angles was $182 \pm 23^\circ$ and $-45 \pm 15^\circ$, respectively. For Frank's lead system these angles were $198 \pm 30^\circ$ and $-50 \pm 13^\circ$. Data from both systems did not show a Gaussian distribution of polar vector directions. A normal range was obtained, therefore, by encircling 96 per cent of each sample on the surface of the globe (fig. 4). Four per cent of the cases with the largest distance from the center of the distribution were not included. Such a range is comparable to that obtained from a mean result plus-minus two standard deviations when a Gaussian distribution is present.

As shown in figure 4 the normal ranges of the two different corrected lead systems are almost identical. Their largest discrepancy at one point was $8^\circ$. This difference was only
Figure 3

Schematic representation of the measurements taken in "edgewise" and "broadside" projections of QRS loops. The main axis of the edgewise projection with the length \( c \) was drawn through the two most distant points of the QRS loop. Parallel to \( c \), a second axis through point \( E \) is shown. This latter point divides QRS portions to the left (a) and right (b) of the observer. The maximal transverse diameter of QRS is indicated by \( f \). Diameter \( e \) shows the distance between the main axis \( c \) and the most distant point from this axis on the QRS loop. A measure of the distance between the two parallel QRS axes is given by \( d \). Besides the ratios \( c/d \) and \( c/f \) as indicators of QRS planarity, the ratio \( b/a \) was used for analysis. In the broadside projection the main axis of QRS was obtained by planimetric division of the loop. Thus, the area of quadrants I plus II equals that of II plus IV. The following ratios based on measurements indicated on the diagram were used for analysis: (1) Length/width; (2) Right/left; (3) DE/EP. The QRS-T angle was measured between the maximal T vector and an axis through point \( E \), perpendicular to the main QRS axis. Angular deviations of \( T \) from this axis were called positive when clockwise and negative when counterclockwise.
slightly in excess of the variations in polar vector directions observed during quiet breathing. This latter variation was found to be ± 3° around a midposition. Since the normal ranges of both lead systems did not differ appreciably, records were considered abnormal in polar vector direction only when they were found outside both of these ranges.

The two lead systems did not differ significantly in the number of pathologic cases with abnormal polar vector directions. The results from the pathologic series could be pooled, therefore, without introducing a noticeable error.

The group of 134 cases with old myocardial infarctions showed, with 75 per cent, the highest proportion of abnormal polar vectors. As shown in figure 5, a wide scatter of directions was found that was not appreciably decreased when the cases were separated according to locations of infarctions.

The cases with right ventricular hypertrophy showed a greater tendency for clustering in polar vector direction. Their mean direction deviated from normal in an inferior and posterior direction as shown in figure 6. Of the 27 cases in this group, 67 per cent fell outside the normal range.

Separation between cases with left ventricular hypertrophy and normals was consider-
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Figure 5

Distribution of polar vector directions for cases with old myocardial infarctions. The wide spread of findings could not be reduced substantially when cases were separated according to locations of infarctions. The majority of polar vectors in the normal range were obtained, however, from records interpreted as showing postero-diaphragmatic lesions.

ably poorer. Only 40 per cent of the total of 67 cases showed abnormal polar vector directions. The majority (classified as type I) was grouped in the upper half of the normal range. A smaller group of cases (type II) deviated markedly from these, however. Their polar vector directions were found mostly below the 'equator' (fig. 7). The two types of records could be easily separated through their different QRS configuration in the horizontal plane projection. The larger group with cephalad polar vector directions (type I) showed a wide open view in this plane, whereas the smaller group (type II) displayed narrow or figure-eight configurations.

No significant difference in QRS duration was found between the two groups. All patients with tracings classified as type II had slight to marked cardiomegaly on x-ray. Of the cases with records of type I, 24 per cent did not show cardiac enlargement. The remaining 76 per cent, however, did not differ significantly in heart size from those of type II. Differentiation of cases on the basis of systolic and diastolic overload did not appear possible, therefore.

Sixty-six per cent of a total of 32 cases with right ventricular conduction defects showed abnormal polar vector directions. The majority of these pointed anteriorly. Only six cases
deviated from normal in posterior direction. These did not differ significantly from the majority in QRS duration.

In the series of 36 cases with left ventricular conduction defects 71 per cent showed abnormal polar vector directions. Most of these pointed inferiorly but no definite grouping could be recognized.

The over-all percentage of abnormal polar vector directions of the total group of 296 pathologic cases was 65.

**Edgewise Projections**

As shown in figure 3, the following measurements were evaluated in this projection: (1) c/d ratio; (2) c/f ratio; (3) b/a ratio. None of the distributions of findings from normals was of the Gaussian type. Therefore, limits of normal were derived from 96 per cent of the normal sample in the same fashion as described for the polar vector. The results are given in table 3.

Both ratios c/d and c/f are indicators of the planarity of QRS loops. In the case of a perfect plane these ratios would be infinity. In a small number of normal cases the magnitude of the minor axis of the QRS plane was immeasurable and one end of the normal range had to be taken as infinity, therefore. The ratio c/d was found to have a considerably smaller normal range than c/f. Except for a negligible difference in cases with left ventricular conduction defects the c/d ratio led to a better differentiation between normal and abnormal (table 3). This separation was

*Figure 6*

Distribution of polar vector directions for cases with right ventricular hypertrophy. The main tendency for deviation from normal appears to be in posterior and inferior direction.
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Table 3

<table>
<thead>
<tr>
<th>Broadside Projections</th>
<th>QRS-T angle</th>
<th>Length/Width</th>
<th>Right/Left</th>
<th>Broadsided projection</th>
<th>Normal Limits for Different Pathologic Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVH</td>
<td>77.0°−33.0°</td>
<td>0.8−2.1</td>
<td>Right</td>
<td>DE/EP</td>
<td>Normal range</td>
</tr>
<tr>
<td>LVCD</td>
<td>3.0−∞</td>
<td>0.3−3.3</td>
<td>Left</td>
<td>DE/EP</td>
<td>Normal range</td>
</tr>
<tr>
<td>RVC</td>
<td>7.4−∞</td>
<td>3.8−∞</td>
<td>Both</td>
<td>DE/EP</td>
<td>Normal range</td>
</tr>
</tbody>
</table>

The number of cases is indicated in percent. For details of measurements see figure 3 and text. LVH, left ventricular hypertrophy; RVC, right ventricular conduction defects.

The limits of normal in this projection were obtained in the same fashion as described for the edgewise projections. The results are given in table 3. Both types of ventricular conduction defects deviated significantly from normal in this projection. The length/width and right/left ratios were the best indicators for abnormalities. Cases with myocardial infarctions, however, deviated from normal only with a small percentage.

The QRS-T angle was found abnormal in a large percentage of the pathologic groups (table 3).

Deformations of the otherwise smooth outline of QRS loops in broadside projections were found in 55 per cent of all normal cases. Compared with pathologic cases these deformities were relatively short, with a mean duration of 12 ± 5 msec. The upper limit of normal was taken as 22 msec. (mean plus 2 standard deviations). In the majority of normal records not more than one deformity was found. Only 10 per cent of the cases showed two deformities and more than two were not found in any normal tracing. Rec-
Distribution of polar vector directions for cases with left ventricular hypertrophy. The majority of these cases did not deviate from the normal range. There is a cluster of polar vectors, however, in the cephalad portion of this range. Polar vectors with positive elevation angles were found in cases with left ventricular hypertrophy of type II, as described in the text.

Discussion

The diagnostic usefulness of the QRS axis in the frontal plane has been recognized since its first description by Einthoven. A spatial counterpart of this axis, however, has found only limited attention in the past, in spite of widespread use of vectorcardiographic methods. Maximal QRS vectors, which have been used most frequently as indicator for spatial orientation, yield frequently unsatisfactory results because they are not necessarily identical in different plane projections. The polar vector introduced by Burger and Vaane, defines the spatial QRS
orientation more accurately as one single term. By means of a VCG lead resolver its determination was found simple and not time-consuming. For a trained ECG technician it takes 2 minutes or less to perform the necessary spatial rotations of the vectorcardiogram. Polar vectors and principal QRS planes can be used as basis for a VCG reference frame which is independent of interindividual variations in spatial QRS orientation. Thus, extraneous factors such as body build, which may influence the spatial orientation, are eliminated in the analysis of QRS configuration and relatively uniform standards are obtained.

Milnor had proposed several years ago a classification system for normal and abnormal vectorcardiograms in their own reference frame. No systemic statistical evaluation of the various diagnostic criteria has been reported, however. As pointed out by Simonson the primary goal in the evaluation of new diagnostic procedures must always be the separation between normal and abnormal. Descriptions of specific abnormalities have been reported too frequently without proper statistical evaluation of the quality of such diagnostic criteria. In the present report, emphasis was put, therefore, primarily on the statistical recognition rate for abnormalities. Thus, parameters that lead to a good separation between normal and abnormal records can be defined and recommended. Criteria that discriminate poorly may not justify further application. Owing to the relatively small number of cases in some of the pathologic categories, no attempt was made to arrive at precise statistical ranges for specific abnormalities. From the results, it became obvious, however, which parameters are best for the recognition of different pathologic entities.
Milnor's classification system\(^4\) was selected because of its simplicity and relative ease of application. Several modifications and extensions were introduced in order to test additional measurements for diagnostic usefulness.

The polar vector direction as an indicator of spatial QRS orientation was found abnormal in 192 of 296 abnormal records (65 per cent). The best discrimination was obtained in the series with old myocardial infarctions. Analysis of the missed cases with normal polar vector directions showed that with one exception these records had been interpreted as posterodiaphragmatic infarctions. The diagnosis had been based on abnormalities of initial QRS vectors. These changes, however, did not lead to a significant shift of the QRS plane, and the polar vector direction remained normal. The recognition rate for all other types of infarction was close to 100 per cent.

The lowest percentage of abnormal polar vector directions was found in the series with left ventricular hypertrophy (40 per cent). Analysis of the missed cases showed that the initial diagnosis had been based on voltage criteria and T and ST changes. Cases with left ventricular hypertrophy of type II (as described above) had abnormal polar vectors, however. This type may represent a more advanced form of hypertrophy or dilatation because in three cases with progressive cardiac disease a transition from type I to type II could be observed over periods from 3 months to 2 years.

Measurements derived from edgewise projections of the QRS loop did not lead to recognition of large percentages of abnormalities. The best parameter of this projection appeared to be the ratio between right and left portions of the principal axis of QRS (b/a of fig. 3). Ratios indicating the planarity of QRS (c/d and c/f of fig. 3) proved to be of relatively poor diagnostic quality. This finding is in disagreement with reports by Rijlant.\(^7\)–\(^8\) In a group of young normal students, that author found a ratio between maximal and minimal axes of edgewise projections of 10 or more. Similar measurements in the present study resulted in a considerably lower limit of normal (7.4 and 3.8 for the ratios c/d and c/f respectively). Since the normal range of the present study was obtained from subjects between the ages of 20 and 73, a comparison of QRS planarity between different age groups was performed. Of a total of 47 subjects below the age of 30, 26 or 55 per cent fell outside the normal range reported by Rijlant. No significant difference between different age groups could be observed. It appears to us that the discrepancy in findings results from differences in lead strength between Rijlant's lead system and those used in the present study (Schnitt and Frank). When the strength of the vertical lead Y is compared to leads X and Z in Rijlant's illustrations,\(^7\)–\(^8\) the former appears disproportionately large. This leads to an elongation of QRS loops in the direction of lead Y with a concomitant increase in the ratio between major and minor axes of these narrow loops.

The different measurements performed in broadside projections showed a recognition rate for abnormalities varying from 2 to 44 per cent. The ratio \(DE/EP\), indicating the relationship between the maximal amplitude of QRS quadrants I and IV, on the one hand, and II and III on the other, was found abnormal in a relatively large number of cases with right ventricular hypertrophy and right ventricular conduction defects. This was due to large terminal QRS components in opposite direction to the main axis. For all other abnormalities, the measurements in the broadside projection proved of relatively little value.

Analysis of QRS deformations in broadside projections yielded the best recognition rates for cases with intraventricular conduction defects. Since these cases are more easily defined by their prolonged QRS duration, it remains doubtful whether these measurements contribute to diagnostic accuracy. They appeared of value, however, in some of the cases with posterodiaphragmatic infarctions where the polar vector had remained normal and in some cases with ventricular hypertrophies.
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Determination of the QRS-T angle in broadside projections improved the diagnostic recognition rate, mainly in the groups with ventricular hypertrophies.

A more conclusive evaluation of the different analytic parameters was compiled in table 5. Percentages of abnormal measurements were calculated for all cases that could not be recognized as abnormal by means of any other parameter. This evaluation indicates that most pathologic records were identified through more than one abnormal finding. This is particularly striking in the group with old myocardial infarctions. Only the polar vector direction seemed to improve the diagnostic accuracy appreciably. Although many of the other measurements were found abnormal, they contributed relatively little to the over-all recognition rate. Determination of the polar vector direction in cases with right ventricular hypertrophy appears to be of greatest significance because 41 per cent of these cases would have been missed without this measurement. Its diagnostic significance in this category has been noted previously by Cohen et al. Tortuosity of QRS loops or the degree of planarity improved diagnostic accuracy so little that it appears questionable whether this measurement should be pursued. By a combination of measurements in the broadside projection together with the polar vector direction, a high recognition of ECG abnormalities is obtained. The QRS-T angle contributed greatly to diagnostic accuracy in cases with ventricular hypertrophies.

The recognition rates for abnormalities can also be evaluated by comparison with more familiar measurements used in clinical electrocardiography. Weisbart and Simonson used normal standards for the evaluation of Q waves in leads II, III, and aVp that are comparable to ours (mean ± 2 standard deviations). Those authors found that in less than 50 per cent of their cases with posterior wall infarctions the duration of Q in lead aVp was outside normal limits. Related items of leads II and III, including amplitude measurements, did not improve the diagnostic accuracy appreciably. It appears, therefore, that determination of polar vectors compares favorably with such items commonly used in clinical electrocardiography. Although many of the other parameters tested in the present study were found abnormal in significant numbers of cases, only a few contributed significantly to diagnostic accuracy.

The similarity in performance between Schmitt’s SVEC III and Frank’s lead system, previously noted in this laboratory and by others, could be confirmed again in this study. Although the mean direction of normal polar vectors differed spatially by 14°, the limits of normal showed a maximal discrepancy of only 8°. Since no Gaussian distribution of polar vector directions was found, the comparison of mean results is of relatively little significance. A far more important finding was the lack of any appreciable difference in the discrimination between normal and abnormal. Although the performance of these two corrected orthogonal lead systems is not identical in a strictly mathematical sense, it appears that for clinical and statistical purposes they are interchangeable.

Summary

Vectorcardiograms from 296 patients with a variety of ECG abnormalities were compared with normal standards obtained from 249 subjects without evidence of heart disease. A reference frame based on the spatial orientation of QRS loops rather than on conventional plane projections was used. Burger’s polar vector and Schellong’s QRS plane form the main parameters of such a reference frame. Spatial QRS orientation is defined by one term, the polar vector, which is perpendicular to the QRS plane. The direction of this vector can be determined through rotation of the QRS loop into its principal plane by means of a VCG lead resolver. Further analysis of QRS in its principal plane then becomes independent of inter-individual variability in spatial QRS direction. Separation between normal and abnormal was used as an indicator for the diagnostic quality of various measurements. Two
corrected orthogonal lead systems designed by Schmitt and Frank were used for the study. These systems did not differ appreciably in the extent of normal ranges nor in the discrimination between normal and abnormal.

The polar vector appeared as the best indicator for abnormalities. In 65 per cent of the pathologic cases this parameter was found outside normal limits. Measurements derived from the contour and principal axes of QRS planes improved the recognition rate for abnormalities. Ratios expressing the degree of QRS planarity, however, contributed little to diagnostic accuracy. The QRS-T angle obtained in the QRS plane improved the recognition rate mainly in the series with ventricular hypertrophies. It could be demonstrated that without evaluation of time and voltage criteria between 85 and 100 per cent of all pathologic records could be recognized as abnormal when the vectorcardiograms were analyzed in their own reference frame. Thus, it appeared that this method of analysis has a considerable diagnostic potential and compares favorably with those used more commonly in clinical electrocardiography and vectorcardiography.

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