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STRUCTURE AND FUNCTION

Evaluation of ECG Criteria for Left Ventricular Hypertrophy Before and After Aortic Valve Replacement Using Magnetic Resonance Imaging

Hugo P. Beyerbacht,[1] Jeroen J. Bax,[1,*] Hildo J. Lamb,[2] Arnoud van der Laarse,[1] Hubert W. Vliegen,[1] Albert de Roos,[2] Aeilko H. Zwinderman,[3] and Ernst E. van der Wall[1]

[1]Department of Cardiology, [2]Department of Radiology, and [3]Department of Medical Statistics, Leiden University Medical Centre, Leiden, The Netherlands

ABSTRACT

Purpose. Evaluation of different electrocardiographic criteria for left ventricular hypertrophy (ECG–LVH criteria) using left ventricular mass index (LVMI) determined by magnetic resonance imaging (MRI). In addition, the relation between LVMI regression after aortic valve replacement and corresponding ECG changes regarding LVH was studied. *Methods*. A group of 31 patients with severe aortic valve disease was studied to assess the presence of ECG–LVH and to measure LVMI and LV end-diastolic volume index (LVEDVI); 13 patients were restudied at 9.8 ± 2.7 months after aortic valve replacement. *Results*. Three criteria had a sensitivity of 100% ($SV_1 + RV_5$ or $RV_6 > 3.0$ mV; SV_1 or $SV_2 + RV_5 \geq 3.5$ mV; SV_1 or $SV_2 + RV_5$ or $RV_6 > 3.5$ mV), at the cost of specificity (50%, 44.4% and 44.4%, respectively). The R in $I > 1.4$ mV had a specificity of 100%, at the cost of both sensitivity and accuracy (13.6% and 54.5%, respectively). The Romhilt-Estes point score system, using ≥4 points as cut-off value for LVH, provided the overall best accuracy of 79.5%. The number of Romhilt-Estes points also showed the best correlation with LVMI, both before and after aortic valve replacement ($r = 0.81$ and $r = 0.67$, respectively). *Conclusions*. Substantial differences in sensitivity, specificity, accuracy, and correlation with LVMI were found among several ECG–LVH criteria. No single criterion performed optimally since the highest sensitivity, specificity, accuracy, and correlation with LVMI were found with different criteria. The present study may therefore contribute to a more targeted use of the existing ECG–LVH criteria.

Key Words: Electrocardiogram; Magnetic resonance imaging; Left ventricular hypertrophy; Aortic valve replacement.

*Correspondence: Jeroen J. Bax, Dept. of Cardiology, Leiden University Medical Center, Albinusdreef 2, 2333 ZA Leiden, The Netherlands; Fax: +31-71-5266809; E-mail: jbax@knoware.nl.

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INTRODUCTION

Left ventricular hypertrophy (LVH) is a well-known risk factor for cardiovascular morbidity and mortality (Kannel, 1983; 1991; Koren et al., 1991; Levy et al., 1990a). Detection of LVH is important since treatment of its cause may result in LVH regression and improve prognosis (Devereux et al., 1996; Kahn et al., 1996; Levy et al., 1994; Muiesan et al., 1995). In patients with aortic regurgitation, electrocardiographically diagnosed LVH and the presence of a "strain" repolarization pattern (Devereux and Reichek, 1982; Huwez et al., 1992; Pringle et al., 1989) is associated with depressed left ventricular (LV) function (Roman et al., 1987; Scognamiglio et al., 1988). Regression of electrocardiographic signs of LVH (ECG–LVH) also reduces the cardiovascular event risk and improves prognosis (Kahn et al., 1996; Levy et al., 1994). However, the definition of ECG–LVH is ill defined since many different ECG–LVH criteria have been reported in the literature (Braunwald, 2001; Casale et al., 1985; Chou, 1991; Dijkstra et al., 2000; Norman and Levy, 1995; Romhilt and Estes, 1968; Sokolow and Lyon, 1949; Wayne Alexander et al., 1997). Until now, there is no consensus about which criteria should be used in daily practice (Dijkstra et al., 2000). In general, most ECG–LVH criteria lack sensitivity, ranging from 11 to 56% (Chou, 1991; Levy et al., 1990b; Reichek and Devereux, 1981; Woythaler et al., 1983). The specificity, however, is usually quite high, with values reported up to 97% (Chou, 1991; Levy et al., 1990b; Reichek and Devereux, 1981; Woythaler et al., 1983). Most ECG–LVH studies rely on M-mode or 2D echocardiography as reference standard for measurement of LV mass. Recent studies have demonstrated that magnetic resonance imaging (MRI) is a more accurate and reproducible tool to quantify LV mass, particularly in distorted left ventricles, because no geometric assumptions are made (Shapiro, 1994). MRI should therefore be considered the present reference standard for noninvasive quantification of LV mass and dimensions (Allison et al., 1993; Bottini et al., 1995; Collins et al., 1989; Friedman et al., 1985; Gardin, 1999; Germain et al., 1992; Missouris et al., 1996; Shapiro, 1994).

The purpose of the present study was to assess the sensitivity, specificity, and accuracy of several well-established and less well-known ECG–LVH criteria, using MRI as reference standard for measurement of left ventricular mass index (LVMI). Furthermore, the correlation between LV weight and size [LVMI and left ventricular end-diastolic index (LVEDVI)] and each ECG–LVH criterion was determined. Finally, we studied the correlation between changes of LVMI and LVEDVI due to aortic valve replacement, and concomitant ECG changes, to evaluate which ECG–LVH criterion performs best in monitoring LVH regression.

METHODS

Patient Population

The patient population consisted of 31 patients (23 men, eight women) with severe aortic valve disease [20 aortic valve stenosis (measured invasively, peak-to-peak gradients), 11 aortic regurgitation] who were studied with a standard 12-lead ECG and by MRI. A subgroup of 13 patients (10 men, 3 women; 10 aortic valve stenosis, 3 aortic regurgitation) was restudied at 9.7 ± 2.8 months after aortic valve replacement. The patient characteristics are summarized in Table 1. At baseline there were no statistically significant differences between the group of 31 patients and the subgroup of 13 patients with follow-up. The research protocol was approved by the hospital's Human Research Committee. All subjects gave informed consent prior to investigation.

ECG–LVH Criteria

Several cardiology text books and ECG text books were used to select 22 well-known and less well-known ECG–LVH criteria (Braunwald, 2001; Casale et al., 1985; Chou, 1991; Dijkstra et al., 2000; Norman and Levy, 1995; Romhilt and Estes, 1968; Sokolow and Lyon, 1949; Wayne Alexander et al., 1997). Although many other ECG–LVH criteria exist, the selection used in the present study contains most of the criteria used in recent studies and daily practice (Dijkstra et al., 2000). The ECG–LVH criteria tested in the present study are listed in Table 2. All electrocardiograms were manually evaluated by two experienced cardiologists.

Assessment of the Left Ventricle by MRI

MRI was performed on a 1.5 Tesla ACS-NT15 system (Philips Medical Systems; Best, The Netherlands) using prospective electrocardiographic gating. The imaging protocol was similar as reported previously (Lamb et al., 1996). Briefly, a stack of short-axis images consisting of 10–12 slices with a thickness of 8 mm and an intersection gap of 1–2 mm (depending on heart size) were acquired using breath hold multi-shot echo planar

Table 1. Patient characteristics.

	All patients pre AVR (n = 31)	With follow-up pre AVR (n = 13)	With follow-up post AVR (n = 13)
Age (years)	61.9 (10.7)	57.9 (12.7)	58.8 (12.5)
Systolic BP (mmHg)	121.4 (25.6)	123.6 (22.2)	126.4 (13.2)
Diastolic BP (mmHg)	67.6 (9.9)	66.4 (6.3)	72.2 (8.2)[a]
Aortic valve gradient (mmHg)	61.8 (32.6)	61.5 (34.0)	N.D.
Aortic regurgitation grade	1.9 (1.5)	2.0 (1.5)	N.D.
MR characteristics			
LVMI (g/m^2) all	129.7 (34.2)	126.3 (26.4)	92.8 (27.2)[a]
LVMI (g/m^2) men	139.4 (32.9) (n = 23)	134.7 (22.1) (n = 10)	101.4 (25.1)[a]
LVMI (g/m^2) women	101.8 (20.0) (n = 8)	98.3 (21.3) (n = 3)	63.9 (1.0)
LVEDVI (ml/m^2) all	100.5 (35.4)	103.2 (35.6)	76.3 (15.7)[a]
LVEDVI (ml/m^2) men	108.3 (37.6) (n = 23)	110.3 (37.6) (n = 10)	79.2 (16.4)[a]
LVEDVI (ml/m^2) women	78.1 (12.5) (n = 8)	79.5 (12.7) (n = 3)	66.8 (9.8)
LVMI/LVEDVI (g/ml)	1.34 (0.25)	1.28 (0.22)	1.21 (0.20)

AVR: aortic valve replacement; ND: not done; BP: blood pressure; LVMI: left ventricular mass index; LVEDVI: left ventricular end-diastolic volume index.
[a] $p < 0.01$ (paired two-tailed Student's t-test, pre AVR vs. post AVR).

Table 2. ECG–LVH criteria.

Romhilt-Estes point score system (≥4 points; ≥5 points), Romhilt and Estes (1968)
$SV_1 + RV_5$ or $RV_6 > 3.5$ mV (Sokolow-Lyon voltage), Sokolow and Lyon (1949)
$SV_1 + RV5$ or $RV_6 > 3.0$ mV
SV_1 or $SV_2 + RV_5 \geq 3.5$ mV
SV_1 or $SV_2 + RV_5$ or $RV_6 > 3.5$ mV
$SV_1 + RV_5 > 3.0$ mV
$SV_2 + RV_5 > 3.5$ mV
$SV_2 + RV_4$ or $RV_5 > 3.5$ mV
$RaVL + SV_3 > 2.8$ mV (male) > 2.0 mV (female) (Cornell voltage), Norman and Levy (1995)
$R_{max} + S_{max} > 4.0$ mV (sum of tallest R and tallest S in $V_{1-6} > 4.0$ mV)
$R_{max} + S_{max} > 4.5$ mV (sum of tallest R and tallest S in $V_{1-6} > 4.5$ mV)
$RS_{max} > 3.5$ mV (sum of R and S from tallest RS in $V_{1-6} > 3.5$ mV)
Total QRS deflection > 17.5 mV (sum of all QRS voltages in 12 leads > 17.5 mV)
RV_5 or $RV_6 > 2.6$ mV
$RV_5 > 2.6$ mV
$RV_6 > 2.0$ mV
RI > 1.4 mV
RI + SIII > 2.5 mV (Gubner-Ungerleider voltage)
(RI − RIII) + (SIII − SI) ≥ +17 (Lewis voltage)
RaVL > 7.5 mV
RaVL > 1.1 mV
"Strain pattern" (≥1 mV ST depression and asymmetric T-wave inversion)

imaging. Images encompassed the entire left ventricle. Normal values for LVMI, LVEDVI, and the cut-off point for LVH in the present study were based on an MRI study in healthy adults by Lorenz et al. (1999). In the present study LVMI values above the reported upper limit of the 95% confidence interval ($> 113\ g/m^2$ for males and $> 95\ g/m^2$ for females) were considered to represent LVH (Lorenz et al., 1999). The normal values for LVEDVI were $69 \pm 11\ ml/m^2$ (95% confidence interval: $47–92\ ml/m^2$) for males and $61 \pm 10\ ml/m^2$ (95% confidence interval: $41–81\ ml/m^2$) for females (Lorenz et al., 1999).

Statistical Methods

Quality assessment of the different ECG–LVH criteria was performed by measurement of the sensitivity, specificity, and accuracy of each criterion for detection of LVH as diagnosed with MRI. Additionally, the correlation between ECG–LVH criteria and LVMI and LVEDVI was determined using all 44 patient-MRI studies (31 before aortic valve replacement, 13 after aortic valve replacement) and the corresponding electrocardiograms. The accuracy was assessed by calculating the percentage of correct diagnoses: "LVH" or "no LVH" for each ECG–LVH criterion, using the patient-MRI studies as gold standard.

At follow-up, the correlation between ECG changes and changes in LVMI and LVEDVI due to aortic valve

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replacement was determined from 26 patient-MRI studies (13 before aortic valve replacement, 13 after aortic valve replacement) and the corresponding electrocardiograms. Paired two-tailed Student's t-tests were used to compare pre- and postoperative data. Correlations were determined using linear regression analysis. A probability (p) value of less than 0.05 was considered statistically significant.

RESULTS

ECG–LVH Criteria Before Aortic Valve Replacement

The sensitivity, specificity, and accuracy of the different ECG–LVH criteria before aortic valve replacement are displayed in ranked order in Table 3A–C. There were four criteria with a sensitivity $\geq 90\%$: $SV_1 + RV_5$ or $RV_6 > 3.0$ mV; SV_1 or $SV_2 + RV_5 \geq 3.5$ mV; SV_1 or $SV_2 + RV_5$ or $RV_6 > 3.5$ mV and $SV_1 + RV_5 > 3.0$ mV. There were four criteria with a specificity $\geq 90\%$: RI > 1.4 mV; the Romhilt-Estes point score ≥ 5 points; RI + SIII > 2.5 mV, and RaVL > 1.1 mV. Finally there were four criteria with an accuracy $\geq 75\%$: Romhilt-Estes point score ≥ 4 points; $SV_1 + RV_5$ or $RV_6 > 3.5$ mV; $SV_1 + RV_5$ or $RV_6 > 3.0$ mV, and SV_1 or $SV_2 + RV_5 \geq 3.5$ mV.

The tested ECG–LVH criteria differed widely as to sensitivity, specificity, and accuracy for LVH detection. As can be seen in Table 3A–C, some of these differences resulted from different cut-off values for LVH, like the Romhilt-Estes point score (≥ 4 points: probable LVH and ≥ 5 points: definite LVH) and $SV_1 + RV_5$ or $RV_6 > 3.5$ mV (Sokolow-Lyon) compared to $SV_1 + RV_5$ or $RV_6 > 3.0$ mV. The Romhilt-Estes point score, using ≥ 4 points as cut-off value, provided the overall best accuracy of 79.5%, compared with 70.5% if a cut-off value for LVH of ≥ 5 points was used. If ≥ 4 points was used as a cut-off value for LVH, the sensitivity and specificity were 77.3% and 77.8% respectively, compared with 45.5% and 94.4% respectively, using a cut-off value ≥ 5 points.

The correlation between different ECG–LVH criteria and LV weight and size is displayed in Table 4. There were four ECG–LVH criteria with a correlation with LVMI ≥ 0.7 : Romhilt-Estes point score; $SV_1 + RV_5$; $SV_1 + RV_5$ or RV_6, and SV_1 or $SV_2 + RV_5$. Three ECG–LVH criteria had a correlation with LVEDVI ≥ 0.7: SV_1 or $SV_2 + RV_5$ or RV_6; $SV_1 + RV_5$ or RV_6, and RaVL + SV_3. Most ECG–LVH criteria correlated about equally well with LVMI and LVEDVI.

ECG–LVH Criteria After Aortic Valve Replacement

At follow-up, the electrocardiograms had changed markedly and showed lower voltages in most leads. For example the combined deflection of $R_{max} + S_{max}$ of each patient, before and after aortic valve replacement, is shown in Fig. 1A. Left ventricular mass index and LVEDVI also decreased significantly in the group with follow-up (Table 1). The individual changes in LVMI after aortic valve replacement are shown in Fig. 1B. The LVMI decreased markedly in 12 out of 13 patients. The changes in LVMI after aortic valve replacement correlated well with the corresponding changes in several, but not all, ECG–LVH criteria (Table 5). Of all criteria, the changes in number of points according to the Romhilt-Estes point score system showed the best correlation with ΔLVMI ($r = 0.67$, $P < 0.05$; Table 5). Other criteria, like the R wave in lead I and the R wave in aVL, showed a poor correlation between ECG changes after aortic valve replacement and ΔLVMI ($r = -0.02$, and $r = -0.11$, respectively). Some ECG–LVH criteria like RI + SIII showed a poor correlation between ΔECG and ΔLVMI ($r = -0.17$) but a much better correlation between ΔECG and ΔLVEDVI ($r = 0.65$, $p < 0.05$; Table 5).

DISCUSSION

The aim of the present study was to assess the value of different ECG–LVH criteria by comparing their sensitivity, specificity, and accuracy in detecting LVH, using MRI as reference standard for measurement of LVMI. A second objective was to assess the correlation between ECG–LVH and both LVMI and LVEDVI. Finally, we wanted to assess the correlation between ECG changes following aortic valve replacement and corresponding changes in LVMI and LVEDVI.

Sensitivity and Specificity of ECG–LVH Criteria

In general, ECG–LVH criteria with a high sensitivity lacked high specificity and vice versa. The ECG–LVH criteria based on extremity leads generally showed a higher specificity and poorer sensitivity compared with ECG–LVH criteria based on chest leads. Moreover, the present study shows that ECG–LVH criteria with a high sensitivity are more accurate and correlate better with LVMI than ECG–LVH criteria with a high specificity (Tables 3A–C and 4A).

Table 3. Sensitivity, specificity, and accuracy of different ECG–LVH criteria.

3A: Sensitivity	%	3B: Specificity	%	3C: Accuracy	%
$SV_1 + RV_5$ or $RV_6 > 3.0$ mV	100.0	RI > 1.4 mV	100.0	Romhilt-Estes ≥4 points	79.5
SV_1 or $SV_2 + RV_5 \geq 3.5$ mV	100.0	Romhilt-Estes ≥ 5 points	94.4	$SV_1 + RV_5$ or $RV_6 > 3.5$ mV	77.3
SV_1 or $SV_2 + RV_5$ or $RV_6 > 3.5$ mV	100.0	RI + SIII > 2.5 mV	94.4	$SV_1 + RV_5$ or $RV_6 > 3.0$ mV	75.0
$SV_1 + RV_5 > 3.0$ mV	95.5	RaVL > 1.1 mV	94.4	SV_1 or $SV_2 + RV5 \geq 3.5$ mV	75.0
$R_{max} + S_{max} > 4.0$ mV	86.4	RaVL + SV_3 > 28 (male) > 20 (female)	88.9	$R_{max} + S_{max} > 4.0$ mV	72.7
Total QRS deflection > 17.5 mV	86.4	$RV_5 > 2.6$ mV	88.9	SV_1 or $SV_2 + RV_5$ or $RV_6 > 3.5$ mV	72.7
$SV_1 + RV_5$ or $RV_6 > 3.5$ mV	81.8	$RV_6 > 2.0$ mV	88.9	$SV_1 + RV_5 > 3.0$ mV	72.7
Romhilt-Estes ≥ 4 points	77.3	RV_5 or $RV_6 > 2.6$ mV	88.9	"Strain pattern"	72.7
$SV_2 + RV_5 > 3.5$ mV	77.3	(RI − RIII) + (SIII − SI) ≥ + 17	88.9	$R_{max} + S_{max} > 4.5$ mV	70.5
$SV_2 + RV_4$ or $RV_5 > 3.5$ mV	77.3	RaVL > 7.5 mV	83.3	Romhilt-Estes ≥ 5 points	70.5
"Strain pattern"	72.7	Romhilt-Estes ≥ 4 points	77.8	$SV_2 + RV_5 > 3.5$ mV	68.2
$R_{max} + S_{max} > 4.5$ mV	68.2	$R_{max} + S_{max} > 4.5$ mV	72.2	$RV_6 > 2.0$ mV	68.2
$RS_{max} > 3.5$ mV	59.1	$RS_{max} > 3.5$ mV	72.2	$RS_{max} > 3.5$ mV	65.9
$RV_6 > 2.0$ mV	50.0	$SV_1 + RV_5$ or $RV_6 > 3.5$ mV	72.2	Total QRS deflection > 17.5 mV	65.9
Romhilt-Estes ≥ 5 points	45.5	"Strain pattern"	66.7	$SV_2 + RV_4$ or $RV_5 > 3.5$ mV	65.9
RaVL > 7.5 mV	40.9	$R_{max} + S_{max} > 4.0$ mV	55.6	RaVL > 7.5 mV	63.6
$RV_5 > 2.6$ mV	31.8	$SV_2 + RV_5 > 3.5$ mV	55.6	(RI − RIII) + (SIII − SI) ≥ + 17	61.4
RV_5 or $RV_6 > 2.6$ mV	31.8	$SV_1 + RV_5$ or $RV_6 > 3.0$ mV	50.0	RaVL + SV_3 > 28 (male) > 20 (female)	59.1
(RI − RIII) + (SIII − SI) ≥ + 17	31.8	$SV_1 + RV_5 > 3.0$ mV	50.0	$RV_5 > 2.6$ mV	59.1
RaVL + SV_3 > 28 (male) > 20 (female)	27.3	$SV_2 + RV_4$ or $RV_5 > 3.5$ mV	50.0	RV_5 or $RV_6 > 2.6$ mV	59.1
RaVL > 1.1 mV	22.7	SV_1 or $SV_2 + RV_5 \geq 3.5$ mV	44.4	RI + SIII > 2.5 mV	59.1
RI + SIII > 2.5 mV	18.2	SV_1 or $SV_2 + RV_5$ or $RV_6 > 3.5$ mV	44.4	RaVL > 1.1 mV	56.8
RI > 1.4 mV	13.6	Total QRS deflection > 17.5 mV	33.3	RI > 1.4 mV	54.5

The cut-off point for LVH within the same ECG criterion also strongly influences sensitivity, specificity, and accuracy. In case of the Romhilt-Estes point score system, only 45% of the patients with MRI-LVH reached the cut-off value of ≥5 points, which is necessary for the diagnosis definite LVH, whereas 77% of the patients with MRI-LVH reached the cut-off value of ≥4 points, indicating that the cut-off value of ≥5 points is rather strict and therefore produces a larger number of false-negative results.

Accuracy of ECG–LVH Criteria

Accuracy might be considered the most useful parameter to assess the quality of an ECG–LVH parameter since it represents the percentage of correct diagnoses ("LVH" and "no LVH") and contains information about false-positive as well as false-negative results. Some well-known ECG–LVH criteria, like the Romhilt-Estes point score (≥4 points: "probable LVH") and $SV_1 + RV_5$ or $RV_6 > 3.5$ mV (Sokolow-Lyon) had a good accuracy. However, the accuracy of several ECG–LVH criteria is rather poor, largely due to the low sensitivity of these criteria. Since for some ECG–LVH criteria the accuracy barely exceeds the 50% a priori chance of choosing correctly between LVH or no LVH, the practical use of these criteria is at least questionable.

Correlation with LVMI and LVEDVI

The present study also demonstrated that most ECG–LVH criteria correlated similarly well with LVMI

Table 4. Correlation between ECG–LVH criteria and LVMI and LVEDVI.

4A: Correlation with LVMI	r	4B: Correlation with LVEDVI	r
Romhilt-Estes point score	0.79[a]	SV_1 or $SV_2 + RV_5$ or RV_6	0.70[a]
$SV_1 + RV_5$	0.72[a]	$SV_1 + RV_5$ or RV_6	0.70[a]
$SV_1 + RV_5$ or RV_6	0.71[a]	RaVL + SV_3	0.70[a]
SV_1 or $SV_2 + RV_5$	0.70[a]	Total QRS deflection	0.69[a]
SV_1 or $SV_2 + RV_5$ or RV_6	0.69[a]	SV_1 or $SV_2 + RV_5$	0.69[a]
Total QRS deflection	0.69[a]	Romhilt-Estes point score	0.68[a]
$R_{max} + S_{max}$	0.68[a]	$SV_1 + RV_5$	0.68[a]
$SV_2 + RV_5$	0.66[a]	$R_{max} + S_{max}$	0.66[a]
$SV_2 + RV_4$ or RV_5	0.63[a]	$SV_2 + RV_5$	0.64[a]
RaVL + SV_3	0.62[a]	$SV_2 + RV_4$ or RV_5	0.59[a]
RV_5	0.59[a]	RV_6	0.58[a]
RV_5 or RV_6	0.59[a]	RV_5 or RV_6	0.56[a]
"Strain pattern"	0.56[a]	RV_5	0.51[a]
RS_{max}	0.54[a]	RI	0.50[a]
RV_6	0.53[a]	RS_{max}	0.49[a]
RI	0.41[b]	RI + SIII	0.48[b]
RI + SIII	0.36[b]	RaVL	0.43[b]
RaVL	0.34[b]	"Strain pattern"	0.41[b]
(RI − RIII) + (SIII − SI)	0.28	(RI − RIII) + (SIII − SI)	0.40[b]

[a]$p < 0.001$; [b]$p < 0.05$.

and LVEDVI, suggesting that LV wall mass and LV cavity size are both responsible for the ECG characteristics typical for "LVH" (Tables 4 and 5). Several ECG–LVH criteria correlated well with LVMI, whereas other criteria showed a better correlation with LVEDVI, indicating that some criteria are expected to perform well in patients with increased LV wall thickness, while other criteria may perform better in patients with a dilated left ventricle.

Correlation with LVMI and LVEDVI After Aortic Valve Replacement

Since other techniques such as 2D echocardiography and MRI are far more sensitive and accurate instruments to determine LV mass, and since the day-to-day variability of ECG voltages is high, the ECG has not been used to a great extent to quantify LVH regression following treatment (Allison et al., 1993; Bottini et al., 1995; Collins et al., 1989; Farb et al., 1990; Friedman et al., 1985; Gardin, 1999; Germain et al., 1992; Lamb et al., 1996; Lorenz et al., 1999; de Vries et al., 1996; Zhou et al., 1993). Most studies related to this subject have been performed before echocardiography became widely available, and describe ECG changes following treatment of hypertension (Helmcke et al., 1957). However, from a theoretical point of view, we found it interesting to investigate whether ECG changes after aortic valve replacement correlated significantly to the observed changes in LVMI and LVEDVI.

After aortic valve replacement the deflection in most ECG leads decreased, reflected by a substantial ΔECG–LVH for most ECG–LVH criteria. The LVMI and LVEDVI also decreased markedly in most patients, and LVMI became normal in all but one patient according to the cut-off values for men and women reported by Lorenz et al. (1999). However, the correlations between ΔECG–LVH and ΔLVMI or ΔLVEDVI differed widely among the tested ECG–LVH criteria (Table 5). Some ECG–LVH criteria correlated well with LVMI before aortic valve replacement, but performed less well after aortic valve replacement. For example, $SV_1 + RV_5$, before aortic valve replacement correlated well with LVMI ($r = 0.72$), whereas after aortic valve replacement the correlation of $\Delta SV_1 + RV_5$ with ΔLVMI was only 0.38. A possible explanation for this finding is that muscular LVH regression proceeds at a different speed as ECG normalization. Another explanation is the small amount of subjects with follow-up. However, other criteria like the Romhilt-Estes point score system (before aortic valve replacement $r = 0.79$; after aortic valve replacement $r = 0.67$) and $SV_2 + RV_4$ or RV_5 (before aortic valve replacement $r = 0.63$; after aortic valve replacement $r = 0.65$) correlated well with LVMI both before and

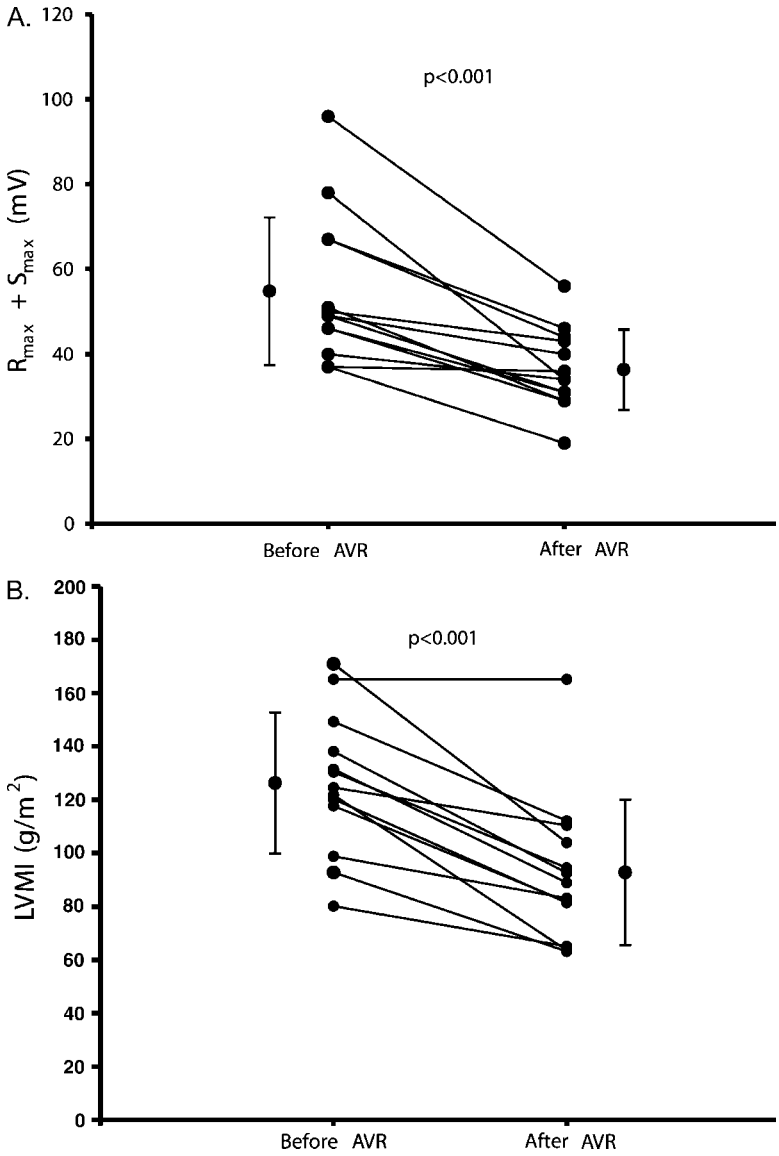

Figure 1. A. Graphic representation of the sum of tallest R wave and tallest S wave in V_{1-6} ($R_{max} + S_{max}$) before and after aortic valve replacement (AVR). Note the consistent and significant decrease of the $R_{max} + S_{max}$ deflection in all patients. B. Graphic representation of the changes in left ventricular mass index (LVMI) after aortic valve replacement (AVR).

after aortic valve replacement, indicating that these criteria could particularly be useful when the ECG is used to monitor LVH regression (Table 4A and 5A). Confirmation of these findings in a larger group of subjects is needed.

The correlation between ΔECG–LVH and ΔLVEDVI was quite good in RI + SIII and in (RI − RIII) + (SIII − SI) ($r = 0.65$ and $r = 0.62$, respectively), whereas before surgery other ECG–LVH criteria like SV1 + RV5 or RV6 ($r = 0.70$) correlated better with LVEDVI. An unexpected finding was that ECG–LVH criteria that correlated well with LVEDVI before aortic valve replacement differ from the ECG–LVH criteria that correlated well with LVEDVI after surgery. The relevance of investigating the correlation between ECG–LVH and LVEDVI was demonstrated by Badano et al., who found a relation among ECG strain pattern, increased LVEDV, and impaired systolic function in patients with aortic regurgitation (Badano et al., 1994). Furthermore, in patients with coronary artery disease,

Table 5. Correlation between ECG changes and changes in LVMI and LVEDVI.

5A: Correlation with ΔLVMI	r	5B: Correlation with ΔLVEDVI	r
Romhilt-Estes point score	0.67[a]	RI + SIII	0.65[a]
$SV_2 + RV_4$ or RV_5	0.65[a]	(RI − RIII) + (SIII − SI)	0.62[a]
RS_{max}	0.63[a]	RI	0.41
$R_{max} + S_{max}$	0.60[a]	RV_6	0.40
$SV_2 + RV_5$	0.58[a]	RaVL	0.38
RV_5 or RV_6	0.57[b]	RaVL + SV_3	0.37
Total QRS deflection	0.55[b]	Total QRS deflection	0.23
SV_1 or $SV_2 + RV_5$	0.51	SV_1 or $SV_2 + RV_5$ or RV_6	0.20
SV_1 or $SV_2 + RV_5$ or RV_6	0.49	$SV_1 + RV_5$ or RV_6	0.11
RV_5	0.46	SV_1 or $SV_2 + RV_5$	0.09
"Strain pattern"	0.44	$SV_2 + RV_5$	−0.01
$SV_1 + RV_5$ or RV_6	0.39	$SV_1 + RV_5$	−0.03
$SV_1 + RV_5$	0.38	$R_{max} + S_{max}$	−0.03
RaVL + SV_3	0.34	SV2 $SV_2 + RV_4$ or RV_5	−0.06
RV_6	0.32	RS_{max}	−0.08
RI	−0.02	Romhilt-Estes point score	−0.10
RaVL	−0.11	"Strain pattern"	−0.12
RI + SIII	−0.17	RV_5 or RV_6	−0.16
(RI − RIII) + (SIII − SI)	−0.23	RV_5	−0.40

[a]$p < 0.05$; [b]$p = 0.05$.

Heupler et al. demonstrated a stronger correlation between ischemia and LVEDV than between ischemia and LV wall thickness (Heupler et al., 1997).

The Optimal Criterion for ECG–LVH

An internationally accepted consensus for the use of ECG–LVH criteria is difficult to reach, since there is no criterion that is optimal for each patient or population. The definition of good-quality and poor-quality ECG–LVH criteria is partly based on the objective of the investigator and the characteristics of the study population. For example, when screening a population for the presence of LVH, good sensitivity is more important than high specificity or accuracy. However, when deciding on medical treatment of LVH, specificity and accuracy may be more important, thus implying the use of other ECG–LVH criteria in both cases, since high sensitivity, high specificity, and high accuracy are found with different criteria. Since the introduction of echocardiography and MRI, ECG–LVH has gradually moved towards functioning as a screening instrument for LVH, which makes good sensitivity more important than excellent specificity. Furthermore, it must be stated that the population in the present study represents a special group, as prior to aortic valve replacement most patients had moderate or severe LVH. Other ECG–LVH studies focused on patients with hypertension, usually with only modest LVH (de Vries et al., 1996; Zhou et al., 1993). Criteria that lack sensitivity will perform poorly if patients have modest LVH only. This may explain the finding that an ECG–LVH criterion that performed well in the present study, such as the Romhilt-Estes point score system, performed less well in other studies (Reichek and Devereux, 1981; de Vries et al., 1996).

The finding that changes in calculated value of several ECG–LVH criteria significantly correlated with ΔLVMI may result from the relatively large decrease in LVMI after aortic valve replacement, as compared to the more modest changes in LVMI following treatment of patients with hypertension (de Vries et al., 1996; Zhou et al., 1993).

Limitations

Changes in whole body impedance (after thoracotomy) may have influenced the ECG pattern, and may have potentially influenced results. The current study focused on the evaluation of LVH in patients with aortic

valve disease, and extrapolation of the results to other patient groups is difficult.

CONCLUSIONS

In patients with moderate to severe LVH due to aortic valve disease, a large number of ECG criteria for LVH showed substantial differences in sensitivity, specificity, accuracy, and correlation with LVMI. Most ECG–LVH criteria correlated about equally well with LVEDVI, suggesting that LV volume and mass both contribute to the ECG characteristics typical for LVH. The ideal ECG–LVH criterion is not available since the highest sensitivity, specificity, accuracy, and correlation with LVMI are not found in a single criterion. The Romhilt-Estes point score system showed the highest accuracy and best correlation with LVMI, both before aortic valve replacement and following LVH regression. Therefore, the results shown in the present study may contribute to a more targeted use of the ECG–LVH criteria, depending on whether high sensitivity, specificity, accuracy, or good correlation with LVMI is desired.

REFERENCES

Allison, J. D., Flickinger, F. W., Wright, J. C., Falls, D. G. 3rd., Prisant, L. M., VonDohlen, T. W., Frank, M. J. (1993). Measurement of left ventricular mass in hypertrophic cardiomyopathy using MRI: comparison with echocardiography. *Magn. Reson. Imaging* 11:329–334.

Badano, L., Rubartelli, P., Giunta, L., Della Rovere, F., Miccoli, F., Lucatti, A. (1994). Relation between ECG strain pattern and left ventricular morphology, left ventricular function, and DPTI/SPTI ratio in patients with aortic regurgitation. *J. Electrocardiol.* 27:189–197.

Bottini, P. B., Carr, A. A., Prisant, L. M., Flickinger, F. W., Allison, J. D., Gottdiener, J. S. (1995). Magnetic resonance imaging compared to echocardiography to assess left ventricular mass in the hypertensive patient. *Am. J. Hypertens.* 8:221–228.

Braunwald, E. (2001). *Heart Disease. A Textbook of Cardiovascular Medicine*. 6th ed. Philadelphia: WB Saunders, pp. 95–98.

Casale, P. N., Devereux, R. B., Kligfeld, P., Eisenberg, R. R., Miller, D. H., Chaudhary, B. S., Phillips, M. C. (1985). Electrocardiographic detection of left ventricular hypertrophy: development and prospective validation of improved criteria. *J. Am. Coll. Cardiol.* 6:572–580.

Chou, T. C. (1991). *Electrocardiography in Clinical Practice*. 3rd ed. Philadelphia: WB Saunders, pp. 37–52.

Collins, H. W., Kronenberg, H. W., Byrd, B. F. 3rd. (1989). Reproducibility of left ventricular mass measurements by two-dimensional and M-mode echocardiography. *J. Am. Coll. Cardiol.* 14:672–676.

Devereux, R. B., Reichek, N. (1982). Repolarization abnormalities of left ventricular hypertrophy. Clinical, echocardiographic and hemodynamic correlates. *J. Electrocardiol.* 15:47–53.

Devereux, R. B., Agabiti-Rosei, E., Dahlöf, B., Gosse, P., Hahn, R. T., Okin, P. M., Roman, M. J. (1996). Regression of left ventricular hypertrophy as a surrogate end-point for morbid events in hypertension treatment trials. *J. Hypertens. Suppl.* 14:S95–S102.

Dijkstra, R. F., Mokkink, H. G., Bakx, J. C., Thien, T., van Schayck, C. P., Verheugt, F. W. (2000). Criteria for electrocardiographic left ventricular hypertrophy as applied by cardiologists. *Cardiologie* 7:317–321.

Farb, A., Devereux, R. B., Kligfield, P. (1990). Day-to-day variability of voltage measurements used in electrocardiographic criteria for left ventricular hypertrophy. *J. Am. Coll. Cardiol.* 15:618–623.

Friedman, B. J., Waters, J., Kwan, O. L., DeMaria, A. N. (1985). Comparison of magnetic resonance imaging and echocardiography in determination of cardiac dimensions in normal subjects. *J. Am. Coll. Cardiol.* 5:1369–1376.

Gardin, J. M. (1999). How reliable are serial echocardiographic measurements in detecting regression in left ventricular hypertrophy and changes in function? *J. Am. Coll. Cardiol.* 34:1633–1636.

Germain, P., Roul, G., Kastler, B., Mossard, J. M., Bareiss, P., Sacrez, A. (1992). Inter-study variability in left ventricular mass measurement. Comparison between M-mode echocardiography and MRI. *Eur. Heart J.* 13:1011–1019.

Helmcke, J. G., Schneckloth, R., Corcoran, A. C. (1957). Electrocardiographic changes of left ventricular hypertrophy: effects of antihypertensive treatment. *Am. Heart J.* 53:549.

Heupler, S., Lauer, M., Williams, M. J., Shan, K., Marwick, T. H. (1997). Increased left ventricular cavity size, not wall thickness, potentiates myocardial ischemia. *Am. Heart J.* 133:691–697.

Huwez, F. U., Pringle, S. D., Macfarlane, P. W. (1992). Variable patterns of ST-T abnormalities in patients with left ventricular hypertrophy and normal coronary arteries. *Br. Heart J.* 67:304–307.

Kahn, S., Frishman, W. H., Weissman, S., Ooi, W. L., Aronson, M. (1996). Left ventricular hypertrophy on electrocardiogram: prognostic implications from a 10-year cohort study of older subjects: a report from the Bronx Longitudinal Aging Study. *J. Am. Geriatr. Soc.* 44:524–529.

Kannel, W. B. (1983). Prevalence and natural history of electrocardiographic left ventricular hypertrophy. *Am. J. Med.* 75:4–11.

Kannel, W. B. (1991). Hypertension, hypertrophy and the occurrence of cardiovascular disease. *Am. J. Med. Sci.* 302:199–204.

Koren, M. J., Devereux, R. B., Casale, P. N., Savage, D. D., Laragh, J. H. (1991). Relation of left ventricular mass and geometry to morbidity and mortality in uncomplicated essential hypertension. *Ann. Intern. Med.* 114:345–352.

Lamb, H. J., Doornbos, J., van der Velde, E. A., Kruit, M. C., Reiber, J. H., de Roos, A. (1996). Echo planar MRI of the heart on a standard system: validation of measurements of left ventricular function and mass. *J. Comput. Assist. Tomogr.* 20:942–949.

Levy, D., Garrison, R. J., Savage, D. D., Kannel, W. B., Castelli, W. P. (1990a). Prognostic implications of echocardiographically determined left ventricular mass in the Framingham Heart Study. *N. Engl. J. Med.* 322:1561–1566.

Levy, D., Labib, S. B., Anderson, K. M., Christiansen, J. C., Kannel, W. B., Castelli, W. P. (1990b). Determinants of sensitivity and specificity of electrocardiographic criteria for left ventricular hypertrophy. *Circulation* 81:815–820.

Levy, D., Salomon, M., D'agostino, R. B., Belanger, A. J., Kannel, W. B. (1994). Prognostic implications of baseline electrocardiography features and their serial changes in subjects with left ventricular hypertrophy. *Circulation* 90:1786–1793.

Lorenz, C. H., Walker, E. S., Morgan, V. L., Klein, S. S., Graham, T. P. Jr. (1999). Normal human right and left ventricular mass, systolic function, and gender differences by cine magnetic resonance imaging. *J. Cardiovasc. Magn. Reson.* 1:7–21.

Missouris, C. G., Forbat, S. M., Singer, D. R., Markandu, N. D., Underwood, R., MacGregor, G. A. (1996). Echocardiography overestimates left ventricular mass: a comparative study with magnetic resonance imaging in patients with hypertension. *J. Hypertens.* 14:1005–1010.

Muiesan, M. L., Salvetti, M., Rizzoni, D., Castellano, M., Donato, F., Agabitti-Rosei, E. (1995). Association of change in left ventricular mass with prognosis during long-term antihypertensive treatment. *J. Hypertens.* 13:1091–1105.

Norman, J. E. Jr., Levy, D. (1995). Improved electrocardiographic detection of echocardiographic left ventricular hypertrophy: results of a correlated data base approach. *J. Am. Coll. Cardiol.* 26:1022–1029.

Pringle, S. D., Macfarlane, P. W., McKillop, J. H., Lorimer, A. R., Dunn, F. G. (1989). Pathophysiologic assessment of left ventricular hypertrophy and strain in asymptomatic patients with essential hypertension. *J. Am. Coll. Cardiol.* 13:1377–1381.

Reichek, N., Devereux, R. B. (1981). Left ventricular hypertrophy: relationship of anatomic, echocardiographic and electrocardiographic findings. *Circulation* 63:1391–1398.

Roman, M. J., Kligfield, P., Devereux, R. B., Niles, N. W., Hochreiter, C., Halle, A., Sato, N., Borer, J. S. (1987). Geometric and functional correlates of electrocardiographic repolarization and voltage abnormalities in aortic regurgitation. *J. Am. Coll. Cardiol.* 9:500–508.

Romhilt, D. W., Estes, E. H. Jr. (1968). A point-score system for the ECG diagnosis of left ventricular hypertrophy. *Am. Heart J.* 6:752–758.

Scognamiglio, R., Fasoli, G., Bruni, A., Dalla-Volta, S. (1988). Observations on the capability of the electrocardiogram to detect left ventricular function in chronic severe aortic regurgitation. *Eur. Heart J.* 9:54–60.

Shapiro, E. P. (1994). Evaluation of left ventricular hypertrophy by magnetic resonance imaging. *Am. J. Cardiac Imaging* 8:310–315.

Sokolow, M., Lyon, T. P. (1949). The ventricular complex in left ventricular hypertrophy as obtained by unipolar precordial and limb leads. *Am. Heart J.* 37:161–186.

de Vries, S. O., Heesen, W. F., Beltman, F. W., Kroese, A. H., May, J. F., Smit, A. J., Lie, K. I. (1996). Prediction of the left ventricular mass from the electrocardiogram in systemic hypertension. *Am. J. Cardiol.* 77:974–978.

Wayne Alexander, R., Schlant, R. C., Fuster, V. H. (1997). *The Heart, Arteries and Veins*. 9th ed. New York: McGraw-Hill, pp. 371–372.

Woythaler, J. N., Singer, S. L., Kwan, O. L., Meltzer, R. S., Reubner, B., Bommer, W., DeMaria, A. (1983). Accuracy of echocardiography versus electrocardiography in detecting left ventricular hypertrophy: comparison with post-mortem mass measurements. *J. Am. Coll. Cardiol.* 2:305–311.

Zhou, S. H., Rautaharju, P. M., Prineas, R., Neaton, J., Crow, R., Calhoun, H., Furberg, C., Cohen, J. (1993). Improved ECG models for estimation of left ventricular hypertrophy progression and regression incidence by redefinition of the criteria for a significant change in left ventricular hypertrophy status. The MRFIT Research Group. Multiple Risk Factor Intervention Trial. *J. Electrocardiol.* 26(Suppl.):108–113.

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