Estimating postoperative left ventricular volume: Identification of responders to surgical ventricular reconstruction

Satoru Wakasa, MD, PhD,[1] Yoshiro Matsui, MD, PhD,[1] Junjiro Kobayashi, MD, PhD,[2] Yasunori Cho, MD, PhD,[3] Hitoshi Yaku, MD, PhD,[4] Goro Matsumiya, MD, PhD,[5] Tadashi Isomura, MD, PhD,[6] Shuichiro Takanashi, MD, PhD,[7] Akihiko Usui, MD, PhD,[8] Ryuzo Sakata, MD, PhD,[9] Tatsuhiko Komiya, MD, PhD,[10] Yoshiki Sawa, MD, PhD,[11] Yoshikatsu Saiki, MD, PhD,[12] Hideyuki Shimizu, MD, PhD,[13] Atsushi Yamaguchi, MD, PhD,[14] Kimikazu Hamano, MD, PhD,[15] and Hirokuni Arai, MD, PhD[16]

[1]Department of Cardiovascular and Thoracic Surgery, Hokkaido University Graduate School of Medicine, Sapporo, Japan; [2]Department of Cardiovascular Surgery, National Cerebral and Cardiovascular Center, Suita, Japan; [3]Department of Cardiovascular Surgery, Tokai University School of Medicine, Isehara, Japan; [4]Department of Cardiovascular Surgery, Kyoto Prefectural University of Medicine, Kyoto, Japan; [5]Department of Cardiovascular Surgery, Chiba University Graduate School of Medicine, Chiba, Japan; [6]Department of Cardiovascular Surgery, Tokyo Heart Center, Tokyo, Japan; [7]Department of Cardiovascular Surgery, Sakakibara Heart Institute, Tokyo, Japan; [8]Department of Cardiac Surgery, Nagoya University Graduate School of Medicine, Nagoya, Japan; [9]Department of Cardiovascular Surgery, Kyoto University Graduate School of Medicine, Kyoto, Japan; [10]Division of Cardiovascular Surgery, Kurashiki Central Hospital, Kurashiki, Japan; [11]Department of Cardiovascular Surgery, Osaka University Graduate School of Medicine, Osaka, Japan; [12]Division of Cardiovascular Surgery, Tohoku University Graduate School of Medicine, Sendai, Japan; [13]Department of Cardiovascular Surgery, Keio University School of Medicine, Tokyo, Japan; [14]Department of Cardiovascular Surgery, Saitama Medical Center, Jichi Medical University, Saitama, Japan; [15]Department of Surgery and Clinical Science, Yamaguchi University Graduate School of Medicine, Ube, Japan, and [16]Department of Cardiovascular Surgery, Tokyo Medical and Dental University Graduate School of Medical and Dental Sciences, Tokyo, Japan

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Corresponding author:
Yoshiro Matsui, MD, PhD
Professor and Director of the Department of Cardiovascular and Thoracic Surgery,
Hokkaido University Graduate School of Medicine,

Kita-15, Nishi-7, Kita-ku, Sapporo 060-8638, Japan
Tel.: +80-11-706-6040, Fax: +81-11-706-7612, E-mail: ymatsui@med.hokudai.ac.jp

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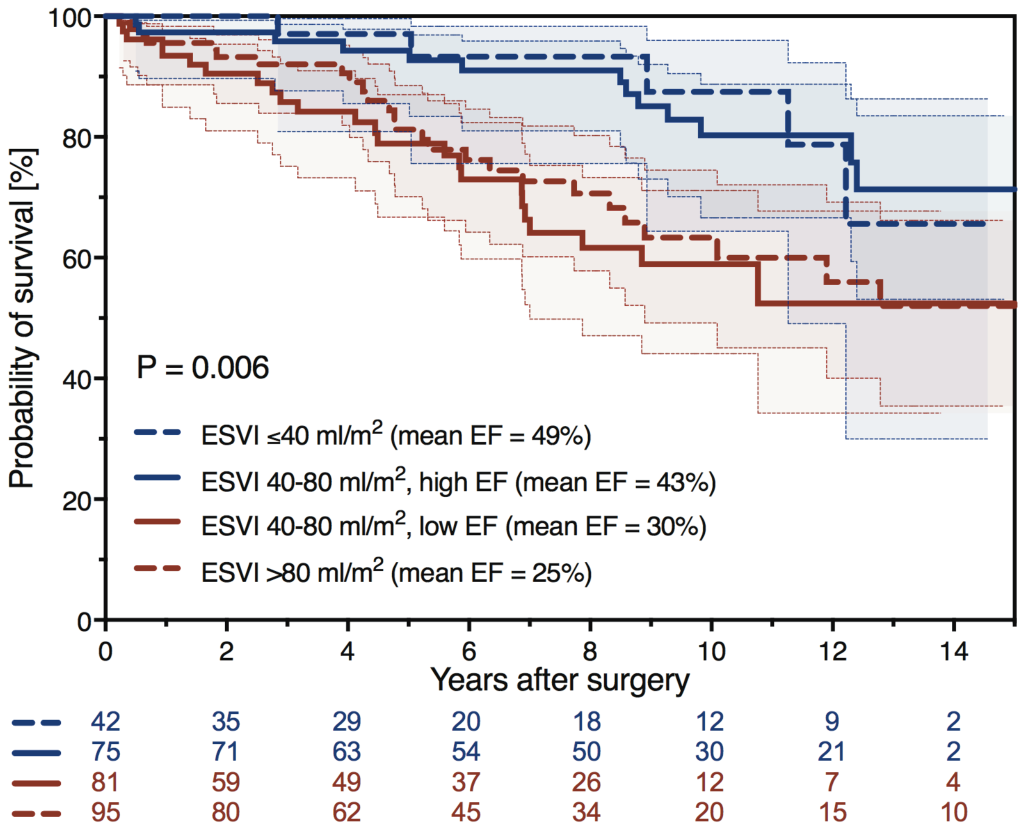
ABBREVIATIONS

CABG = coronary artery bypass grafting
EF = ejection fraction
ESVI = end-systolic volume index
HR = hazard ratio
IQR = interquartile range
LV = left ventricle
LVG = left ventriculography
MR = mitral regurgitation
MRI = magnetic resonance imaging
MV = mitral valve
NYHA = New York Heart Association
QGS = quantitative gated single photon computed emission tomography
SD = standard deviation
SVR = surgical ventricular reconstruction

CENTRAL PICTURE LEGEND

Postoperative ESVI and EF were associated with survival after CABG ± SVR.



CENTRAL MESSAGE

Since SVR could provide survival benefit by improving EF for those with postoperative ESVI within a specific range, responders to SVR could be identified by estimating postoperative ESVI.

PERSPECTIVE STATEMENT

Although the postoperative ESVI and EF are benchmarks of SVR, they are unpredictable and vary among patients. This makes it difficult to identify who would benefit from SVR. This study elucidated the relationships among SVR, postoperative ESVI, EF and survival. Our results can help identify who would be associated with a higher survival rate by adding SVR to CABG compared with CABG alone.

ABSTRACT

Objectives

The postoperative left ventricular end-systolic volume index (ESVI) and ejection fraction (EF) are benchmarks of surgical ventricular reconstruction (SVR) but remain unpredictable. This study aimed to identify who could be associated with a higher long-term survival rate by adding SVR to coronary artery bypass grafting (CABG) than CABG alone (responders to SVR).

Methods

Subjects were 293 patients (median age, 63 years; 255 men) who underwent CABG for ischemic heart disease with left ventricular dysfunction in 16 cardiovascular centers in Japan. The relationships among SVR, postoperative ESVI, EF, and survival were analyzed to identify responders to SVR.

Results

SVR was performed in 165 patients (56%). The ESVI and EF significantly improved (ESVI, 91 ml/m^2 to 64 ml/m^2; EF, 28% to 35%) for all patients. The postoperative ESVI and EF were estimated and SVR was found to be significantly associated with both ESVI (14.5 ml/m^2 reduction, P <0.001) and EF (3.1% increase, P = 0.003). During the median follow-up of 6.8 years, 69 patients (24%) died. Only the postoperative EF was significantly associated with survival (hazard ratio = 0.925, 95% CI = 0.885-0.968), although this effect was found limited to those with postoperative ESVI of 40-80 ml/m^2 in the subgroup analysis (hazard ratio = 0.932, 95% CI = 0.894-0.973).

Conclusions

Adding SVR to CABG could reduce the mortality risk by increasing EF for those with postoperative ESVI within a specific range. The postoperative ESVI could demarcate responders to SVR and its estimation can help in surgical decision making.

INTRODUCTION

The ideal candidate for surgical ventricular reconstruction (SVR) has not been identified, since the survival benefit of adding SVR to coronary artery bypass grafting (CABG) for those with ischemic heart disease remains unproven.[1] Volume reduction of the left ventricle (LV) is one of the goals of SVR because the dilated LV after myocardial infarction predicts mortality.[2] In fact, the postoperative LV end-systolic volume index (ESVI) <60 ml/m^2, a >30% ESVI reduction, and >33% ESVI reduction with a resultant postoperative ESVI <90 ml/m^2 are considered to be desired goals of SVR, since these are associated with lower mortality rates after SVR.[3-5] On the other hand, the postoperative ESVI <70 ml/m^2 could demarcate candidates for SVR, because this is associated with a higher survival rate for those with CABG plus SVR than those with CABG alone.[4] However, the volume reduction effect by SVR has limits. The maximum values of preoperative LV sizes to achieve postoperative ESVI <60 ml/m^2 are 65 mm for LV end-diastolic diameter and 94 ml/m^2 for ESVI.[3] On the other hand, since the LV volume reduction by SVR may cause a decrease of stroke volume,[6] a sufficient LV ejection fraction (EF) should be preserved postoperatively. Otherwise, reduced LV stroke volume results in low output syndrome.[7] Although SVR was reported to improve EF with a reduction of the LV volume,[6, 8] the postoperative values of such parameters vary depending on each patient's condition. This makes it difficult to identify who would benefit from SVR, because there remains no method to estimate the postoperative ESVI and EF after SVR specifically and individually. Therefore, we hypothesized that elucidation of the specific effects of SVR on ESVI and EF could make it possible to estimate the postoperative ESVI and EF, and this could help identify who would be associated with a higher long-term survival rate by adding SVR to CABG than CABG alone (i.e., responder to SVR). Thus, this study aimed to identify the responders to SVR by elucidating the relationships among SVR, postoperative ESVI, EF, and survival.

METHODS

We conducted a retrospective multicenter study to investigate the effects of SVR on postoperative ESVI, EF, and survival in those who underwent CABG for ischemic heart disease with LV dysfunction (EF ≤40% in any modality). We used data from a dedicated database, the SURgical VentrIcular reconstruction for severe VEntricular dysfunction (SURVIVE) registry database, which was constructed to collect data on patients with heart failure and LV systolic dysfunction who had undergone cardiac surgery in 17 hospitals in Japan since 1999. Among 1701 patients registered, 1385 underwent CABG for ischemic heart disease. Although 414 patients who had complete datasets of pre- and post-operative LV volume were candidates, another 121 were excluded considering the bias of LV volume measurement and diversity of surgical procedures. The Bland-Altman analysis was performed to determine the magnitude and directions of intermodality bias for the ESVI and EF using limits of agreement (defined as ±1.96 SD from the mean difference) in patients who had data from multiple modalities.[9] Then, the ESVI and EF of quantitative gated single photon computed emission tomography (QGS), left ventriculography (LVG), and 2D echocardiography were compared with magnetic resonance imaging (MRI) as the reference standard, and a considerable bias was found between 2D echocardiography and other modalities (Figure E1). Then, those with data only from 2D echocardiography were excluded from the study, and other modalities were selected in the following order for those with multiple modality data: MRI, QGS, and LVG. Moreover, those with surgical procedures that had been performed for the small number of patients (e.g., mitral valve replacement, chordal cutting, LV linear closure, and SVR without anterior wall incision) were excluded. Finally, the study subjects were 293 patients who underwent CABG for ischemic heart disease between November 1999 and September 2015 (Figure 1), and the complete datasets of the preoperative and postoperative ESVI and EF from the same modality were acquired from MRI, QGS, and LVG for 49 (17%), 35 (12%), and 209 patients (71%), respectively. Completeness of follow-up was calculated at each time point using a simplified person-time method.[10] The median follow-up was 6.8 years (interquartile range, 3.2-9.8 years) and the rates of complete follow-up at 3 years, 5 years, and 10 years were 90%, 85%, and 73%, respectively. Mortality was detected on the basis of medical records or follow-up inquiries to the attending cardiologists that were made in each hospital. The study protocol was approved by the institutional review boards of all the participating hospitals, and the requirement for obtaining informed consent was waived.

Procedures

All SVR procedures included in this study had anterior wall incision, and the types of procedure were selected based on the surgeons' preferences. They comprised endoventricular circular patch plasty[11] for 73 patients (25%), septal anterior ventricular exclusion[12] for 54 patients (18%), overlapping left ventriculoplasty[13] for 21 patients (7%), and an endocardial linear infarct exclusion technique[14] for 17 patients (6%). The endoventricular patch was used in the former 2 procedures but not in the latter 2. Mitral valve (MV) repair was performed in 100 patients (34%). Forty-seven patients (16%) underwent submitral procedures, including papillary muscle approximation in 43 patients (15%) and papillary muscle suspension in 18 patients (6%). The annuloplasty ring for MV repair was generally downsized but was true-sized for some of those with submitral procedures.

Statistical analysis

Continuous variables were expressed as mean ± standard deviation (SD) when normally distributed or medians with interquartile ranges (IQRs) when not normally distributed. All continuous variables were tested for normality using the Shapiro-Wilk test. The categorical variables were expressed as numbers and percentages. Those with missing data for variables used were dropped from each analysis. Student's and paired t-tests were used for comparisons of normally distributed variables, while the Mann–Whitney U-test and Wilcoxon's signed rank test were performed for unpaired and paired data without normal distribution, respectively. Categorical variables were compared using the chi-square test or Fisher's exact test, as appropriate. The standardized difference (Cohen's d) was calculated for each variable in comparison between those with and without SVR.[15] Correlations between variables were assessed using Pearson's correlation coefficients (r) when normally distributed or Spearman's rank correlation coefficients (r_s) when not normally distributed. Survival analysis was performed using the Kaplan-Meier method, wherein those who were lost to follow-up were censored at the date of their latest follow-up.

We hypothesized that adding SVR to CABG could result in a significant reduction of ESVI and increase of EF; the ESVI reduction and EF increase could provide a survival benefit; therefore, adding SVR to CABG could improve the postoperative survival. However, since it is considered that SVR is not always beneficial regardless of the extent of LV remodeling,[16] we also hypothesized that the effect of SVR has the upper and lower limits, which could be indicated by the extent of LV remodeling and demarcate the responders to SVR. Therefore, the analyses were performed in the following order. First, the multiple linear regression analysis was performed with the stepwise method ($P < 0.10$) to estimate the postoperative ESVI and EF, taking into account the contribution of SVR (Appendix 1). Second, the Cox regression analysis was performed to elucidate the effect of postoperative ESVI and EF on survival, where continuous variables were natural log transformed when not normally distributed (Appendix 2). In this analysis, propensity score was calculated and entered into the multivariable Cox proportional hazards model to reduce the treatment bias, taking into account the observational nature of this study; the probability of receiving SVR for each patient was calculated using multivariable logistic regression analysis (Appendix 3). Variables for all the multivariable analyses were selected considering their confounding and clinical relevance as well as multicollinearity (variance inflation factor <5.0). Finally, subgroup analysis using Cox proportional hazards models were performed to determine the upper and lower limits in the effect of SVR. A P-value of <0.05 was considered to indicate statistical significance in all the tests. All analyses were performed using IBM SPSS Statistics (version 24, IBM Corporation, Armonk, New York, USA).

RESULTS

Baseline characteristics and surgical data

Table 1 shows the baseline characteristics and surgical data. The median age was 63 years (IQR, 57–71 years) and 255 patients (87%) were men. The preoperative ESVI and EF were 91 ml/m^2 (IQR, 66-128 ml/m^2) and 28% (IQR, 20%-34%), respectively; there was a significant correlation between them (r_s = -0.746, P <0.001, Figure E2). The percentage of viable segments in the LV myocardium was obtained in 126 patients (43%) using MRI (52%) and scintigraphy (48%). The median percent viability values were 69% (IQR, 56%-81%) and 81% (IQR, 69%-94%) for those with and without SVR, respectively (P = 0.002). There were weak correlations between the percent viability and preoperative ESVI (r_s = -0.236, P = 0.008) and EF (r_s = 0.220, P = 0.013).

Estimation of postoperative ESVI and EF

The postoperative ESVI and EF were evaluated 15 days (median) after surgery (IQR, 11-20 days), and their values were 64 ml/m^2 in median (IQR, 47-88 ml/m^2) and 35% ± 11% (P < 0.001 compared with the preoperative value for each parameter), respectively. The median ESVI reduction rate (postoperative change divided by preoperative value) was 30% (IQR, 9%-43%) and significantly differed between those with and without SVR (SVR, 37% reduction from 103 ml/m^2 to 65 ml/m^2, P <0.001; no SVR, 16% reduction from 78 ml/m^2 to 62 ml/m^2, P <0.001; P <0.001 for SVR vs. no SVR). Those with SVR were also associated with a greater increase of postoperative EF (a difference between pre- and postoperative values) than those without SVR (SVR, 8% increase from 26% to 34%, P <0.001; no SVR, 6% increase from 30% to 36%, P <0.001; P = 0.025 for SVR vs. no SVR).

The stepwise multiple linear regression analysis identified the following variables that estimated the postoperative ESVI and EF: gender, preoperative ESVI, preoperative EF, LV aneurysm, submitral procedure, SVR for postoperative ESVI and preoperative ESVI, preoperative EF, MV repair, and SVR for postoperative EF (Table 2). Then, it was ascertained that the best equations to calculate the estimated values of postoperative ESVI and EF for the final sample size of 290 patients were as given below:

Postoperative ESVI = 34.8 + 11.2 (gender) + 0.51 (preoperative ESVI) – 0.44 (preoperative EF) – 6.4 (LV aneurysm) – 10.9 (submitral procedure) – 14.5 (SVR) ($r^2 = 0.58$)

Postoperative EF = 21.4 – 0.04 (preoperative ESVI) + 0.64 (preoperative EF) – 4.3 (MV repair) + 3.1 (SVR) ($r^2 = 0.50$)

where gender = 1 if male and 0 if female, and LV aneurysm, submitral procedure, MV repair, and SVR = 1 if they are associated or performed and 0 if not.
Thus, adding SVR to CABG could result in a significant reduction of ESVI and increase of EF.

Effects of postoperative ESVI and EF on mortality

Of the 293 patients, 69 (24%) died during the study period (25% and 22% of those with and without SVR, respectively, $P = 0.58$). The Kaplan-Meier analysis demonstrated that the 3-, 5-, and 10-year survival rates were 92%, 87%, and 70%, respectively. Table 3 summarizes the results of the univariable and multivariable Cox proportional hazards models. The multivariable Cox proportional hazards model demonstrated that only the postoperative EF was significantly associated with postoperative survival (HR = 0.925, 95% confidence interval = 0.885-0.968, $P = 0.001$). Figure 2 shows a significant difference in survival times among different postoperative EF values. These results suggested that adding SVR to CABG could provide survival benefit by increasing EF.

Upper and lower limits in effects of SVR

Since there was a significant correlation between postoperative ESVI and EF ($r_s = -0.778$, $P < 0.001$, Figure E2), we performed subgroup analysis to elucidate whether the postoperative ESVI (i.e., the extent of LV remodeling) limited the effect of EF on survival. As a result, it was found that postoperative EF was significantly associated with survival in those with ESVI of 40-80 ml/m^2 (HR = 0.932, 95% CI = 0.894-0.973, $P = 0.001$), although it was not in other subgroups (Figure 3): postoperative ESVI of 40 ml/m^2 and 80 ml/m^2 could correspond to the lower and upper limits of effective SVR, respectively. Since SVR would reduce ESVI by 14.5 ml/m^2, those who were estimated to have postoperative ESVI within the target range (40-80 ml/m^2) could have a survival benefit from the increase of EF by SVR. The estimated increase of EF by 3.1% with SVR in those with ESVI of 40-80 ml/m^2 would result in approximately 21% reduction in mortality risk. Thus, estimation of ESVI can help find the responders to SVR. The values dividing each subgroup were determined considering the results of Cox proportional hazards models with various categorizations (Figure E3). The details of the subgroups of postoperative ESVI are shown in Table E1.

DISCUSSION

We demonstrated that the postoperative EF was significantly associated with survival after CABG with or without SVR, although this association was limited within a specific range of postoperative ESVI. Since SVR could provide a significant reduction of ESVI and increase of EF, adding SVR to CABG could provide a survival benefit by increasing EF for the selected patients regarding postoperative ESVI. Thus, estimating postoperative ESVI could help identify who would benefit from CABG plus SVR compared with CABG alone.

In this study, we found that SVR was one of the variables that were significantly associated with the postoperative ESVI and EF: adding SVR to CABG could result in a 14.5 ml/m^2 reduction of ESVI and a 3.1% increase of EF. On the other hand, although the postoperative ESVI (<60-70 ml/m^2) could have predicted a higher survival rate,[3, 4] only the postoperative EF was identified to be significantly associated with the postoperative survival in the multivariable Cox proportional hazards model. Thus, it was suggested that SVR could provide survival benefit not by reducing ESVI but by increasing EF. Moreover, it was also demonstrated that the absolute value of postoperative EF, rather than the extent of postoperative improvement of EF, was the significant variable. Some previous studies focused on myocardial viability, which could be indicated by the extent of postoperative improvement of EF, as an important predictor of survival after CABG for ischemic heart disease, although it remains controversial.[17-21] Our results suggested that it could be required for better survival to keep postoperative EF as high as possible, regardless of the postoperative change of this parameter. Therefore, in consideration of whether SVR should be added or not, the perspective that a higher postoperative EF could be estimated with SVR than without it could encourage surgeons to perform the procedure. On the other hand, it is doubted whether all the patients could have survival benefit from SVR by increasing EF, since it is considered that SVR could not change the fate of the extremely deteriorated LV and would not be required for the LV with sufficient ability.[16] Thus, it would be natural that the extent of LV remodeling limited the positive effect of EF increase by SVR on survival.

Since the postoperative EF significantly correlated with ESVI, we conducted subgroup analysis dividing the subjects according to the postoperative ESVI (i.e., the extent of LV remodeling) and found that the beneficial effect of postoperative EF was limited to those with postoperative ESVI of 40-80 ml/m^2. Since the IQR of preoperative ESVI in this patient group was 79-111 ml/m^2, this result was consistent with previous reports that suggested that those with mid-range preoperative ESVI were responders to SVR, with ranges of 80-120 ml/m^2 reported by Skelley et al.[22], 100-130 ml/m^2 by Yamazaki et al.[23], and 105-150 ml/m^2 by Kainuma et al.[24] Thus, those who are estimated to have the postoperative ESVI within the target range of 40-80 ml/m^2 could be responders to SVR, since the increase of EF by adding SVR could be beneficial only within this range of ESVI.

On the other hand, it is not simple to identify the responders to SVR, since the postoperative ESVI cannot be estimated by a single effect of SVR. Several factors are involved in the estimation, and the surgical technique is just one of these. Actually, the extent of preoperative LV remodeling (i.e., preoperative ESVI and EF) affected ESVI more dominantly. This would be consistent with the previous reports that showed a wide range of perioperative LV volumes and its reduction rates,[22, 25-27] suggesting that the volume reduction effect of SVR could be affected and the postoperative LV volume could vary depending on the individual condition of each patient. These results could also explain why it is difficult to prove the benefit of SVR by a simple comparison study, such as a randomized controlled trial.[1]

SVR may not be a procedure that provides a survival benefit for all patients who undergo CABG for ischemic heart disease. However, as conventional surgery could be an alternative to transplantation and ventricular assist device therapy for highly selected patients,[28] SVR could provide a survival benefit if the indication is carefully determined. On the other hand, the purpose of this study was to identify who could benefit from SVR plus CABG compared with CABG alone, by elucidating the specific effects of SVR on ESVI and EF; this is different from estimating survival time of individual patients if SVR was performed, which we had reported previously.[29] In surgical decision making, we should take into consideration not only the benefit of adding SVR to CABG but also the mortality risk of the entire surgical procedure: long-term survival could not always be expected even if adding SVR improved survival to some extent. For high-risk patients, ventricular assist device and transplantation should be considered even if the postoperative ESVI could be estimated within the target range for SVR (Table 4).

Limitations

One of the major limitations of this study was its retrospective design. Selection bias for surgical procedures could have affected our results. Therefore, we calculated propensity score and entered it into the multivariable model to reduce the bias. Moreover, since the relationship between ESVI and EF was quite similar between those with and without SVR (Figure E2), we assumed that both LV with or without SVR could be within the same spectrum of LV remodeling, and they could be analyzed as a whole. Second, since our database had a non-negligible amount of missing data for possibly important parameters, such as pulmonary artery pressure, LV diastolic function, and percent viability in the LV, we excluded those parameters from the analyses to defend the sample size, because the analysis, which enrolled the percent viability for less than half of the patients, demonstrated no significant improvement in predictive power of the equations for postoperative ESVI and EF. A prospective study including such parameters with sufficient number of cases will contribute to further clarification by improving the estimation of the postoperative parameters.

CONCLUSIONS

Adding SVR to CABG could provide a survival benefit by increasing EF for those with postoperative ESVI within a specific range. Thus, the postoperative ESVI could demarcate responders to SVR and the estimation of this parameter can help identify who would benefit from CABG plus SVR rather than CABG alone. In surgical decision making, however, not only the benefit of adding SVR but also the risk of entire procedure should be taken into consideration.

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APPENDIX 1

The postoperative ESVI and EF were estimated using stepwise multiple linear regression analysis based on the following clinically relevant variables without missing values: age, gender, NYHA functional class, inotrope use, preoperative ESVI, preoperative EF, LV aneurysm, number of anastomoses in CABG, MV repair, submitral procedure, and SVR.

APPENDIX 2

The multivariable Cox proportional hazards model for postoperative survival was constructed to elucidate whether the postoperative ESVI and EF would estimate survial. The following variables were selected considering the results of previous studies and the bias for receiving SVR (inclusive of variables with proportion of missing values ≤3%): SVR, propensity score, postoperative ESVI, postoperative EF, ESVI reduction rate, and increase of EF.

APPENDIX 3

The propensity score was calculated using multivariable logistic regression analysis with the following variables considering their clnical relevance and standardized differences (>0.1), inclusive of variables with proportion of missing values ≤3%: age, gender, number of coronary lesions, left main disease, atrial fibrillation, LV aneurysm, preoperative NYHA functional class, inotrope use, preoperative MR grade, preoperative LV end-diastolic diameter, preoperative ESVI, and preoperative EF.

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Table 1. Baseline characteristics and surgical data of subjects

Variables	No SVR N=128	SVR N=165	P values	Standardized difference (Cohen's d)
Age, years	62 (57, 70)	64 (57, 72)	0.49	0.082
Male, n (%)	112 (88%)	143 (87%)	0.86	0.025
Number of coronary lesions	3 (3, 3)	3 (2, 3)	0.002	0.281
Left main, n (%)	24 (19%)	21 (13%)	0.19	0.167
Anterior descending, n (%)*	126 (99%)	116 (95%)	0.06	0.252
Circumflex, n (%)*	111 (87%)	98 (81%)	0.22	0.177
Right, n (%)*	111 (87%)	87 (71%)	0.002	0.407
Atrial fibrillation, n (%)	8 (6%)	15 (9%)	0.39	0.105
Diabetes, n (%)**	73 (58%)	49 (49%)	0.18	0.189
Dialysis, n (%)	4 (3%)	6 (4%)	1.0	0.028
LV aneurysm, n (%)	47 (37%)	52 (32%)	0.38	0.109
%Viable segments in the LV, %**	81 (69, 94)	69 (56, 81)	0.002	0.565
NYHA functional class			<0.001	0.661
I	3 (2%)	4 (2%)		
II	76 (59%)	47 (29%)		
III	36 (28%)	80 (49%)		
IV	13 (10%)	34 (21%)		
Inotrope use, n (%)	4 (3%)	13 (8%)	0.13	0.203
IABP, n (%)	8 (6%)	6 (4%)	0.41	0.122
PCPS, n (%)	0	1 (0.6%)	1.0	0.103

Beta-blocker, n (%)*	76 (69%)	85 (52%)	0.004	0.355
LV end-diastolic diameter, mm†	59±8	63±9	<0.001	0.436
Preoperative EF, %	30 (22, 36)	26 (18, 32)	<0.001	0.478
Preoperative ESVI, ml/m^2	78 (56, 106)	103 (77, 141)	<0.001	0.649
Mitral regurgitation grade†			0.05	0.381
None	29 (24%)	18 (11%)		
1+	51 (43%)	76 (46%)		
2+	22 (18%)	45 (27%)		
3+	13 (11%)	19 (12%)		
4+	5 (4%)	7 (4%)		
Tricuspid regurgitation grade, n (%)*			<0.001	0.761
None	62 (53%)	33 (20%)		
1+	44 (38%)	105 (64%)		
2+	11 (9%)	20 (12%)		
3+	0	6 (4%)		
4+	0	0		
CABG, n (%)	128 (100%)	165 (100%)	-	-
Mammary artery use, n (%)**	121 (97%)	104 (92%)	0.15	0.202
Number of anastomoses	4 (3, 4)	3 (2, 3)	<0.001	0.432
SVR, n (%)	0	165 (100%)	-	-
With patch	0	127 (77%)	-	-
MV repair, n (%)	24 (19%)	76 (46%)	<0.001	0.596

Ring size, mm	26 (26, 28)	26 (26, 28)	0.35	0.217
Submitral procedure, n (%)†	10 (8%)	37 (23%)	0.001	0.406
Maze, n (%)	1 (0.8%)	7 (4%)	0.14	0.212
Tricuspid annuloplasty, n (%)	8 (6%)	16 (10%)	0.39	0.125
Aortic crossclamp time, min**	97 (50, 141)	96 (62, 149)	0.45	0.119
Cardiopulmonary bypass time, min**	172 (126, 256)	176 (130, 234)	0.90	0.018

CABG = coronary artery bypass grafting, EF = ejection fraction, ESVI = end-systolic volume index, IABP = intraaortic balloon pumping, LV = left ventricle, MV = mitral valve, NYHA = New York Heart Association, PCPS = percutaneous cardiopulmonary support, PM = papillary muscle, SVR = surgical ventricular reconstruction

†Proportion of those with missing values ≤3%, *proportion of those with missing values 3-15%, **proportion of those with missing values >15%.

Table 2. Results of multivariable linear regression analysis for estimation of postoperative ESVI and EF

Variables	Regression coefficient	95% CI	P values
Postoperative ESVI			
Male gender	11.2	3.34, 19.2	0.005
Preoperative ESVI, ml/m^2	0.51	0.43, 0.59	<0.001
Preoperative EF, %	-0.44	-0.84, -0.05	0.027
LV aneurysm	-6.44	-12.4, -0.45	0.035
Submitral procedure	-10.9	-18.6, -3.30	0.005
SVR	-14.5	-20.0, -9.00	<0.001
Postoperative EF			
Preoperative ESVI, ml/m^2	-0.04	-0.07, -0.01	0.005
Preoperative EF, %	0.64	0.50, 0.78	<0.001
MV repair	-4.32	-6.49, -2.15	<0.001
SVR	3.11	1.09, 5.12	0.003

CI = confidence interval, EF = ejection fraction, ESVI = end-systolic volume index, LV = left ventricle, MR = mitral regurgitation, MV = mitral valve, NYHA = New York Heart Association, SVR = surgical ventricular reconstruction

Table 3. Results of Cox proportional hazards models for postoperative survival

Variables	Univariable		Multivariable	
	HR (95% CI)	P values	HR (95% CI)	P values
Postoperative ESVI (log-transformed)	1.947 (1.170, 3.240)	0.010	0.601 (0.223, 1.615)	0.31
Postoperative EF	0.956 (0.935, 0.978)	<0.001	0.925 (0.885, 0.968)	0.001
ESVI reduction rate (log-transformed)	1.829 (0.710, 4.710)	0.21	1.147 (0.340, 3.866)	0.83
EF increase (log-transformed)	1.050 (0.562, 1.960)	0.88	2.930 (0.989, 8.680)	0.052
SVR	2.108 (1.272, 3.494)	0.004	1.731 (0.953, 3.143)	0.07
Propensity score	6.930 (2.007, 23.93)	0.002	1.221 (0.226, 6.578)	0.82

CI = confidence interval, EF = ejection fraction, ESVI = end-systolic volume index, HR = hazard ratio, SVR = surgical ventricular reconstruction

Table E1. Perioperative parameters of patients in each subgroup of postoperative ESVI

	Postoperative ESVI ≤40 ml/m^2 N=42		Postoperative ESVI 40-80 ml/m^2 N=156		Postoperative ESVI >80 ml/m^2 N=95	
	No SVR N=18	SVR N=24	No SVR N=69	SVR N=87	No SVR N=41	SVR N=54
Age, years	68 (57, 76)	68 (60, 75)	62 (58, 70)	66 (55, 72)	62 (56, 67)	63 (57, 69)
Male, n (%)	13 (72%)	21 (88%)	60 (87%)	74 (85%)	39 (95%)	48 (89%)
Inotrope use, n (%)	1 (6%)	1 (4%)	1 (1%)	3 (3%)	2 (5%)	9 (17%)
NYHA class	2 (2, 3)	3 (2, 3)	2 (2, 3)	3 (2, 3)	2 (2, 3)	3 (3, 4)
MR grade	1 (0, 1.5)	1 (0, 1)	1 (0, 2)	1 (1, 2)	1 (1, 2)	2 (1, 3)
MV repair, n (%)	2 (11%)	5 (21%)	11 (16%)	36 (41%)	11 (27%)	35 (65%)
Preoperative EF, %	33 (31, 38)	37 (32, 40)	34 (28, 37)	26 (20, 31)	22 (17, 28)	19 (13, 25)
Postoperative EF, %	48±9	50±8	38±8	35±9	26±7	24±7
EF change, %	13 (10, 15)	13 (7, 20)	6 (3, 10)	10 (3, 14)	3 (-0.5, 7)	5 (1, 10)
Preoperative ESVI, ml/m^2	54 (45,67)	64 (42, 74)	67 (53, 85)	96 (79, 111)	122 (93, 142)	146 (127, 168)
Postoperative ESVI, ml/m^2	33 (31, 38)	34 (27, 37)	57 (48, 68)	59 (50, 70)	98 (86, 138)	100 (89, 127)
ESVI reduction rate, %	40 (21, 56)	45 (34, 55)	15 (-5, 28)	39 (27, 50)	6 (-11, 27)	29 (13, 42)

EF = ejection fraction, ESVI = end-systolic volume index, MR = mitral regurgitation, MV = mitral valve, NYHA = New York Heart Association, SVR = surgical ventricular reconstruction

FIGURE LEGENDS

Figure 1. CONSORT diagram of recruitment of the study.

CABG = coronary artery bypass grafting, Echo = echocardiography, LV = left ventricle, LVG = left ventriculography, MRI = magnetic resonance imaging, MV = mitral valve, QGS = quantitative gated SPECT, SVR = surgical ventricular reconstruction

Figure 2. Postoperative survival curves for 3 different groups divided according to tertile values of postoperative EF. Shaded areas indicate 95% confidence intervals.

EF = ejection fraction

Figure 3. Effect of postoperative EF on survival in each subgroup regarding postoperative ESVI.

CI = confidence interval, EF = ejection fraction, ESVI = end-systolic volume index, Pt = patient

Figure 4. Flowchart of the surgical decision pathway to SVR.

CABG = coronary artery bypass grafting, ESVI = end-systolic volume index, HTx = heart transplantation, LV = left ventricle, VAD = ventricular assist device, SVR = surgical ventricular reconstruction

Figure E1. Summary of the Bland-Altman analysis of intermodality agreement for ESVI and EF. Echo = echocardiography, EF = ejection fraction, ESVI = end-systolic volume index, LVG = left ventriculography, MRI = magnetic resonance imaging, QGS = quantitative gated SPECT, - = P <0.05 underestimation vs. MRI, + = P <0.05 overestimation vs. MRI

Figure E2. Correlation between pre- and post-operative ESVI and EF for those with (A) and without (B) SVR.

EF = ejection fraction, ESVI = end-systolic volume index, r_s = Spearman's rank correlation coefficient, SVR = surgical ventricular reconstruction

Figure E3. Results of subgroup analyses for effect of postoperative EF on survival using various categorizations according to postoperative ESVI.

CI = confidence interval, EF = ejection fraction, ESVI = end-systolic volume index, Pt = patient

VIDEO LEGEND

Four different SVR and submitral procedures were included in our study: endoventricular circular patch plasty and septal anterior ventricular exclusion by Dr. Isomura, papillary muscle approximation and overlapping left ventriculoplasty by Dr. Matsui, and endocardial linear infarct exclusion technique by Dr. Yaku.

Figure 1.

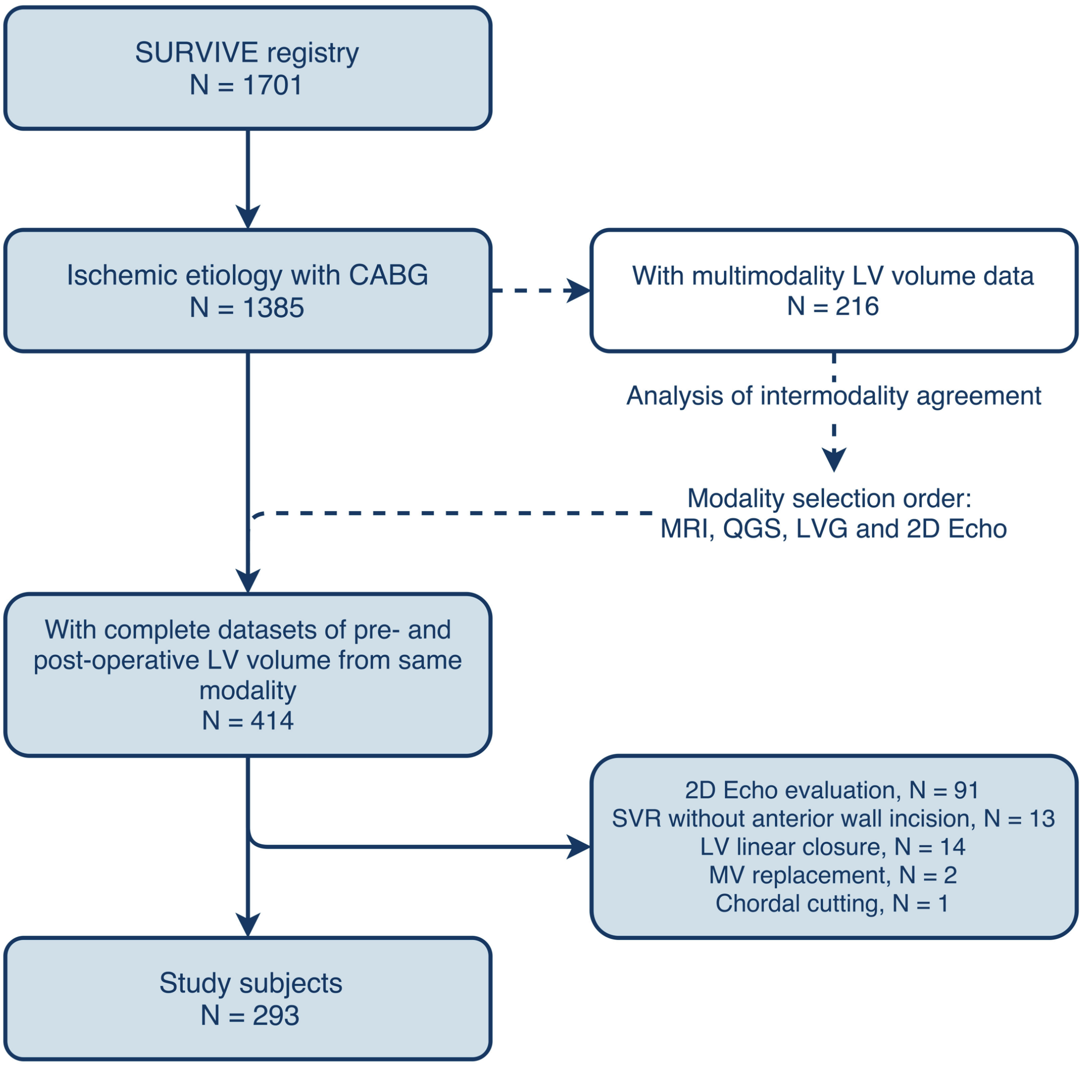

SURVIVE registry
N = 1701
Ischemic etiology with CABG
N = 1385
With multimodality LV volume data
N = 216
Analysis of intermodality agreement
Modality selection order:
MRI, QGS, LVG and 2D Echo
With complete datasets of pre- and post-operative LV volume from same modality
N = 414
2D Echo evaluation, N = 91
SVR without anterior wall incision, N = 13
LV linear closure, N = 14
MV replacement, N = 2
Chordal cutting, N = 1
Study subjects
N = 293

Figure 2.

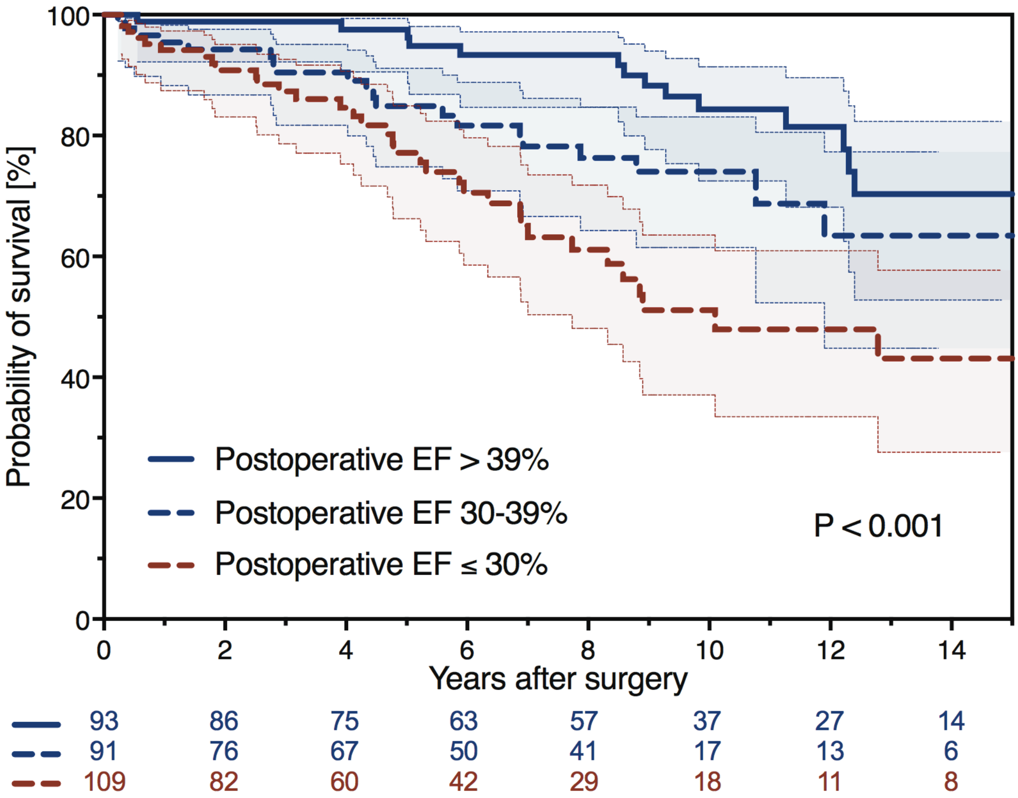

Probability of survival [%]
100
80
60
40
20
0
0
2
4
6
8
10
12
14
Years after surgery
Postoperative EF > 39%
Postoperative EF 30-39%
Postoperative EF ≤ 30%
P < 0.001
93 86 75 63 57 37 27 14
91 76 67 50 41 17 13 6
109 82 60 42 29 18 11 8

Figure 3.

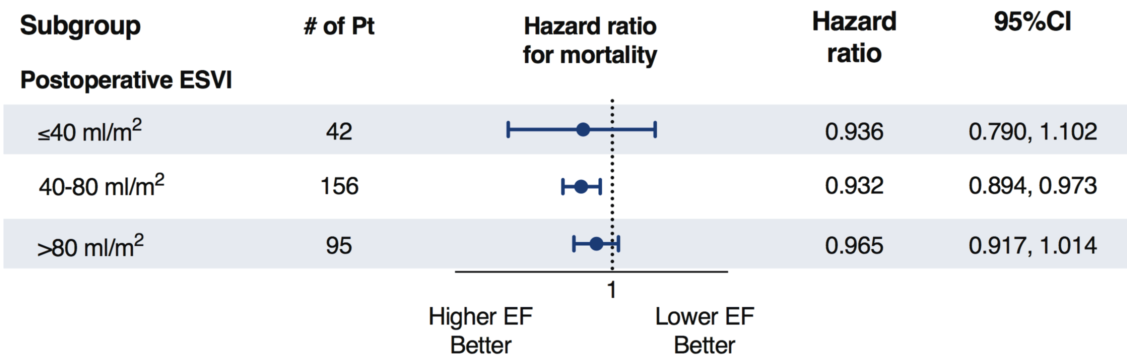

Subgroup
# of Pt
Hazard ratio for mortality
Hazard ratio
95%CI
Postoperative ESVI
≤40 ml/m2
42
0.936
0.790, 1.102
40-80 ml/m2
156
0.932
0.894, 0.973
>80 ml/m2
95
0.965
0.917, 1.014
1
Higher EF Better
Lower EF Better

Figure 4.

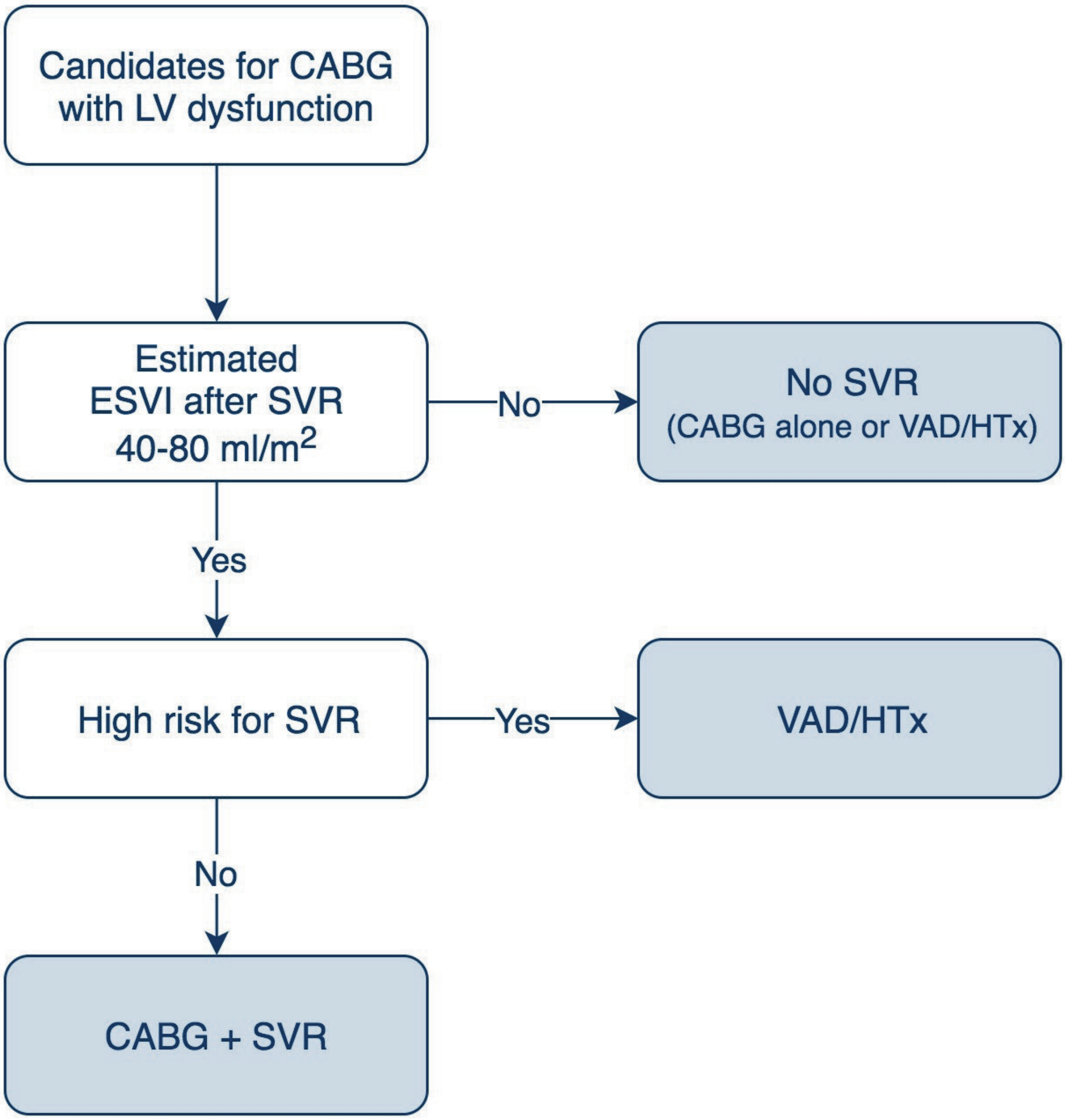
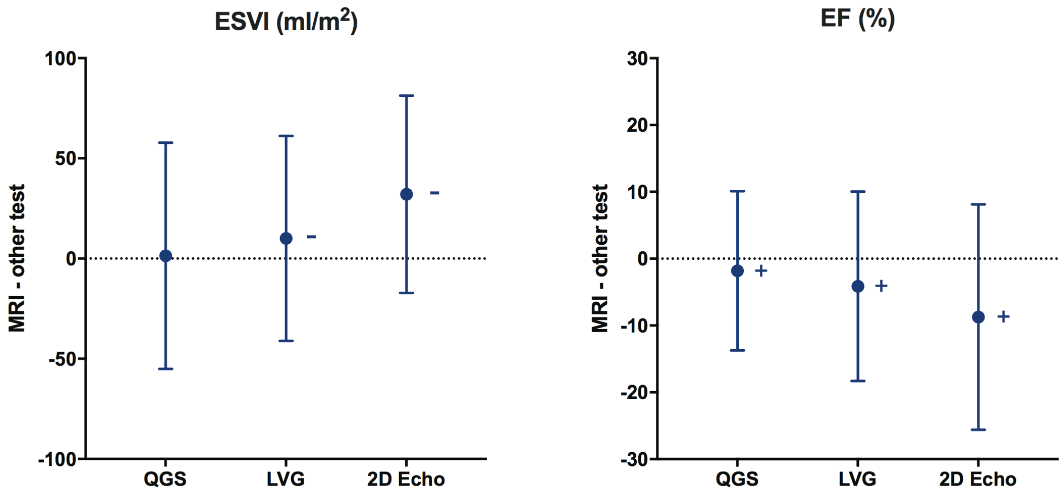

Candidates for CABG with LV dysfunction
Estimated ESVI after SVR 40-80 ml/m2
No
No SVR
(CABG alone or VAD/HTx)
Yes
High risk for SVR
Yes
VAD/HTx
No
CABG + SVR

Figure E1.



ESVI (ml/m^2)
MRI - other test
100
50
0
-50
-100
QGS
LVG
2D Echo
EF (%)
MRI - other test
30
20
10
0
-10
-20
-30
QGS
LVG
2D Echo

Figure E2.

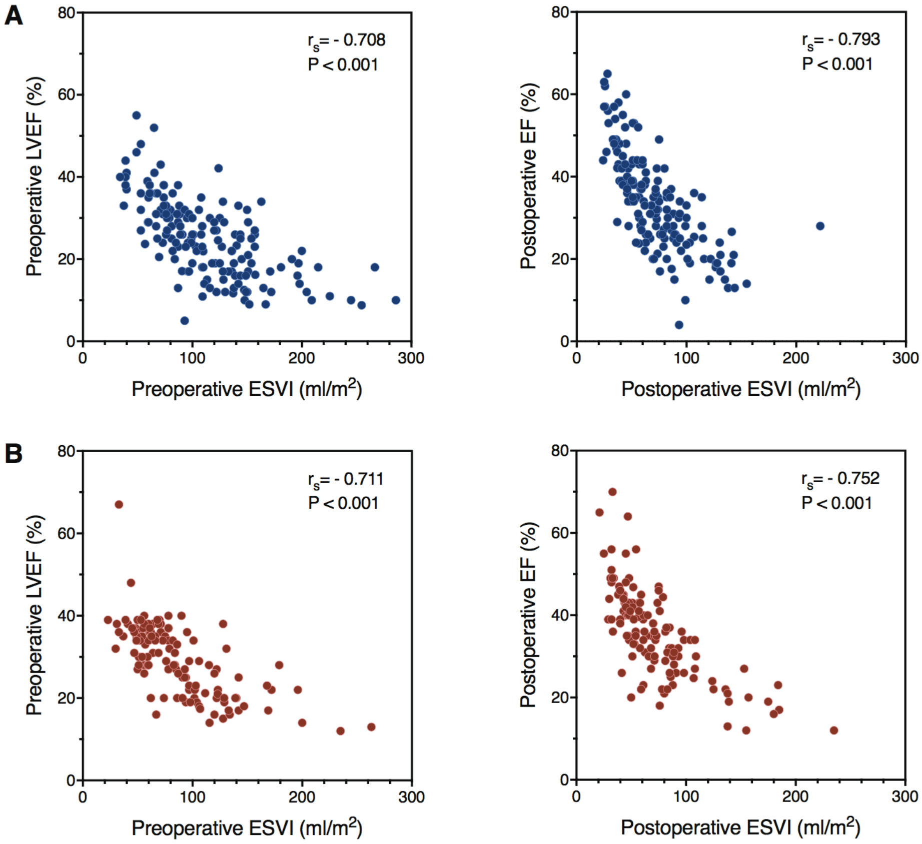
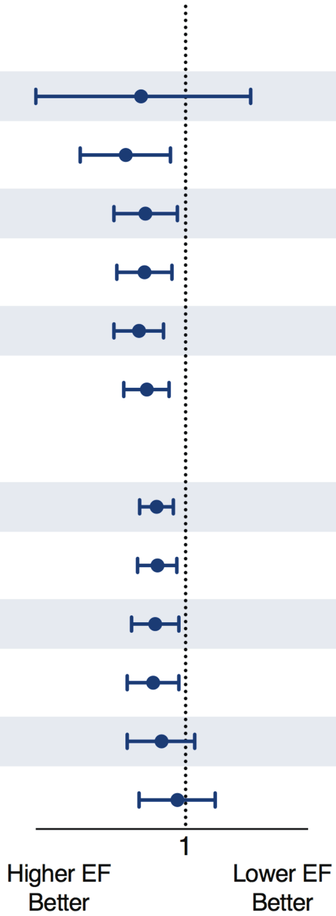

A
B
rs= - 0.708
P < 0.001
rs= - 0.793
P < 0.001
rs= - 0.711
P < 0.001
rs= - 0.752
P < 0.001
Preoperative LVEF (%)
Postoperative EF (%)
Preoperative ESVI (ml/m2)
Postoperative ESVI (ml/m2)
0
20
40
60
80
100
200
300

Figure E3.

Hazard ratio for mortality



Subgroup	# of Pt	Hazard ratio	95%CI
Postoperative ESVI			
Lower limits			
≤40 ml/m^2	42	0.936	0.790, 1.102
≤50 ml/m^2	88	0.915	0.855, 0.978
≤60 ml/m^2	131	0.942	0.899, 0.988
≤70 ml/m^2	164	0.941	0.903, 0.980
≤80 ml/m^2	198	0.933	0.899, 0.968
≤90 ml/m^2	231	0.944	0.912, 0.976
Upper limits			
>40 ml/m^2	251	0.958	0.934, 0.982
>50 ml/m^2	205	0.959	0.931, 0.987
>60 ml/m^2	162	0.956	0.923, 0.990
>70 ml/m^2	129	0.953	0.917, 0.990
>80 ml/m^2	95	0.965	0.917, 1.014
>90 ml/m^2	62	0.988	0.933, 1.045