Published in final edited form as:

J Cardiovasc Transl Res. 2019 April ; 12(2): 135–141. doi:10.1007/s12265-018-9812-2.

Speckle-tracking Echocardiographic Strain Analysis Reliably Estimates Degree of Acute LV Unloading during Mechanical LV Support by Impella

Nadjib Hammoudi, MD^{*,1,2}, Shin Watanabe, MD^{*,1}, Olympia Bikou, MD¹, Alexandre Ceccaldi, MD², Kenneth Fish, PhD¹, Kelly P. Yamada, VMD¹, Satoshi Miyashita, MD¹, Guillaume Lebreton, MD³, Roger J. Hajjar, MD¹, Kiyotake Ishikawa, MD¹

¹Cardiovascular Research Center, Icahn School of Medicine at Mount Sinai, New York, NY, USA

²Sorbonne Universités, UPMC Univ Paris 06, Institut de Cardiologie (AP-HP), Centre Hospitalier Universitaire Pitié-Salpêtrière, Institute of Cardiometabolism and Nutrition (ICAN), ACTION Study Group, INSERM UMRS 1166, Paris, France.

³Sorbonne Universités, UPMC Univ Paris 06, Institut de Cardiologie (AP-HP), Thoracic and Cardiovascular Surgery department, Paris, France.

Abstract

Background—Non-invasive means of evaluating appropriate cardiac unloading remain to be established. We hypothesized that myocardial deformation assessed by echocardiographic speckle-tracking strain analysis can reliably estimate the degree of left ventricular (LV) unloading under mechanical circulatory support.

Methods and Results—A total of 24 Yorkshire pigs underwent Impella-mediated acute LV unloading 1–2 weeks after myocardial infarction (MI). Echocardiographic and invasive pressure-volume measurements were used to evaluate the degree of LV unloading. Pressure-volume analysis before and after LV unloading exhibited a significant decrease in stroke work ($3,399 \pm 1,440$ to $1,244 \pm 659$ mmHg*mL, $p < 0.001$), suggesting reduced external cardiac work. Both longitudinal strain ($-14.6 \pm 4.1\%$ to $-10.6 \pm 2.3\%$, $p < 0.001$) and circumferential strain ($-18.7 \pm 6.1\%$ to $-9.3 \pm 3.5\%$, $p < 0.001$) decreased after LV unloading, and there were linear relationships between stroke work and echocardiographic longitudinal ($r = -0.61$, $p < 0.001$) as well as circumferential strains ($r = -0.75$, $p < 0.001$).

Conclusion—Echocardiographic LV strain analysis offers a non-invasive assessment of LV unloading in subacute MI.

Address for correspondence: Kiyotake Ishikawa, Cardiovascular Research Center, Mount Sinai School of Medicine, One Gustave L. Levy Place, Box 1030, New York, NY 10029-6574 USA, Phone: +1-212-241-8374 Fax: +1-212-241-4080, kiyotake.ishikawa@mssm.edu.

*These authors contributed equally

Human subjects/informed consent statement

No human studies were carried out by the authors for this article.

Animal experiments

All institutional and national guidelines for the care and use of laboratory animals were followed and approved by the appropriate institutional committees.

Keywords

mechanical support; LS; CS; contraction; sub-acute MI; ischemic heart failure

Introduction

Acute left ventricular (LV) unloading using percutaneous LV assist devices is an emerging approach to treat patients with acute cardiac failure[1–3]. Impella is currently the most popular percutaneous LV assist device used in the clinic to treat patients with acute decompensated cardiac failure. Unloading of the LV has been shown to protect the heart from cell death in acute myocardial infarction (MI) by reducing cardiac oxygen consumption[4], reducing wall stress[5], and increasing coronary flow[4]. Since the magnitude of these effects is expected to correlate to the degree of LV unloading[6], reliable methods to evaluate appropriate unloading of the LV are necessary to promote this promising approach in the clinical setting.

At the bedside, echocardiography offers a non-invasive assessment of cardiac function in real time, rendering it as the principal modality to evaluate hemodynamically ill patients. Unfortunately, Doppler-based measurements in Impella-supported patients are subjected to mechanical noise produced by the Impella rotor and continuous mechanical flow. Speckle-tracking echocardiography (STE) is a method attracting increasing attention in recent years[7,8]. It uses the bright speckles in echocardiographic gray-scale images to evaluate tissue deformation. Because these speckles are not subject to mechanical noise, STE may be a viable approach to evaluate heart function and work in the setting of mechanical LV unloading with interfering noise.

We hypothesized that myocardial deformation assessed by echocardiographic STE strain analysis can be used to estimate the degree of LV unloading. The present study was designed to test this hypothesis using a pig model of subacute MI.

Methods

All animal protocols complied with the National Institutes of Health Guide for the Care and Use of Laboratory Animals and standards of US regulatory agencies. Protocols were approved by the Institutional Animal Care and Use Committee of the Icahn School of Medicine at Mount Sinai. A total of 24 Yorkshire pigs (7 males and 17 females) that survived acute MI induction were subjected to an acute LV unloading experiment using Impella CP, one to two weeks after MI. All animals underwent echocardiographic and hemodynamic assessments before and after acute LV unloading.

Percutaneous MI induction

To reflect heterogeneous MI phenotypes found in the clinical setting, pigs with different MI profiles were included. Detailed methods of percutaneous MI induction have been published elsewhere[9] and the impact of MI has been extensively characterized. Briefly, a coronary balloon was delivered either to the left anterior descending artery (n=21) or to the circumferential artery (n=3) using a percutaneous approach. MI was induced by occluding

the coronary artery for 90–120 minutes followed by reperfusion (n=8). Sixteen pigs received thrombus injection to induce transmural scar after reperfusion[10].

Hemodynamic analysis and LV unloading

A high fidelity pressure-volume catheter (Millar Instruments, Houston, TX) was inserted into percutaneously established access in the right carotid artery and LV pressure and volume data were continuously collected[11]. A Swan-Ganz catheter (Edwards Lifesciences, Irvine, CA) was used to assess cardiac output using thermodilution. An MPVS Ultra System (Millar Instruments) was used to acquire analog pressure-volume signals and convert to digital data. Data analyses were performed using an iox2 application (Emka Technologies, Falls Church, VA). Volume data was calibrated using cardiac output derived from Swan-Ganz (α), and three-dimensional echocardiography (3DE) derived end-diastolic volume (parallel conductance). After baseline hemodynamic evaluation, Impella CP (Abiomed Inc. Danvers, MA) was inserted through separate percutaneously established access in the left carotid or femoral artery. Anticoagulation was managed by intravenous injection of heparin. A full pump support was attempted in all animals, but was precluded in 6 pigs due to right ventricular failure that was unmasked by LV support. In these 6 animals, Impella flow was adjusted to the maximum achievable flow without inducing right ventricular failure. The impact of mechanical LV support on right ventricular function and morphology has been recently reported[12].

Echocardiographic study

Pigs underwent trans-thoracic echocardiographic studies before and 2 hours after the initiation of LV unloading. A Philips iE-33 ultrasound system (Philips Medical Systems, Andover, MA, USA) was used to acquire echocardiographic data with a multi-frequency imaging transducer. A 3DE study was performed before LV unloading and LV volumes as well as ejection fraction were measured using Q-Lab software (Figure 1). Two-Dimensional longitudinal images were obtained from the sub-sternal access, and cross sectional short-axis images at the mid-papillary level were obtained from the para-sternal access. The sector size and depth were adjusted to achieve optimal visualization of LV myocardium at the highest possible frame rate (mean values were 70 ± 11 and 85 ± 10 frames/s for apical and short axis views, respectively). Change in LV ejection fraction before and after LV unloading was evaluated by area-length method in 2D images. The 2D images were loaded into the QSTATION 3.7, which uses Q-Lab 10.7 (Philips Medical Systems, Andover, MA, USA) for strain analysis using a speckle-tracking algorithm. In each view, the myocardium was automatically divided by the software into six segments. The peak longitudinal strain (LS) and circumferential strain (CS) were measured from an average strain curve representing all analyzed segments from apical 4 chambers and mid-papillary short-axis views, respectively. The adequacy of tracking was verified visually. If needed, the region of interest, endocardial and epicardial borders were adjusted manually to achieve optimal tracking. Technical difficulties in obtaining good quality echocardiographic images in some of the animals precluded evaluation of LS (n=1) and CS (n=3) during LV unloading. In other datasets, 275 (97.5%) of the 282 myocardial segments were appropriately tracked in apical views and 267 (99%) of the 270 myocardial segments were tracked in short axis views. LS and CS strain analysis was performed by an investigator blinded to the LV unloading status and the

hemodynamic data. Inter-observer variability was assessed in 10 randomly chosen images by another investigator blinded to the hemodynamic data.

Statistical Analysis

Continuous variables are expressed as mean $\pm$ standard deviation. The paired-T test was used to compare the differences before and after LV unloading. Linear regression analysis was used to examine the relationships between LV stroke work and strains. Interclass correlation coefficient (ICC) was calculated to assess the agreement between the investigators. A p-value of <0.05 was considered statistically significant. Statistical analysis was performed with SPSS V.23 for windows (IBM Corp, Armonk, NY). Plot graphs were created by using GraphPad Prism version 6.00 for Windows (GraphPad Software, La Jolla California).

Results

One female pig after left anterior descending artery infarction presented with a continuous junctional rhythm during echocardiography before Impella, and showed dyssynchrony of the LV contraction. This animal was excluded from the analysis to avoid potential interference from the dyssynchrony. All other pigs ($n=23$) were in sinus rhythm. Animals exhibited decreased LV ejection fraction ($69.7 \pm 7.0\%$ vs $38.5 \pm 9.2\%$, $p<0.001$) and increased LV volumes (LV end-diastolic volume: $76 \pm 14\text{ml}$ vs $114 \pm 17\text{ ml}$, $p<0.001$, end-systolic volume: $23 \pm 7\text{ ml}$ vs $71 \pm 17\text{ ml}$, $p<0.001$) after MI (before MI vs at the time of acute LV unloading experiment, respectively) (Figure 1). Significant mechanical noise was detected with Doppler-based measurements in all studied animals, precluding reliable cardiac function and flow evaluation using Doppler-based approaches. No apparent interference from the mechanical noise was noted for strain analyses.

Hemodynamic parameters acquired by invasive pressure-volume catheter before and 2 hours after LV unloading are shown in Table 1. Impella-mediated LV unloading significantly reduced LV end-diastolic pressure, dP/dt maximum, dP/dt minimum, end-diastolic volume, and stroke volume. LV stroke work also decreased significantly, indicating efficient reduction of external LV work by mechanical LV unloading (Figure 2). At the same time, the majority of pigs exhibited decreases in LV ejection fraction, LS, and CS after Impella-mediated LV unloading (Figure 3). Regression analysis demonstrated significant linear relationships between LV stroke work and LV ejection fraction ($r=0.63$, $p<0.001$), LS ($r=-0.61$, $p<0.001$), as well as CS ($r=-0.75$, $p<0.001$) (Figure 4). LV stroke work also exhibited significant linear correlations to dP/dt maximum ($r=0.62$, $p<0.001$), dP/dt minimum ($r=-0.65$, $p<0.001$), LV end-diastolic volume ($r=0.41$, $p=0.005$), and stroke volume ($r=0.84$, $p<0.001$). Inter-observer variability suggested good reproducibility of analysis in both LS (ICC=0.92) and CS (ICC=0.95).

Discussion

In this study, we demonstrated that Impella-mediated acute LV unloading significantly reduces LV stroke work, and STE-derived LS and CS exhibit linear relationships to LV stroke work. These data suggest that the degree of LV unloading can be non-invasively

estimated by STE-based strain analyses in subacute MI setting. It is of note that the studied animals had heterogeneous profiles of subacute MI, i.e. complete transmural MI with thrombus injection, semi-transmural MI with ischemic reperfusion, anterior MI, and posterior MI. Similar variability is expected in clinical MI, thus demonstrating that the utility of strain assessment in our pig population ensures its clinical utility.

Reduced LV stroke work after Impella LV support is consistent with unloading of the LV. LV stroke work represents the amount of LV work executed against the external environment, and with its reduction, it is expected that the LV is effectively unloaded and myocardial oxygen consumption is reduced. Based on the emerging concept that LV unloading may protect the heart from cardiac injury in acutely decompensated cardiac diseases[5,13,14,3], reliable methods to assess appropriate degree of unloading are required. Currently, invasive approaches such as myocardial oxygen consumption and pressure-volume relationship assessments are the gold-standard to precisely evaluate the extent of LV work. However, these approaches may not be optimal for evaluating the degree of LV unloading in a clinical setting, because they require insertion of additional catheters into severely sick patients with percutaneous LV assist devices already in place. This can increase the risk of infection, thromboembolism, and bleeding.

Our data suggest that STE-based echocardiographic strain analysis offers non-invasive evaluation of LV unloading in a safe and reliable manner. Both LS and CS showed linear correlations to reduced LV stroke work, suggesting that global reduction of LV work and oxygen consumption can be detected by echocardiography. In our dataset, LV ejection fraction measured by 2D area-length method, which is one of the most commonly used approaches to evaluate cardiac function in clinic, also showed similar strength of correlation to the LV stroke work. Unfortunately, the current study was not designed to determine the most sensitive method and was underpowered for comparison between the variables. Nevertheless, superior sensitivity of LV strain analysis over LV ejection fraction to detect subtle changes in LV function has been reported[15,16]. Similar to invasively assessed LV stroke work[3,17], myocardial deformation mirrors the complex interaction of LV preload, afterload and contractility[18]. Whether it allows better estimation of LV unloading and, if so, which of the strain parameters show the best estimate remain to be examined in future studies.

In this study, we used pressure-volume loop derived stroke work to estimate the degree of LV unloading. While LV stroke work reflects LV external work, it does not account for internal work[19]. Acute LV unloading using mechanical support is expected to reduce internal LV work as well. Therefore, assessment of pressure-volume area during the preload reduction studies would have provided a more accurate LV work assessment, as this parameter also accounts for internal work[20,3]. Unfortunately, preload reduction (inferior vena cava occlusion) under Impella support resulted in a pump flow reduction due to the suction effect in a majority of animals, precluding reliable assessment of this metric in the animals studied. Future studies using a combination of pressure-volume assessment together with myocardial oxygen consumption may provide better understandings of LV internal work reduction under LV unloading.

Limitation

Our study has several limitations. First, echocardiographic assessments were conducted at only two time points: before and after the maximum achievable mechanical support. To more precisely evaluate relationships between varying degrees of LV unloading and strains, strain evaluation during step-wise changes in LV mechanical support would be ideal. Unfortunately, technical difficulty in repeatedly changing body position in anesthetized pigs with multiple catheters inserted precluded this evaluation. Second, our pig studies were conducted 1–2 weeks after MI, and whether CS and LS also correlate with LV stroke work in more acute or chronic settings remains unclear. Third, the pig apex is located relatively medial compared to the human apex. Although cardiac anatomy of the pig is very similar to that of humans, different orientation of the heart may have affected the analysis due to the software setting that was designed to analyze the human heart. Nevertheless, using the Q-Lab software, we have previously reported its feasibility and utility in evaluating function of the pig heart[21,22,9,23]. Finally, although the investigators were blinded for the unloading status, the Impella cannula was visible on LV unloading images and precluded complete blinding.

Conclusion

Acute LV unloading using Impella reduces LV stroke work in post-MI pigs. Both LS and CS assessed by STE exhibited significant linear relationships with the LV stroke work, suggesting its utility in non-invasively assessing the degree of LV unloading at the bedside using echocardiography.

Acknowledgement

The authors thank Lauren Leonardson, LVT for her excellent technical support.

Sources of Funding

This study was supported by National Institute of Health (NIH) R01 HL139963 (K.I.), HL117505, HL 119046, HL129814, HL128072, HL131404, HL135093, a P50 HL112324 (R.J.H.), American Heart Association- Scientist Development Grant 17SDG33410873 (K.I.), and two Transatlantic Fondation Leducq grants. O.B. was supported by the Deutsche Herzstiftung. We would like to acknowledge the Gene Therapy Resource Program (GTRP) of the National Heart, Lung, and Blood Institute, NIH.

Disclosures

K.I. received a research grant from Abiomed Inc (Danvers, Massachusetts) and the Impella device was provided from the company. N.H. reports consulting/advisory activities for Philips. G.L. received a research grant from Abiomed Inc not related to current study.

Abbreviations

2DE	Two-dimensional echocardiography
3DE	Three-dimensional echocardiography
CS	Circumferential strain
ICC	Interclass correlation coefficient

LS	Longitudinal strain
LV	Left ventricular
MI	Myocardial infarction
STE	Speckle-tracking echocardiography

References

1. Kuchibhotla S, Esposito ML, Breton C, Pedicini R, Mullin A, O'Kelly R, et al. (2017). Acute Biventricular Mechanical Circulatory Support for Cardiogenic Shock. *Journal of the American Heart Association*, 6(10), doi:ARTN e00667010.1161/JAHA.117.006670.
2. Burzotta F, Trani C, Doshi SN, Townend J, van Geuns RJ, Hunziker P, et al. (2015). Impella ventricular support in clinical practice: Collaborative viewpoint from a European expert user group. *International Journal of Cardiology*, 201, 684–691, doi:10.1016/j.ijcard.2015.07.065. [PubMed: 26363632]
3. Burkhoff D, & Naidu SS (2012). The science behind percutaneous hemodynamic support: A review and comparison of support strategies. *Catheterization and Cardiovascular Interventions*, 80(5), 816–829, doi:10.1002/ccd.24421. [PubMed: 22431494]
4. Meyns B, Stolinski J, Leunens V, Verbeken E, & Flameng W (2003). Left ventricular support by catheter-mounted axial flow pump reduces infarct size. *Journal of the American College of Cardiology*, 41(7), 1087–1095, doi:10.1016/S0735-1097(03)00084-6. [PubMed: 12679206]
5. Kapur NK, Qiao XY, Paruchuri V, Morine KJ, Syed W, Dow S, et al. (2015). Mechanical Pre-Conditioning With Acute Circulatory Support Before Reperfusion Limits Infarct Size in Acute Myocardial Infarction. *Jacc-Heart Failure*, 3(11), 873–882, doi:10.1016/j.jchf.2015.06.010. [PubMed: 26541785]
6. Soucy KG, Bartoli CR, Phillips D, Giridharan GA, Sobieski MA, Wead WB, et al. (2017). Continuous-Flow Left Ventricular Assist Device Support Improves Myocardial Supply:Demand in Chronic Heart Failure. *Annals of Biomedical Engineering*, 45(6), 1475–1486, doi:10.1007/s10439-017-1804-x. [PubMed: 28168379]
7. Collier P, Phelan D, & Klein A (2017). A Test in Context: Myocardial Strain Measured by Speckle-Tracking Echocardiography. *Journal of the American College of Cardiology*, 69(8), 1043–1056, doi:10.1016/j.jacc.2016.12.012. [PubMed: 28231932]
8. Prastaro M, Pirozzi E, Gaibazzi N, Paolillo S, Santoro C, Savarese G, et al. (2017). Expert Review on the Prognostic Role of Echocardiography after Acute Myocardial Infarction. *Journal of the American Society of Echocardiography*, 30(5), 431–, doi:10.1016/j.echo.2017.01.020. [PubMed: 28477781]
9. Ishikawa K, Aguero J, Tilemann L, Ladage D, Hammoudi N, Kawase Y, et al. (2014). Characterizing preclinical models of ischemic heart failure: differences between LAD and LCx infarctions. *Am J Physiol Heart Circ Physiol*, 307(10), H1478–1486, doi:10.1152/ajpheart.00797.2013. [PubMed: 25217654]
10. Watanabe S, Fish K, Kovacic JC, Bikou O, Leonardson L, Nomoto K, et al. (2018). Left Ventricular Unloading Using an Impella CP Improves Coronary Flow and Infarct Zone Perfusion in Ischemic Heart Failure. *Journal of the American Heart Association*, 7(6), doi:10.1161/JAHA.117.006462.
11. Ishikawa K, Aguero J, Oh JG, Hammoudi N, Fish LA, Leonardson L, et al. (2015). Increased Stiffness Is the Major Early Abnormality in a Pig Model of Severe Aortic Stenosis and Predisposes to Congestive Heart Failure in the Absence of Systolic Dysfunction. *Journal of the American Heart Association*, 4(5), doi:ARTN e00192510.1161/JAHA.115.001925.
12. Addetia K, Uriel N, Maffessanti F, Sayer G, Adatya S, Kim GH, et al. (2017). 3D Morphological Changes in LV and RV During LVAD Ramp Studies. *JACC Cardiovasc Imaging*, doi:10.1016/j.jcmg.2016.12.019.

13. Sun XT, Li J, Zhao WP, Lu SY, Guo CF, Lai H, et al. (2016). Early Assistance With Left Ventricular Assist Device Limits Left Ventricular Remodeling After Acute Myocardial Infarction in a Swine Model. *Artificial Organs*, 40(3), 243–251, doi:10.1111/aor.12541. [PubMed: 26332939]
14. Perry P, David E, Atkins B, & Raff G (2017). Novel application of a percutaneous left ventricular assist device as a bridge to transplant in a paediatric patient with severe heart failure due to viral myocarditis. *Interactive Cardiovascular and Thoracic Surgery*, 24(3), 474–476, doi:10.1093/icvts/ivw387. [PubMed: 28040759]
15. Potter E, & Marwick TH (2018). Assessment of Left Ventricular Function by Echocardiography: The Case for Routinely Adding Global Longitudinal Strain to Ejection Fraction. *JACC Cardiovasc Imaging*, 11(2 Pt 1), 260–274, doi:10.1016/j.jcmg.2017.11.017. [PubMed: 29413646]
16. Smiseth OA, Torp H, Opdahl A, Haugaa KH, & Urheim S (2016). Myocardial strain imaging: how useful is it in clinical decision making? *Eur Heart J*, 37(15), 1196–1207, doi:10.1093/eurheartj/ehv529. [PubMed: 26508168]
17. Burkhoff D, & Naidu SS (2012). The science behind percutaneous hemodynamic support: a review and comparison of support strategies. *Catheter Cardiovasc Interv*, 80(5), 816–829, doi:10.1002/ccd.24421. [PubMed: 22431494]
18. Burns AT, La Gerche A, D'Hooge J, MacIsaac AI, & Prior DL (2010). Left ventricular strain and strain rate: characterization of the effect of load in human subjects. *Eur J Echocardiogr*, 11(3), 283–289, doi:10.1093/ejehocardiogr/jep214. [PubMed: 20026455]
19. Burkhoff D, Sayer G, Doshi D, & Uriel N (2015). Hemodynamics of Mechanical Circulatory Support. *Journal of the American College of Cardiology*, 66(23), 2664–2674.
20. Suga H (1990). Cardiac mechanics and energetics--from Emax to PVA. *Front Med Biol Eng*, 2(1), 3–22. [PubMed: 2271404]
21. Ishikawa K, Aguero J, Oh JG, Hammoudi N, Fish LA, Leonardson L, et al. (2015). Increased stiffness is the major early abnormality in a pig model of severe aortic stenosis and predisposes to congestive heart failure in the absence of systolic dysfunction. *Journal of the American Heart Association*, 4(5), doi:10.1161/JAHA.115.001925.
22. Ishikawa K, Watanabe S, Hammoudi N, Aguero J, Bikou O, Fish K, et al. (2018). Reduced longitudinal contraction is associated with ischemic mitral regurgitation after posterior MI. *Am J Physiol Heart Circ Physiol*, 314(2), H322–H329, doi:10.1152/ajpheart.00546.2017. [PubMed: 29101180]
23. Ishikawa K, Kawase Y, Ladage D, Chemaly ER, Tilemann L, Fish K, et al. (2012). Temporal changes of strain parameters in the progress of chronic ischemia: with comparison to transmural infarction. *Int J Cardiovasc Imaging*, 28(7), 1671–1681, doi:10.1007/s10554-012-0010-z. [PubMed: 22231467]

Figure 1. Impact of MI on 3DE parameters.

A: Representative LV 3DE analysis using Q-Lab software in a pig after MI. B: Quantitation data of 3DE demonstrated decreased LV ejection fraction and increased LV end-diastolic as well as end-systolic volumes. 3DE=three-dimensional echocardiography, LV=left ventricular, MI=myocardial infarction,

Figure 2. LV stroke work is reduced after Impella mediated LV unloading.

A: Representative LV pressure-volume loops before (baseline) and after (Imp) LV unloading with Impella. B: LV stroke work was significantly reduced after LV unloading. Paired T-test was used for deriving p-value.

Figure 3. LS and CS before and after LV unloading using Impella.

A: Representative images of strain analysis for LS (top) and CS (bottom) before (left) and after (right) LV unloading using Impella. B: Both LS and CS showed significant reduction in absolute values after LV unloading using Impella. LVEF evaluated by 2D area-length method also showed decrease after LV unloading. Paired T-test was used for deriving p-values. In our previous studies, both CS and LS for normal pigs were approximately -20% to -25% [9,23]. 2D=two-dimensional, CS=circumferential strain, EF=ejection fraction, LS=longitudinal strain, LV=left ventricular,

Figure 4. Linear correlations between LV stroke work and strains.

Both circumferential strain (left) and longitudinal strain (right) exhibited significant linear relationships to LV stroke work. LVEF evaluated by 2DE showed positive relationship with the LV stroke work. Open circles indicate before (baseline) and closed circles indicate after (Imp) LV unloading.

Table.

PV catheter derived parameter changes before and after LV unloading

	Baseline	Unloading	p
Maximum LV pressure (mmHg)	110 ± 21	100 ± 28	0.20
End-diastolic pressure (mmHg)	22.8 ± 6.6	13.8 ± 7.5	<0.001
dP/dt maximum (mmHg/s)	1682 ± 589	1132 ± 378	0.001
dP/dt minimum (mmHg/s)	-1698 ± 476	-1192 ± 412	<0.001
Tau (msec)	57 ± 12	60 ± 12	0.42
End-diastolic volume (mL)	113 ± 16	84 ± 14	<0.001
End-systolic volume (mL)	73 ± 21	72 ± 18	0.89
Stroke volume (mL)	44 ± 13	27 ± 10	<0.001
Stroke work (mmHg*mL)	3399 ± 1440	1244 ± 659	<0.001

LV = left ventricular, PV=pressure-volume, p-values are derived from paired T-test