Improvement of left ventricular function assessment by global longitudinal strain after successful percutaneous coronary intervention for chronic total occlusion

Misato Chimura, Shinichiro Yamada, Yoshinori Yasaka, Hiroya Kawai
Himeji Cardiovascular Center, Himeji, Japan
* mstogncmr@gmail.com

Abstract

The benefit of revascularization of chronic total occlusion (CTO) in percutaneous coronary intervention (PCI) is controversial. On the other hand, left ventricular (LV) global longitudinal strain (GLS) is a more sensitive marker of LV myocardial ischemia and LV function than LV ejection fraction (EF). The purpose of this study was to investigate the impact of revascularization of CTO on LV function using LV GLS. A total of 70 consecutive patients (65.1±8.9 years, 59 males, LVEF 51.0±12.0%) with CTO who had a positive functional ischemia and underwent PCI, were included in this study. Echocardiography was performed before and 9 months after the procedure with conventional assessment including LV end-diastolic and end-systolic volume (LVEDV, LVESV), LVEF, and with 2DSTE analysis of GLS. Successful PCI was obtained in 60 patients (86%). There were no stent thromboses during follow-up. GLS showed a significant improvement 9 months after successful PCI (pre-PCI -12.4±4.1% vs. post-PCI -14.5±4.1%, P<0.01), whereas in failed PCI group that did not change significantly (pre-PCI -13.2±4.2% vs. post-PCI -14.0±4.7%, P = 0.64). LVEF, LVEDV and LVESV did not change significantly during follow-up in both successful and failed groups. Successful PCI for CTO improved LV function, assessed by LV GLS.

Introduction

Chronic total occlusions (CTO) are defined as lesions with TIMI (Thrombolysis in Myocardial Infarction) grade 0 flow for more than three months. CTO lesions are identified in 18.4% in patients undergoing elective percutaneous coronary intervention (PCI) in the absence of previous coronary artery bypass surgery or those presenting with acute myocardial infarction [1]. Several previous studies reported the effect of successful PCI for CTO, such as improvement of quality of life, exercise capacity, and reducing the need for late CABG surgery [2, 3]. However the benefits of revascularization using PCI for CTO are still controversial. Two-dimensional speckle-tracking echocardiography (2DSTE) is emerging as a novel technique to allow the assessment of LV systolic and diastolic function through the quantification of active myocardial deformation [4–6]. The global longitudinal strain (GLS) assessed with 2DSTE, which
evaluates the longitudinal myocardial deformation, is more reproducible than left ventricular ejection fraction (LVEF) or wall motion score index (WMSI), is advantageous over the color kinesis technique and is proven to be effective in detecting the LV myocardial ischemia [7–13]. Moreover, in patients with cardiovascular disease, myocardial dysfunction occurs even if overall LVEF is preserved, and that may be associated with impaired LV longitudinal deformation [14]. Accordingly, the purpose of this study was to investigate the impact of revascularization of CTO on LV function using LV GLS.

Methods

Patients

We conducted a retrospective study in a cohort of 70 consecutive patients with CTO who had attempted PCI at Himeji Cardiovascular Center between May 2009 and February 2014. All patients had single vessel coronary artery disease with CTO and had a positive functional ischemia study. We excluded patients who had an anticipated noncompliance with dual antiplatelet treatment for at least 12 months, the history of coronary artery bypass surgery, severe valvular disease, other co-morbid systemic disease and atrial fibrillation. CTO was defined as a coronary artery obstruction with thrombolysis in myocardial infarction (TIMI) grade 0 and all patients had a native vessel occlusion estimated to be of at least 3 months duration based on the time from diagnosis made on coronary angiography [15]. PCI and stent implantation were performed in a standard manner. Drug-eluting stents (DESs) were used in all of the PCI procedures. After the PCI, all of the patients were prescribed lifelong aspirin and clopidogrel for at least 12 months. Collateral channels and their Rentrop classification were analyzed in the preprocedural coronary angiography. Successful PCI was defined as follows; the residual stenosis < 50% by visual estimation, a restoration of TIMI flow 3 in the target vessel after stent implantation and no immediate angiographic complications. Failed PCI was defined as failure to cross the occlusion or reduce obstruction to less than 50% in the target CTO [16].

All of the patients underwent an extensive baseline clinical history taking and physical examination, 12-lead electrocardiography, and transthoracic echocardiography. This study was approved by the research ethics committee of Himeji Cardiovascular Center and carried out in accordance with approved guidelines. Written informed consent was obtained from all patients.

Transthoracic echocardiography

Echocardiography was performed before and 9 months after the procedure (Fig 1). Comprehensive transthoracic echocardiography was performed by experienced research sonographers by using commercially available Aplio (Toshiba Medical Systems, Tokyo, Japan). Two-dimensional and color Doppler echocardiography were performed in standard parasternal and apical views. LV end-diastolic volume (EDV), end-systolic volume (ESV), and LVEF were measured using a modified Simpson method. All images were stored online and measured with offline software later by independent investigators who were blinded to the clinical data.

LV strain measurements

The LV GLS was obtained by using 2DST software (Toshiba Medical Systems, Tokyo, Japan). The endocardial border was traced manually in the end-diastolic frame. The software automatically tracked the myocardium throughout the cardiac cycle. The peak values of segmental longitudinal strain were obtained from greyscale-recorded images in the apical four-chamber, two-chamber, and long-axis views with a frame rate between 50 and 70 frames per second, and GLS was obtained by averaging the peak values [17] (Fig 2). The coefficients of variation of
Fig 1. Patient flow chart.

https://doi.org/10.1371/journal.pone.0217092.g001

https://doi.org/10.1371/journal.pone.0217092.g002

Fig 2. Example of the measurement of left ventricular (LV) global longitudinal strain (GLS) with a two-dimensional speckle-tracking echocardiography (2DSTE) in a patient with chronic total occlusion who underwent successful percutaneous coronary intervention (PCI). Figure (a) and (b) showed apical four-chamber view. White broken lines indicated the LV global strain curves for GLS. Yellow arrow indicated the mean LV global peak longitudinal strain; GLS: −22.5% (c).

https://doi.org/10.1371/journal.pone.0217092.g002
interobserver variability for GLS was 8%. The coefficients of variation of intraobserver variability for GLS was 3% in our previous study [18].

Statistical analysis

Data are expressed as mean ± standard deviation for continuous variables, and median and interquartile range for non-normally distributed continuous variables. Data from the successful and failed PCI groups were compared by using the Student’s t-test and one-way analysis of variance (ANOVA) for normally distributed continuous variables, the Wilcoxon–Mann–Whitney test for non-normally distributed continuous variables, and the χ² test or Fisher’s exact test for categorical variables. Changes in the LVEDV, LVESV, LVEF and GLS data between the before and the 9 months after the procedure were assessed by ANOVA. A value of p < 0.05 were considered statistically significant. MedCalc Version 12.7.8 (Acacialaan 22, B-8400 Ostend, Belgium) was used for all analyses.

Results

Between January 2009 and December 2013, a total of 70 CTO lesions (in 70 patients) were targeted, and 60 lesions were successfully revascularized with PCI, and 10 lesions were failed (Fig 1). No procedural complications (coronary perforation, cardiac tamponade or emergent cardiac surgery) were observed in any patients undergoing CTO-PCI attempt. During the 9-month from the procedure, there were no changes in prescribed medical treatment, such as beta-blockers, angiotensin receptor blockers or angiotensin converting enzyme inhibitors, and nitrates, and no cardiac resynchronization therapy and pacemaker were implanted.

Clinical and angiographic data

Baseline characteristics are shown in Table 1. The mean age of the patients was 65.1 ± 8.9 years. Eighty-four percent of the patients were male, 57% of the patients had a history of hypertension, 57% of the patients had a history of diabetes mellitus, 89% of the patients had a history of dyslipidemia, 50% of the patients were smokers, 58% of the patients were on ACEI and/or ARB, 53% of the patients were on beta-blockers, 39% of the patients were on nitrates, and 87% of the patients were on statins.

| Table 1. Patient baseline characteristics. |
|-------------------------------------------|
| **Demographics**                           |
| Age (years)                                | 65.1 ± 8.9 | 65.2 ± 9.0 | 64.2 ± 8.6 | 0.74 |
| Male, n (%)                                | 59 (84)    | 51 (85)    | 8 (80)     | 0.90 |
| Hypertension, n (%)                        | 64 (91)    | 55 (92)    | 9 (90)     | 0.86 |
| Diabetes Mellitus, n (%)                   | 40 (57)    | 33 (55)    | 7 (70)     | 0.38 |
| Dyslipidemia, n (%)                        | 62 (89)    | 53 (88)    | 9 (90)     | 0.89 |
| Smoking, n (%)                             | 35 (50)    | 30 (50)    | 5 (50)     | 0.66 |
| Systolic BP (mm Hg)                        | 131 ± 24   | 132 ± 25   | 125 ± 18   | 0.45 |
| Heart rate (beats/min)                     | 68±11      | 67±11      | 71±14      | 0.30 |
| **Laboratory data**                        |
| Serum creatinine (mg/dL)                   | 1.1 ± 1.0  | 1.1 ± 1.0  | 1.0 ± 0.7  | 0.66 |
| **Medications**                            |
| ACEI and/ or ARB, n (%)                    | 41 (58)    | 35 (58)    | 6 (60)     | 0.92 |
| Beta-blockers, n (%)                       | 37 (53)    | 32 (53)    | 5 (50)     | 0.85 |
| Nitrates, n (%)                            | 27 (39)    | 22 (37)    | 5 (50)     | 0.65 |
| Statin, n (%)                              | 61 (87)    | 52 (87)    | 9 (90)     | 0.78 |

ARB, angiotensin II receptor blocker; ACEI, angiotensin converting enzyme inhibitor; BP, blood pressure; and PCI, percutaneous coronary intervention

https://doi.org/10.1371/journal.pone.0217092.t001
diabetes and 91% of the patients had hypertension. There were no significant difference in baseline characteristics between successful and failed PCI group. The angiographic characteristics of CTO lesions are shown in Table 2. The most common location of CTO was right coronary artery (RCA), followed by left anterior descending artery (LAD) and left circumflex artery (LCX). A total of 60 CTOs were revascularized, 19 CTOs in LAD, 31 CTOs in RCA, and 10 CTOs in LCX. Location of CTO and grade of collateral flow (Rentrop score) did not differ significantly between successful and failed PCI group. There were no stent thromboses during the 9 month follow-up.

### Echocardiographic measurement

Echocardiographic parameters are shown in Table 3. There were no significant differences in baseline LV function and volume between successful and failed PCI groups. GLS showed a significant improvement 9 months after successful PCI group (pre-PCI -12.4±4.1% vs. post-PCI -14.5±4.1%, P < 0.01), whereas that did not change significantly after failed PCI group (pre-PCI -13.2±4.2% vs. post-PCI -14.0±4.7%, P = 0.64). On the other hands, LVEF (pre-PCI 50.2 ±12.3% vs. post-PCI 52.4±10.7%, P = 0.33, pre-PCI 55.9±8.9% vs. post-PCI 53.2±9.9%, P = 0.53), LVEDV (pre-PCI 122.9±39.1ml vs. post-PCI 121.1±41.1ml, P = 0.72, pre-PCI 116.1±51.2ml vs. post-PCI 117.6±49.7ml, P = 0.88) and LVESV (pre-PCI 58.5±32.3ml vs. post-PCI 55.7±33.9ml, P = 0.39, pre-PCI 48.1±30.0ml vs. post-PCI 49.3±36.3ml, P = 0.97) showed no significant changes both successful and failed PCI groups during the 9 month follow-up, respectively (Figs 3 and 4).

### Table 2. Lesion characteristics.

| Lesion characteristics | All Patients (n = 70) | Successful PCI (n = 60) | Failed PCI (n = 10) | p Value |
|------------------------|-----------------------|-------------------------|---------------------|---------|
| Chronic total occlusion location | | | | |
| RCA/LCX/LAD, n (%) | 37/11/22 | 31/10/19 | 6/1/3 | 0.79 |
| Rentrop score (0/1/2/3) | 0/1/60/9 | 0/1/51/8 | 0/0/9/1 | 0.89 |
| Number of treated with stents, n (%) | N/A | 57 (95) | N/A | N/A |
| Number of stents per lesion, n (%) | N/A | 1.5 ± 0.5 | N/A | N/A |
| Stent length, (mm. per stented lesion) | N/A | 38 ± 16 | N/A | N/A |
| Stent thrombosis, n (%) | N/A | 0 (0) | N/A | N/A |

LAD, left anterior descending artery; LCX, left circumflex artery; and RCA, right coronary artery; other abbreviations are as defined in Table 1.

https://doi.org/10.1371/journal.pone.0217092.t002

### Table 3. Echocardiographic measures.

| Echocardiographic measures | All Patients (n = 70) | Successful PCI (n = 60) | Failed PCI (n = 10) | p Value |
|---------------------------|-----------------------|-------------------------|---------------------|---------|
| Echocardiographic data | | | | |
| LVEDV (mL) | 121.9 ± 40.7 | 122.9 ± 39.1 | 116.1 ± 51.2 | 0.63 |
| LVESV (mL) | 57.0 ± 31.9 | 58.5 ± 32.3 | 48.1 ± 30.0 | 0.35 |
| LVEF (%) | 51.0 ± 12.0 | 50.2 ± 12.3 | 55.9 ± 8.9 | 0.11 |
| E/A ratio | 0.72 ± 0.20 | 0.72 ± 0.19 | 0.73 ± 0.21 | 0.85 |
| GLS (%) | -12.2 ± -4.7 | -12.4 ± -4.1 | -13.2 ± -4.2 | 0.47 |

E/A ratio, ratio of early transmtiral flow to atrial contraction; GLS, global longitudinal strain; LVEF, left ventricular ejection fraction; LVEDV, left ventricular end-diastolic volume; and LVESV, left ventricular end-systolic volume; other abbreviations are as defined in Tables 1 or 2.

https://doi.org/10.1371/journal.pone.0217092.t003
Discussion

In this study, we investigated the impact of revascularization of CTO on LV function using LV GLS. Successful PCI for CTO improved LV function assessed by LV GLS. To the best of our knowledge, this is the first study to demonstrate the comparison with successful and failed CTO-PCI patients with a positive functional ischemia before PCI, according to LV function evaluated with LV GLS before and after 9 month PCI.

CTO is common, being reported in 30% of patients undergoing coronary angiography [19, 20]. However, the benefits of PCI for CTO are controversial. The procedure lasted several hours with significant radiation exposure and contrast dose. Furthermore the higher complication rates of CTO procedure even in experienced dedicated PCI operators and the higher
failure rates of CTO-PCI, were still reported [21–26]. Therefore, it is important to select the patients suitable for CTO-PCI and to assess the impact of CTO revascularization by conventional assessment.

Several investigators reported the effect of revascularization of CTO on LV function. Henriques et al. reported that they did not find an overall benefit for CTO-PCI in terms of LVEF or LVEDV [27]. Mashayekhi et al. reported that no benefit was seen for CTO-PCI in terms of the segmental wall thickening, LVEF and LVEDV [28]. In this study, LVEF and LVEDV also showed no significant changes both successful and failed PCI groups during the 9 month follow-up, respectively. However, since there was report that reduced major adverse coronary event rates at 12 months in CTO-PCI compared with optimal medical therapy [28], we assessed cardiac function evaluated by GLS, with the idea that some improvement in cardiac function that can not be assessed by LVEF or LVEDV in successful CTO-PCI group.

GLS assessed with 2DSTE is a new echocardiographic technique for the evaluation of global myocardial function. This method is based on tracking the characteristics speckle patterns created by interference of ultrasound beams in the myocardium. Its accuracy has been confirmed using CMR [29] and it does not require special equipment. Kalam et al. showed that the subendocardial longitudinal fiber is more sensitive to myocardial ischemia and the depressed LV longitudinal function occurred at an earlier stage than abnormal radial contraction, as assessed by the LVEF [30]. GLS represents the subendocardial longitudinal fiber movement [31], therefore, in the case of preserved LVFE CTO patients, GLS assessed by 2DSTE is a quite suitable method to evaluate the change of myocardial ischemic burden.

In this study, we studied of preserved LVEF patients with positive functional ischemia of CTO lesion before PCI, and assessed the effect of revascularization of CTO on LV function using GLS assessed by 2DSTE before and 9 months after procedure. GLS showed a significant improvement 9 months after successful PCI, whereas that in failed PCI group did not change significantly. These results indicated that CTO revascularization improves LV function.

Limitation
This study is limited by the fact that it was a single center, retrospective study and had a small sample size, which might diminish the power of the drawn statistical inference. A further study with a large scale prospective, multicenter design is thus required to confirm our results. An additional limitation to this study is that radial and circumferential strain were not explored. However, it has been recently reported that longitudinal deformation may be a more sensitive marker of cardiac function compared with radial and circumferential strain, especially in chronic ischemic patients [32], so not assessing the radial and circumferential strain dose not affect the result. And then the assessment of the success or failure of the PCI was done immediately after the PCI; it may not reflect what happened later during the 9 months.

Conclusion
Successful PCI for CTO improved LV function, assessed by LV GLS.

Acknowledgments
The authors greatly thank the doctors of the Department of Cardiology and the sonographers of Echo Lab at Himeji Cardiovascular Center for their help in this study.

Author Contributions
Conceptualization: Misato Chimura, Yoshinori Yasaka, Hiroya Kawai.
**Data curation:** Misato Chimura, Yoshinori Yasaka.

**Formal analysis:** Misato Chimura, Shinichiro Yamada.

**Investigation:** Misato Chimura.

**Project administration:** Misato Chimura.

**Writing – original draft:** Misato Chimura.

**Writing – review & editing:** Misato Chimura, Shinichiro Yamada, Hiroya Kawai.

**References**

1. Fefer P, Knudtson ML, Cheema AN, Galbraith PD, Osherov AB, Yalonetskyy S, et al. Current perspectives on coronary chronic total occlusions: the Canadian Multicenter Chronic Total Occlusions Registry. J Am Coll Cardiol. 2012; 59:991–997. https://doi.org/10.1016/j.jacc.2011.12.007 PMID: 22402070

2. Grantham JA, Jones PG, Cannon L, Spertus JA. Quantifying the early health status benefits of successful chronic total occlusion recanalization: Results from the FlowCardia’s Approach to Chronic Total Occlusion Recanalization (FACTOR) Trial. Circ Cardiovasc Qual Outcomes 2010; 3:284–290 https://doi.org/10.1161/CIRCOUTCOMES.108.825760 PMID: 20388873

3. Mehran R, Claessen BE, Godino C, Dangas GD, Obunai K, Kanwal S, et al. Multinational Chronic Total Occlusion Registry. Long-term outcome of percutaneous coronary intervention for chronic total occlusions. JACC Cardiovasc Interv 2011; 4:952–961 https://doi.org/10.1016/j.jcici.2011.03.021 PMID: 21939934

4. Leitman M, Lysyansky P, Sidenko S, Shir V, Peleg E, Binenbaum M, et al. Two-dimensional strain-a novel software for real-time quantitative echocardiographic assessment of myocardial function. J Am Soc Echocardiogr 2004; 17:1021–1029 https://doi.org/10.1016/j.echo.2004.06.019 PMID: 15452466

5. Ng AC, Tran da T, Newman M, Allman C, Vidaic J, Kadappu KK, et al. Comparison of myocardial tissue velocities measured by two-dimensional speckle tracking and tissue Doppler imaging. Am J Cardiol 2008; 102:784–789 https://doi.org/10.1016/j.amjcard.2008.05.027 PMID: 18774007

6. Blessberger H, Binder T. NON-invasive imaging: Two dimensional speckle tracking echocardiography: basic principles. Heart 2010; 96:716–722 https://doi.org/10.1136/hrt.2007.141002 PMID: 20424157

7. Liou K, Negishi K, Ho S, Russell EA, Cranney G, Ooi SY. Detection of Obstructive Coronary Artery Disease Using Peak Systolic Global Longitudinal Strain Derived by Two-Dimensional Speckle-Tracking: A Systematic Review and Meta-Analysis. J Am Soc Echocardiogr 2016; 29:724–735 https://doi.org/10.1016/j.echo.2016.03.002 PMID: 27155815

8. Liu C, Li J, Ren M, Wang ZZ, Li ZY, Gao F, et al. Multilayer longitudinal strain at rest may help to predict significant stenosis of the left anterior descending coronary artery in patients with suspected non-ST-elevation acute coronary syndrome. Int J Cardiovasc Imaging 2016; 32:1675–1685 PMID: 27522670

9. Dimitriu-Leen AC, Scholte AJ, Katsanos S, Hoogslag GE, van Rosendael AR, van Zwet EW, et al. Influence of Myocardial Ischemia Extent on Left Ventricular Global Longitudinal Strain in Patients After ST-Segment Elevation Myocardial Infarction. Am J Cardiol 2017; 119:1–6 https://doi.org/10.1016/j.amjcard.2016.08.091 PMID: 27776800

10. Dattilo G, Imbalzano E, Lamari A, Casale M, Paunovic N, Busacca P, et al. Ischemic heart disease and early diagnosis. Study on the predictive value of 2D strain. Int J Cardiol 2016; 215:150–156 https://doi.org/10.1016/j.ijcard.2016.04.035 PMID: 27111182

11. Liel-Cohen N, Tsadok Y, Beeri R, Lysyansky P, Agmon Y, Feinberg MS, et al. A new tool for automatic assessment of segmental wall motion based on longitudinal 2D strain: a multicenter study by the Israeli Echocardiography Research Group. Circ Cardiovasc Imaging 2010; 3:47–53 https://doi.org/10.1161/CIRCIMAGING.108.841874 PMID: 19928289

12. Reisner SA, Lysyansky P, Agmon Y, Muttak D, Lessick J, Friedman Z. Global longitudinal strain: a novel index of left ventricular systolic function. J Am Soc Echocardiogr 2004; 17:630–633 https://doi.org/10.1016/j.echo.2004.02.011 PMID: 15163933

13. Stanton T, Leano R, Marwick TH. Prediction of all-cause mortality from global longitudinal speckle strain: comparison with ejection fraction and wall motion scoring. Circ Cardiovasc Imaging. 2009; 2:356–364 https://doi.org/10.1161/CIRCIMAGING.109.862334 PMID: 19808623

14. Shah AM, Solomon SD. Phenotypic and pathophysiological heterogeneity in heart failure with preserved ejection fraction. Eur Heart J 2012; 33:1716–1717 https://doi.org/10.1093/eurheartj/ehs124 PMID: 22730487
15. Di Mario C, Werner GS, Sianos G, Galassi AR, Böttner J, Dudek D, et al. European perspective in the recanalisation of Chronic Total Occlusions (CTO): consensus document from the EuroCTO Club. EuroIntervention 2007;3:30–43
16. George S, Cockburn J, Clayton TC, Ludman P, Cotton J, Spratt J, et al. British Cardiovascular Intervention Society; National Institute for Cardiovascular Outcomes Research. Long-term follow-up of elective chronic total coronary occlusion angioplasty: analysis from the U.K. Central Cardiac Audit Database. J Am Coll Cardiol 2014; 64:235–243 https://doi.org/10.1016/j.jacc.2014.04.040 PMID: 25034057
17. Kalam K, Otahal P, Marwick TH. Prognostic implications of global LV dysfunction: a systematic review and meta-analysis of global longitudinal strain and ejection fraction. Heart 2014; 100:1673–1680 https://doi.org/10.1136/heartjnl-2014-305538 PMID: 24860005
18. Chimura M, Onishi T, Tsukishiro Y, Sawada T, Kiuchi K, Shimanoe A, et al. Longitudinal strain combined with delayed-enhancement magnetic resonance improves risk stratification in patients with dilated cardiomyopathy. Heart 2017; 103:679–686 https://doi.org/10.1136/heartjnl-2016-309746 PMID: 27799316
19. Kahn JK. Angiographic suitability for catheter revascularization of total coronary occlusions in patients from a community hospital setting. Am Heart J 1993; 126:561–564 PMID: 8362709
20. Werner GS, Gitt AK, Zeymer U, Juenger C, Towae F, Wienbergen H, et al. Chronic total coronary occlusions in patients with stable angina pectoris: impact on therapy and outcome in present day clinical practice. Clin Res Cardiol 2009; 98:435–441 https://doi.org/10.1016/j.cler.2009.04.008 PMID: 19539251
21. Stone GW, Reifart NJ, Moussa I, Hoyer A, Cox DA, Colombo A, et al. Percutaneous recanalization of chronically occluded coronary arteries: A consensus document: part II. Circulation 2005; 112:2530–2537 https://doi.org/10.1161/CIRCULATIONAHA.105.583716 PMID: 16230504
22. Prasad A, Rihal CS, Lennon RJ, Wiste HJ, Singh M, Holmes DR Jr. Trends in outcomes after percutaneous coronary intervention for chronic total occlusions: A 25-year experience from the Mayo Clinic. J Am Coll Cardiol 2007; 49:1611–1618 https://doi.org/10.1016/j.jacc.2006.12.040 PMID: 17433951
23. Stone GW, Reifart NJ, Moussa I, Hoyer A, Cox DA, Colombo A, et al. Percutaneous recanalization of chronically occluded coronary arteries: A consensus document: part II. Circulation 2005; 112:2530–2537 https://doi.org/10.1161/CIRCULATIONAHA.105.583716 PMID: 16230504
24. Henrique JP, Hoebers LP, Råmunddal T, Laanmets P, Eriksen E, Bax M, et al. Percutaneous coronary intervention for Concurrent Chronic Total Occlusions in Patients With STEMI: The EXPLORE Trial. J Am Coll Cardiol 2016; 15:1622–1632.
25. Voiolaris AG, Melkert R, Serruys PW. Long-term luminal narrowing after successful elective coronary angioplasty of total occlusions. A quantitative angiographic analysis. Circulation 1995; 91:2140–2150 PMID: 7697842
26. Galassi AR, Tomaselio SD, Reifart N, Werner GS, Sianos G, Bonnier H, et al. In-hospital outcomes of percutaneous coronary intervention in patients with chronic total occlusion: insights from the ERCTO (European Registry of Chronic Total Occlusion) registry. EuroIntervention 2011; 7:472–497 https://doi.org/10.1016/j.euro.2009.04.008 PMID: 19539251
27. Henrique JP, Hoebers LP, Råmunddal T, Laanmets P, Eriksten E, Bax M, et al. Percutaneous Intervention for Concurrent Chronic Total Occlusions in Patients With STEMI: The EXPLORE Trial. J Am Coll Cardiol 2016; 15:1622–1632.
28. Mashayekhi K, Nührenberg TG, Toma A, Gick M, Ferenc M, Hochholzer W, et al. A Randomized Trial to Assess Regional Left Ventricular Function After Stent Implantation in Chronic Total Occlusion: The REVASC Trial. JACC Cardiovasc Interv 2018; 19:1982–1991
29. Amundsen BH, Helles-Valle T, Edvardsen T, Torp H, Crosby J, Lyseggene E, et al. Noninvasive myocardial strain measurement by speckle tracking echocardiography: validation against sonomicrometry and tagged magnetic resonance imaging. J Am Coll Cardiol 2006; 47:789–793 https://doi.org/10.1016/j.jacc.2005.10.040 PMID: 16487846
30. Sabbah HN, Marzilli M, Stein PD. The relative role of subendocardium and subepicardium in left ventricular mechanics. Am J Physiol 1981; 240:H920–926 https://doi.org/10.1152/ajpheart.1981.240.6.H920 PMID: 7246754
31. Hashimoto I, Xi L, Heijmadi Bhat A, Jones M, Zetts AD, Sahn DJ. Myocardial strain rate is a superior method for evaluation of left ventricular subendocardial function compared with tissue Doppler imaging. J Am Coll Cardiol 2003; 42:1574–1583 PMID: 14607441
32. Sengupta PP, Narula J. Reclassifying heart failure: predominantly subendocardial, subepicardial, and transmural. Heart Fail Clin 2008; 4:379–382 https://doi.org/10.1016/j.hfc.2008.03.013 PMID: 18598989