https://nephropathol.com DOI: 10.34172/jnp.2025.25554 J Nephropathol. 2025;x(x):e25554

Journal of Nephropathology

Echocardiographic assessment of aortic stiffness and cardiac function in end-stage renal disease patients undergoing hemodialysis

Kannika Logu[1,2], Karthikeyan Balakrishnan[1], Melina Sahay[3], Melvin George[3], Sriram Damal Kandadai[3], Dhandapani Vellala Elumalai[2], Vengatesh Munisamy[2], Saravanan Ayyavoo[4*]

[1]Department of Cardiology, Hindu Mission Hospital, Chennai, Tamilnadu, India
[2]Department of Cardiology, SRM Medical College Hospital and Research Centre, Kattankulathur, Chengalpattu, Tamilnadu, India
[3]Department of Clinical Research, Hindu Mission Hospital, Chennai, Tamilnadu, India
[4]Department of physiology, SRM Medical College Hospital and Research Centre, Kattankulathur, Chengalpattu, Tamilnadu, India

ARTICLE INFO

Article type:
Original Article

Article history:
Received: 18 Jun. 2024
Revised: 10 Dec. 2024
Accepted: 16 Aug. 2025
Published online: 22 Sep. 2025

Keywords:
Aortic stiffness
Aortic elasticity markers
End-stage renal disease
Myocardial performance index
Echocardiogram

ABSTRACT

Introduction: End-stage renal disease (ESRD) is strongly associated with increased cardiovascular morbidity and mortality, with aortic stiffness emerging as a key predictor of adverse outcomes. Echocardiographic assessment of aortic stiffness and cardiac function provides valuable insights into these vascular changes. However, limited research has explored the extent of aortic stiffness and its clinical implications in ESRD patients. This study aimed to assess aortic stiffness and cardiovascular function in ESRD patients using echocardiographic parameters, including aortic strain, distensibility, and stiffness index.

Objectives: Our study aimed to evaluate aortic stiffness by measuring aortic strain, aortic distensibility, and the aortic stiffness index, as well as assess cardiac function using echocardiographic parameters—including left ventricular ejection fraction (LVEF), isovolumic relaxation time (IVRT), isovolumic contraction time (IVCT), ejection time (ET), and TEI index—between ESRD patients and a control group to determine the extent of cardiovascular alterations associated with renal dysfunction

Patients and Methods: In this comparative observational study, a total of 323 patients were enrolled, comprising 173 ESRD patients and 150 controls. Echocardiographic assessments were conducted to evaluate aortic stiffness index, aortic strain, aortic distensibility, and cardiac function parameters such as LVEF, IVRT, IVCT, and TEI index. Patients were screened based on estimated glomerular filtration rate (eGFR) and underwent echocardiographic evaluation using the Mindray DC-60 machine by a single operator.

Results: ESRD patients demonstrated significantly higher aortic stiffness ($P=0.030$) and reduced aortic strain and distensibility ($P<0.000$) compared to controls, indicating impaired vascular compliance. Additionally, ESRD patients had lower LVEF ($P<0.000$), prolonged IVRT ($P<0.000$), IVCT ($P=0.009$), and ET ($P=0.001$), reflecting compromised myocardial function. No significant differences were observed in left atrial diameter, systolic aortic diameter, or E/A ratio.

Conclusion: Aortic stiffness is significantly increased in ESRD patients undergoing hemodialysis, correlating with impaired cardiac function and vascular remodeling. These findings highlight the importance of routine cardiovascular assessment in ESRD patients to improve risk stratification and clinical management. Further large-scale, longitudinal studies are needed to validate these findings and explore potential therapeutic strategies.

Original Article

Implication for health policy/practice/research/medical education:
Our study underscores the critical role of aortic stiffness in cardiovascular risk assessment among end-stage renal disease (ESRD) patients undergoing hemodialysis. The findings highlight the need for integrating echocardiographic evaluation into routine clinical practice to enhance early detection and management of cardiovascular dysfunction in this population.

Please cite this paper as: Logu K, Balakrishnan K, Sahay M, George M, Kandadai SD, Elumalai DV, Munisamy V, Ayyavoo S. Echocardiographic assessment of aortic stiffness and cardiac function in end-stage renal disease patients undergoing hemodialysis. J Nephropathol. 2025;x(x):e25554. DOI: 10.34172/jnp.2025.25554.

*Corresponding author: Saravanan Ayyavoo: Email: cardiacresearch@13gmail.com, hod.physiology.ktr@srmist.edu.in

Introduction

Cardiovascular disease (CVD) is a major contributor to morbidity among individuals with end-stage renal disease (ESRD) undergoing hemodialysis, leading to significant complications and reduced quality of life (1). In India, ESRD has a prevalence of 232 cases per million, with a strong association with increased cardiovascular events, particularly as renal disease progresses (2). According to the United States Renal Data System (USRDS), nearly 50% of ESRD patients are at heightened risk of developing cardiovascular complications, underscoring the need for proactive cardiovascular management in this group (3).

The elevated cardiovascular risk in ESRD patients is not solely attributed to traditional risk factors such as diabetes mellitus, dyslipidemia, hypertension, and atherosclerosis. Instead, non-traditional factors like reduced glomerular filtration rate (GFR), arteriosclerosis, systolic and diastolic heart failure, ischemic heart disease, and vascular remodeling—including the development of aortic stiffness—play a crucial role (4).

Aortic stiffness is an early subclinical marker of cardiac involvement, independent of left ventricular (LV) remodeling and excessive collagen fiber accumulation in chronic heart conditions. It has been strongly linked to increased cardiovascular risk and myocardial remodeling in chronic kidney disease (CKD) (5). While renal transplantation or potential recovery in kidney function may influence aortic stiffness progression, its precise role remains under investigation.

Several studies have explored the relationship between aortic stiffness and cardiovascular events in ESRD and CKD patients. However, its role in renal impairment progression remains less studied (6). Increased aortic stiffness correlates with elevated pulse pressure and systolic blood pressure, both of which contribute to renal dysfunction. In advanced ESRD cases, blood pressure fluctuations due to arterial stiffness may impact renal perfusion and patient survival (7,8).

Given the growing importance of aortic stiffness as a crucial risk element in cardiovascular events, particularly impactful in individuals with ESRD (9), Therefore, this study aimed to assess aortic stiffness and cardiovascular function in ESRD patients undergoing hemodialysis by utilizing echocardiographic measurements to evaluate key parameters, including aortic strain, distensibility, and stiffness index.

Objectives

Our study aimed to evaluate aortic stiffness by measuring aortic strain, aortic distensibility, and the aortic stiffness index, as well as assess cardiac function using echocardiographic parameters—including left ventricular ejection fraction (LVEF), isovolumic relaxation time (IVRT), isovolumic contraction time (IVCT), ejection time (ET), and TEI index—between ESRD patients and a control group to determine the extent of cardiovascular alterations associated with renal dysfunction

Patients and Methods

Patients' selection and data collection

This study included ESRD patients undergoing hemodialysis at a quaternary care hospital's nephrology and cardiology department between February 2023 and June 2023. A total of 323 patients were enrolled, comprising 173 cases and 150 controls. The study was approved by the institutional ethics committee of the hospital. All procedures were conducted in accordance with the guidelines outlined in the Declaration of Helsinki. Comprehensive data, including patient demographics, dialysis history, medical records, and cardiac risk factors, were collected. Patients were initially screened based on estimated glomerular filtration rate (eGFR) and subsequently assessed using echocardiographic measurements.

Study design

This was a comparative observational study aimed at evaluating aortic stiffness and cardiovascular function in ESRD patients using echocardiographic parameters. Echocardiographic measurements were performed using the Mindray DC-60 machine by a single operator. Key parameters assessed included aortic diameter change, aortic strain (%), aortic distensibility, and the aortic stiffness index. Additionally, mitral early diastolic velocity (E), late diastolic velocity (A), and myocardial performance index (TEI or MPI index) were evaluated using Doppler echocardiography (10).

Several methods exist for measuring aortic stiffness, including applanation tonometry, brachial-ankle pulse wave velocity, carotid-femoral pulse wave velocity, and transthoracic echocardiography. While carotid-femoral pulse wave velocity via applanation tonometry is considered the most accurate, its time-consuming nature limits routine clinical use. Therefore, M-mode echocardiography was chosen for its non-invasive, practical, and widely accessible nature (11).

Statistical analysis

Data were analysed using SPSS version 16.0 software. Continuous variables were expressed as means and standard deviation. The chi-square statistic was used to assess statistically significant differences between two groups' proportions. Student T-test was performed to compare the two different groups. A P value of ≤0.05 was considered statistically significant in all two-tailed analysis.

Results

Table 1 indicates that age and gender distribution did not show significant differences between patients and controls, indicating an even distribution across the study groups. However, the patient group had a significantly higher proportion of males (60.1%) compared to the control group (40.0%, $P<0.000$). The prevalence of diabetes mellitus (63.6%) and hypertension (79.8%) was also notably higher among patients. Both systolic blood pressure (SBP) and diastolic blood pressure (DBP) were significantly elevated in ESRD patients compared to controls ($P<0.05$), highlighting a strong association between renal failure and hypertension.

Table 2 shows that diabetic ESRD patients had a significantly lower LVEF (59.73% versus 63.31%; $P<0.000$), indicating compromised cardiac function. Additionally, the diastolic aortic diameter was significantly larger in diabetic patients ($P<0.018$), suggesting increased vascular remodeling. Isovolumetric contraction time (IVCT) was also significantly prolonged ($P=0.001$), reflecting altered myocardial contraction. Other echocardiographic parameters did not show significant differences between the two group.

Table 3 indicates that ESRD patients with hypertension had a significantly lower LVEF ($P=0.005$) compared to normotensive patients, suggesting impaired systolic function. Additionally, diastolic aortic diameter was significantly larger in hypertensive patients ($P=0.007$), indicating increased arterial stiffness. Prolongation of IVRT ($P=0.003$), IVCT ($P=0.005$), and ET ($P=0.031$) further suggests diastolic dysfunction. Other parameters, including the E/A ratio and TEI index, showed no significant differences between the group.

Table 4 shows that ESRD patients had a significantly lower LVEF ($P<0.001$) compared to controls, indicating reduced cardiac function. Both systolic ($P=0.004$) and diastolic ($P<0.001$) aortic diameters were significantly larger in ESRD patients, suggesting vascular remodeling. Additionally, IVRT ($P<0.001$), IVCT ($P=0.009$), and ET ($P=0.001$) were prolonged, reflecting impaired myocardial relaxation and contraction. The TEI index was significantly elevated ($P<0.001$), indicating worse overall myocardial performance. No significant differences were observed in left atrial diameter, E/A ratio, or late diastolic velocity (A).

Table 5 indicates that aortic strain and distensibility

Table 1. Baseline demographic and clinical characteristics of ESRD patients and controls

Parameters	Patients (n=173)	Controls (n=150)	*P* value
Age (y)	59.49±13.720	56.59±16.183	0.083
Male	104 (60.1%)	60 (40.0%)	<0.001
Female	69 (39.9%)	90 (60.0%)	
HR	88.03±17.159	84.72±14.689	0.066
SBP (mm Hg)	141.16±29.528	126.33±21.282	<0.001
DBP (mm Hg)	80.40±15.934	77.07±10.778	0.031
DM	110 (63.6%)	63 (42%)	-
HTN	138 (79.8%)	55 (36.6%)	-

SBP, Systolic blood pressure; DBP, Diastolic blood pressure; DM, Diabetes mellitus; HTN, Hypertension; HR, Heart rate.

Table 2. Comparison of echocardiographic parameters between diabetic and non-diabetic ESRD Patients

Parameters	Diabetics	Non- diabetics	*P* value
LVEF%	59.73±8.18	63.31±7.65	**<0.001**
Left atrial diameter (cm)	3.79±2.41	3.80±0.52	0.975
Systolic aortic diameter (cm)	3.03±0.45	3.05±0.47	0.545
Diastolic aortic diameter (cm)	2.67±0.43	2.54±0.41	**0.018**
E (cm/s)	74.79±24.62	72.34±19.44	0.228
A (cm/s)	76.31±22.72	73.60±21.22	0.252
E/A	1.43±4.97	1.01±0.37	0.420
IVRT (ms)	78.32±20.82	71.25±19.72	0.068
IVCT	85±22.82	78.12±18.31	**0.001**
ET (ms)	23.12±52.04	21.87±47.49	0.260
TEI Index	2.20±5.88	1.22±3.56	0.189

LVEF: Left ventricular ejection fraction; E: Early diastole; A: Late diastole; IVRT: Isovolumic relaxation time; IVCT: Isovolumetric contraction time; ET: Ejection time; TEI or MPI: Myocardial performance index.

Table 3. Comparison of echocardiographic parameters between hypertensive and normotensive individuals in ESRD patients

Parameters	Hypertension	Normal	*P* value
LVEF %	59.73±8.18	62.31±7.65	**0.005**
Left atrial diameter (cm)	3.82±0.55	3.76±2.74	0.768
Systolic aortic diameter (cm)	3.03±0.45	3.05±0.47	0.664
Diastolic aortic diameter (cm)	2.67±0.43	2.54±0.41	**0.007**
E (cm/s)	74.79±24.62	72.34±19.44	0.349
A(cm/s)	76.31±22.72	73.60±21.22	0.287
E/A	1.43±4.97	1.01±0.37	0.353
IVRT (ms)	78.32±20.82	71.25±19.72	**0.003**
IVCT	85±22.82	78.12±18.31	**0.005**
ET (ms)	23.12±52.04	21.87±47.49	**0.031**
TEI index	59.73±8.18	62.31±7.65	0.98

LVEF: Left ventricular ejection fraction; E: Early diastole; A: Late diastole; IVRT: Isovolumic relaxation time; IVCT: Isovolumetric contraction time; ET: Ejection time; TEI or MPI: Myocardial performance index.

Table 4. Comparison of echocardiographic parameters between ESRD patients and controls

	Controls	Patients	*P* value
LVEF%	63.62±5.578	58.19±9.020	0.001
Left atrial diameter (cm)	3.65±2.487	3.93±0.496	0.150
Systolic aortic diameter (cm)	2.96±0.483	3.11±0.465	0.004
Diastolic aortic diameter (cm)	2.49±0.388	2.75±0.426	0.001
E (cm/s)	71.08±18.117	76.29±26.018	0.041
A(cm/s)	75.32±20.772	75.26±23.379	0.979
E/A	0.99±0.383	1.53±5.361	0.226
IVRT (ms)	68.77±17.709	81.62±21.244	0.001
IVCT	79.06±19.482	85.31±22.704	0.009
ET (ms)	216.65±46.044	235.05±53.026	0.001
TEI index	0.73±0.283	2.79±6.898	0.001

LVEF: Left ventricular ejection fraction; E: Early diastole; A: Late diastole; IVRT: Isovolumic relaxation time; IVCT: Isovolumetric contraction time; ET: Ejection time; TEI or MPI: Myocardial performance index.

Table 5. Assessment of aortic stiffness and elasticity in ESRD patients and controls

Parameters	Controls	Patients	*P* value
Aortic diameter change	0.51±0.321	0.45±0.270	0.097
Aortic strain %	21.04±14.939	14.42±10.909	0.001
Aortic stiffness index	0.56±1.786	0.30±0.209	0.030
Aortic distensibility	1.03±1.871	0.64±0.983	0.001

were significantly reduced in ESRD patients ($P < 0.001$), reflecting decreased vascular elasticity. Conversely, the aortic stiffness index was significantly elevated ($P = 0.030$), suggesting increased arterial rigidity. These alterations in aortic properties highlight the impact of ESRD on vascular compliance and blood pressure regulation.

Discussion

Our findings highlight significant alterations in echocardiographic parameters among ESRD patients undergoing hemodialysis, emphasizing the strong association between renal dysfunction, arterial stiffness, and cardiac impairment. Aortic stiffness is commonly associated with aging, male gender, diabetes mellitus, hypertension, dyslipidemia, CVD, and impaired renal function. However, our study challenges the notion that age is the primary determinant of aortic stiffness in ESRD patients undergoing hemodialysis. In contrast, McIntyre et al, identified age as a key factor in elderly CKD stage 3 patients. The age-related increase in aortic stiffness is typically linked to excessive collagen production and elastin degradation in the extracellular matrix. Similarly,

Briet et al emphasized the role of aging in the pathogenesis and progression of vascular rigidity (12).

A potential correlation between gender and ESRD progression was observed in our study, with a significantly higher prevalence in male patients (60%) (5). Our findings also support prior research indicating that diabetic nephropathy—either alone or combined with hypertensive nephropathy—is a leading cause of ESRD. We found that 63.6% of ESRD patients had diabetes, and 79.8% had hypertension, reinforcing their role as major contributors to ESRD (6). Comparatively, Jameel et al reported lower percentages (32% diabetes, 39% hypertension), possibly due to demographic differences, sample size variations, or methodological differences. These findings underscore the importance of managing diabetes and hypertension to potentially slow ESRD progression (13).

In ESRD, elevated blood pressure is a common finding in hemodialysis patients, contributing to increased cardiac afterload, left ventricular hypertrophy, myocardial ischemia, and vascular stiffness. Interestingly, conflicting evidence exists regarding both increased and decreased SBP and their impact on CVD outcomes (13-15). Lacson et al reported that reduced SBP in hypertensive patients is also linked to adverse outcomes, highlighting the complexities of blood pressure management in ESRD. Our study reinforces the importance of effectively managing both systolic and diastolic blood pressure in this population (15).

Echocardiography serves as a valuable tool for assessing cardiac structural and functional changes due to kidney impairment (2). In our study, echocardiographic evaluation revealed significant impairments in LVEF, ET, IVRT, IVCT, E (early diastolic filling), left atrium (LA), diastolic aortic diameter, and TEI index in ESRD patients compared to controls. However, systolic aortic diameter, left atrial diameter, A (late diastolic filling), and E/A ratio did not show significant differences. These results contrast with findings by Dincer et al, who reported significant reductions in mitral E and A-wave velocities and the E/A ratio following hemodialysis. Such discrepancies highlight the complexity of interpreting echocardiographic parameters in hemodialysis patients and the need for further research with larger, more diverse patient populations.

Assessment of aortic elasticity parameters, including aortic stiffness index, aortic distensibility, and aortic strain, revealed statistically significant differences between ESRD and control groups. Our study found increased aortic stiffness index in ESRD-hemodialysis patients, consistent with Erdogan et al, and Kalçık et al further suggested that increased aortic stiffness may indicate elastic impairment of the aorta and its association with coronary artery disease (16,17). However, while our study observed increased aortic distensibility in ESRD patients, this contrasts with Erdogan et al, who reported reduced distensibility (16). Similarly, Kalçık et al linked reduced aortic distensibility to compromised aortic elasticity and coronary artery disease, emphasizing the need for further research (17). The study by Li et al in healthy individuals also suggested that ascending aortic stiffness increases, while distensibility decreases with age, further underscoring the complexity of aortic compliance across different populations (18).

Aortic strain, which measures the degree of aortic expansion during ventricular ejection, was notably increased in ESRD patients in our study. Current research suggests that aortic strain and distensibility serve as potential markers for cardiovascular risk, with strain being more relevant in younger individuals and stiffness in older populations (19). These findings emphasize the potential of aortic strain as a marker for assessing cardiovascular risk and guiding preventive interventions based on patient-specific profiles (20).

Despite these findings, the scarcity of studies using these specific methods highlights the need for larger-scale research to validate our results. Expanding sample sizes and including diverse populations could provide more definitive insights into variations in aortic elasticity between ESRD patients and controls. Such research could further establish the diagnostic and prognostic value of these markers, contributing significantly to the understanding of ESRD-related cardiovascular complications.

Conclusion

Our study highlights the significant impact of aortic stiffness on cardiovascular health in ESRD patients undergoing hemodialysis. Additionally, the observed alterations in echocardiographic parameters emphasize the need for routine cardiovascular assessment in ESRD patients to improve risk stratification and clinical management. Further research with larger cohorts is warranted to validate these findings and explore potential therapeutic interventions aimed at mitigating vascular stiffness and its complications.

Limitations of the study

Our study had certain limitations. While it included 323 patients, only 173 were diagnosed with ESRD, which may affect the generalizability of the results, a larger cohort would enhance the robustness of the findings and improve statistical power. Instead of focusing solely on stage 5 ESRD, including patients from different CKD stages would have provided more accurate and comprehensive results. Additionally, unaccounted factors such as medication use, inflammatory markers, and lifestyle

variables may have influenced cardiovascular parameters. The lack of follow-up data also limits the assessment of aortic stiffness progression and its long-term impact on patient outcomes.

Acknowledgments

We express my gratitude to Hindu Mission Hospital, with special appreciation to the Departments of Cardiology, Nephrology, and Clinical Research.

Authors' contribution

Conceptualization: Karthikeyan Balakrishnan, Saravanan Ayyavoo, Kannika Logu.
Data curation: Kannika Logu.
Formal analysis: Kannika Logu, Dhandapani Vellala Elumalai.
Investigation: Kannika Logu, Karthikeyan Balakrishnan.
Methodology: Kannika Logu, Vengatesh Munisamy.
Project administration: Kannika Logu, Saravanan Ayyavoo, Karthikeyan Balakrishnan.
Resources: Saravanan Ayyavoo.
Software: Melina Sahay, Melvin George.
Supervision: Karthikeyan Balakrishnan, Saravanan Ayyavoo, Melvin George.
Validation: Dhandapani Vellala Elumalai.
Visualization: Sriram Damal Kandadai, Karthikaeyan Balakrishnan.
Writing–original draft: Kannika Logu, Melina Sahay.
Writing–review & editing: Kannika Logu, Melina Sahay, Melvin George

Conflicts of interest

The authors declare that they have no competing interests.

Ethical issues

This study adhered to the ethical standards outlined in the Declaration of Helsinki. Written informed consent was obtained from all participants prior to any intervention. The study received approval from the Institutional Ethics Committee of Hindu Mission Hospital, Tambaram (IEC Approval No. HMH/IEC/2022/STEA22). The authors have fully complied with ethical guidelines, ensuring no instances of plagiarism, data fabrication, or duplicate publication.

Funding/Support

None.

References

1. Fox CS, Matsushita K, Woodward M, Bilo HJ, Chalmers J, Heerspink HJ, et al; Chronic Kidney Disease Prognosis Consortium. Associations of kidney disease measures with mortality and end-stage renal disease in individuals with and without diabetes: a meta-analysis. Lancet. 2012;380:1662-73. doi:10.1016/S0140-6736(12)61350-6.
2. Modi GK, Jha V. The incidence of end-stage renal disease in India: a population-based study. Kidney Int. 2006;70:2131-3. doi:10.1038/sj.ki.5001958.
3. National Institutes of Health. US renal data systems: USRDS 2010 annual data report: atlas of end-stage renal disease in the United States. Bethesda (MD): NIH; 2010. Available from: http://www.usrds.org/2010/view/default.asp. doi:10.1053/j.ajkd.2011.11.015.
4. Lainščak M. Cardiovascular risk in chronic kidney disease. EJIFCC. 2009;20:73-6.
5. Essig M, Escoubet B, de Zuttere D, Blanchet F, Arnoult F, Dupuis E, et al. Cardiovascular remodelling and extracellular fluid excess in early stages of chronic kidney disease. Nephrol Dial Transplant. 2008;23:239-48. doi:10.1093/ndt/gfm542.
6. Voicehovska JG, Bormane E, Grigane A, Moisejevs G, Moreino E, Trumpika D, et al. Association of arterial stiffness with chronic kidney disease progression and mortality. Heart Lung Circ. 2021;30:1694-701. doi:10.1016/j.hlc.2021.08.011.
7. Blacher J, Guerin AP, Pannier B, Marchais SJ, Safar ME, London GM. Impact of aortic stiffness on survival in end-stage renal disease. Circulation. 1999;99:2434-9. doi:10.1161/01.cir.99.18.2434.
8. Go AS, Chertow GM, Fan D, McCulloch CE, Hsu CY. Chronic kidney disease and the risks of death, cardiovascular events, and hospitalization. N Engl J Med. 2004;351:1296-305. doi:10.1056/NEJMoa041031.
9. Agarwal R, Nissenson AR, Batlle D, Coyne DW, Trout JR, Warnock DG. Prevalence, treatment, and control of hypertension in chronic hemodialysis patients in the United States. Am J Med. 2003;115:291-7. doi:10.1016/s0002-9343(03)00366-8.
10. Sahin DY, Gür M, Elbasan Z, Kalkan GY, Ozdoğru I, Kivrak A, et al. Myocardial performance index and aortic distensibility in patients with different left ventricle geometry in newly diagnosed essential hypertension. Blood Press. 2013;22:329-35. doi:10.3109/08037051.2013.778006.
11. Kim HL, Lim WH, Seo JB, Kim SH, Zo ZH, Kim MA. The comparison of the impact of arterial stiffness and central pressure on left ventricular geometry and diastolic function. Clin Hypertens. 2019;25:18. doi:10.1186/s40885-019-0125-9.
12. Briet M, Boutouyrie P, Laurent S, London GM. Arterial stiffness and pulse pressure in CKD and ESRD. Kidney Int. 2012;82:388-400. doi:10.1038/ki.2012.131.
13. Jameel FA, Junejo AM, Khan QUA, Date S, Faraz A, Rizvi SHM, et al. Echocardiographic changes in chronic kidney disease patients on maintenance hemodialysis. Cureus. 2020;12:e8969. doi:10.7759/cureus.8969.
14. Shen Y, Dai Y, Wang XQ, Zhang RY, Lu L, Ding FH, et al. Searching for optimal blood pressure targets in type 2 diabetic patients with coronary artery disease. Cardiovasc Diabetol. 2019;18:160. doi:10.1186/s12933-019-0959-1.
15. Li Z, Lacson E Jr, Lowrie EG, Ofsthun NJ, Kuhlmann MK, Lazarus JM, et al. The epidemiology of systolic blood pressure

and death risk in hemodialysis patients. Am J Kidney Dis. 2006;48:606-15. doi:10.1053/j.ajkd.2006.07.005.
16. Erdogan MA, Ciftci H. Assessment of aortic stiffness, myocardial performance index and cardiac functions in patients with end-stage renal disease. J Turgut Ozal Med Cent. 2018;25:14-20. doi:10.5455/jtomc.2018.01.014.
17. Kalçık M, Yesin M, Güner A, Bayam E, Doğan T, Yetim M, et al. Investigation of elastic properties of aorta in patients with coronary slow flow. J Clin Exp Invest. 2019;10:em00725. doi:10.5799/jcei/5834.
18. Li N, Beck T, Chen J, Biermann C, Guo L, Sun H, et al. Assessment of thoracic aortic elasticity: a preliminary study using electrocardiographically gated dual-source CT. Eur Radiol. 2011;21:1564-72. doi:10.1007/s00330-011-2077-7.
19. Oishi Y, Mizuguchi Y, Miyoshi H, Iuchi A, Nagase N, Oki T. A novel approach to assess aortic stiffness related to changes in aging using a two-dimensional strain imaging. Echocardiography. 2008;25:941-5. doi:10.1111/j.1540-8175.2008.00725.x.
20. Boutouyrie P, Chowienczyk P, Humphrey JD, Mitchell GF. Arterial stiffness and cardiovascular risk in hypertension. Circ Res. 2021;128:864-86. doi:10.1161/CIRCRESAHA.121.318061.