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Noninvasive left ventricular end-diastolic pressure assessment using a novel workflow and device in primary care settings to enhance heart failure diagnosis

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Abstract

Objective. Heart failure (HF) is underdiagnosed in high-risk patients, motivating the development of screening workflows towards earlier identification. The objective of this study is to evaluate the feasibility and screening yield of a non-provider-based, noninvasive left ventricular end-diastolic pressure (LVEDP) assessment as a marker of HF risk within routine outpatient primary care settings. *Approach*. A dedicated, screening-only 'heart health clinic' workflow, using noninvasive estimation of LVEDP and the Kansas City Cardiomyopathy Questionnaire (KCCQ-12), was assessed. Primary care patients at high-risk for HF were contacted directly and scheduled for focused screening visits performed by trained medical assistant 'superusers,' independent of a provider visit. *Main results*. Of $n = 1238$ patients who arrived for screening, $n = 1141$ (92.2%) had conclusive LVEDP estimates. LVEDP was estimated to be elevated (defined as > 18 mmHg) in 40.1% of screened patients, with a higher prevalence in women than men (46.6% vs. 31.9%; $p < 0.0001$). Age and body mass index were found to be similar between elevated and non-elevated LVEDP groups. Among patients with elevated LVEDP, 426 (93.0%) completed all KCCQ-12 subdomains, with overall summary (OS) scores classifying 42.3% as asymptomatic Stage-B HF (KCCQ-OS $=$ 100), 45.1% as New York Heart Association (NYHA) I (KCCQ-OS 80–99), and the rest as NYHA II–IV (KCCQ-OS < 80). *Significance*. These findings indicate that the overall workflow does not introduce significant bias, supporting the practicality and feasibility of incorporating noninvasive LVEDP assessment into scalable HF risk screening in general outpatient populations.

1. Introduction

Heart failure (HF) prevention, especially in at-risk individuals, depends on early identification through scalable, general population-driven screening workflows rather than symptom-driven care alone (Jafari *et al* 2020, Bozkurt 2022). Indeed, it has been proposed that screening strategies and their corresponding tools/devices must be evaluated not only by their diagnostic performance, but by their feasibility and practical integration within population-level care models (Wang *et al* 2003, Khan *et al* 2025). Recent data from the HF Society of America (Bozkurt *et al* 2023) reports that approximately 33% of individuals over the age of 65 with comorbidities such as diabetes mellitus (DM) and chronic kidney disease fall into Stage-A HF, which places them at significant risk despite the absence of structural heart disease or symptoms. However, without treatment, HF progression can often lead to irreversible structural changes: the Atherosclerosis Risk in Communities study (Bergamasco *et al* 2022) (median age 75.4 years, $n = 6118$) further found that 29.2% of participants aged 65 years and older had Stage-B (also known as asymptomatic (Bozkurt *et al* 2021)) or Stage-C HF. Hence early detection is not only important for identifying

undiagnosed or at-risk individuals, but also for better facilitating guideline directed medical therapy to slow the progression in those identified with HF (especially in the earlier stages).

A universal definition of HF (Bozkurt *et al* 2021) characterizes HF as a clinical syndrome caused by structural or functional cardiac abnormalities corroborated by, for example, objective evidence of cardiogenic congestion. Operationally, this definition can be expressed (Bonow *et al* 2011) as the inability of the heart to pump sufficient blood to meet metabolic needs (or to do so at the expense of elevated filling pressures), and, within this framework, hemodynamic markers of elevated filling pressures become essential for identifying early functional impairment. In keeping with the universal definition, elevated left ventricular end-diastolic pressure (LVEDP) is employed here as evidence of congestion. Elevated LVEDP is a well-established objective measure that is indicative of poor left ventricular function in both HF with preserved ejection fraction as well as HF with reduced ejection fraction, regardless of the underlying cause (Pfeffer *et al* 2019, Sandhu *et al* 2021). The gold standard for LVEDP evaluation, however, is an invasive methodology (via left heart catheterization) that is impractical for widespread screening, particularly in asymptomatic patients. Among common noninvasive tests (Heidenreich and Sandhu 2024) for estimating elevated left ventricular filling pressures (i.e. the ratio of early diastolic mitral inflow velocity to annulus velocity, global longitudinal strain, left atrial volume index, or N-terminal pro B-type natriuretic peptide), no single threshold consistently demonstrates both sensitivity and specificity exceeding 70% (Heidenreich and Sandhu 2024). In order to address the performance constraints of such common noninvasive markers as well as the practical limitations of invasive left heart catheterization, the recently Food and Drug Administration (FDA)-cleared (510k) Vivio System (Ventric Health) has been developed as a noninvasive hemodynamic monitoring tool that can be easily integrated into routine patient care for assessing LVEDP (Cantu-Martinez *et al* 2025, Shavelle *et al* 2026). In a recent multicenter study (Shavelle *et al* 2026), the Vivio System identified elevated LVEDP with a sensitivity/specificity of 80%/83% in an independent all patients validation cohort and 80%/66% in an independent clinically-indicated left heart catheterization cohort, demonstrating robust performance for early HF screening.

In contrast to previous evaluations (Cantu-Martinez *et al* 2025) of the noninvasive Vivio System, which were conducted during routine primary-care encounters (e.g. annual wellness visits or standard office visits, which may derive from initial illness concerns, other screenings, or chronic care management), the present study examines the device within a distinctly different workflow: dedicated, Vivio-facilitated screening-only multicenter 'heart health clinics'. In particular, trained medical assistant 'superusers' conducted focused, 15 min appointments at 25 sites, independent of a provider visit. Patients who were conclusively estimated to have elevated LVEDP were then offered the Kansas City Cardiomyopathy Questionnaire (KCCQ) to quantify their corresponding health status. Such a workflow models a unique operational setting, enabling an assessment of device performance and patient characteristics within a streamlined, high-throughput screening environment. Accordingly, this work evaluates the feasibility and screening yield of noninvasive LVEDP assessment for identifying individuals at elevated risk of HF progression in such a dedicated outpatient workflow, rather than its incremental diagnostic value beyond routine clinician-performed history and physical examination. By focusing on practicality, scalability, and workflow integration, this model is consistent with contemporary HF prevention frameworks that emphasize risk-based screening strategies for informing subsequent clinical diagnostic evaluations (Wang *et al* 2003, Jafari *et al* 2020, Bozkurt 2022, Khan *et al* 2025).

2. Methods

2.1. Study population & design: heart health monitoring clinics

In contrast to previous studies (Cantu-Martinez *et al* 2025), the overall analysis herein draws on data collected from 25 sites that implemented the Vivio System as part of a targeted outreach program rather than as part of a routine primary care clinical visit. Between 10 June and 13 November 2025, adults undiagnosed but considered at elevated risk for HF (including those with a history of DM, CKD, chronic obstructive pulmonary disease, or clinician-identified concerns) were contacted directly to schedule dedicated noninvasive LVEDP assessments (via the Vivio System) with four trained 'superusers' at various sites. Such 'superusers' were certified medical assistants who completed a standardized, device-specific training and certification focused on the Vivio acquisition protocol. The superuser model was implemented to maximize operating efficiency and minimize overhead associated with training personnel within a high-throughput screening workflow. Superusers conducted screening-only visits independent of a provider encounter, did not possess diagnostic authority, and were responsible solely for test acquisition and workflow execution (without interpretation or clinical recommendations). Compared with routine clinic medical assistants, they operated dedicated screening sessions and performed substantially

higher test volumes (often exceeding 100 tests per month and, at times, up to 200 tests per month) versus approximately 10–20 tests per month during standard office visits (Cantu-Martinez *et al* 2025).

Appointments were scheduled in dedicated 15 min windows reserved for Vivio-based screening. Upon arrival, the patient was escorted to an examination room, where the superuser explained the purpose and noninvasive nature of the assessment. After the brief explanation, the superuser administered the test according to standardized protocol, repeating the measurement if an error or inconclusive result occurred. Participants with an elevated estimated LVEDP on screening were then invited to complete the 12-item KCCQ within the same appointment. Results were not discussed at the time of testing; all Vivio estimations and corresponding KCCQ scores were documented in the electronic medical record for provider review and clinical follow-up as appropriate or necessary.

The Vivio System results and the corresponding KCCQ responses (scores) were also stored as de-identified data in a secure database maintained by Ventric Health. The study protocol was reviewed by the Advarra Institutional Review Board (IRB) and was determined to be exempt from human subject research requirements in accordance with applicable federal regulations (since it involved the analysis of existing, de-identified data).

2.2. Noninvasive LVEDP assessment: the Vivio System

The Vivio System (Ventric Health) performs noninvasive LVEDP assessment through the use of two integrated elements: a modified pneumatic brachial blood-pressure cuff and a time-synchronized single-lead electrocardiogram (ECG) (Shavelle *et al* 2026). During the measurement sequence, the cuff first obtains routine systolic, diastolic, and mean arterial blood-pressure values before reinflating to a supra-systolic level (systolic blood pressure + 35 mmHg) in order to record approximately 40 s of brachial pulse-waveform data in parallel with the ECG signal. These signals are acquired simultaneously and analyzed based on an extraction and inference framework to classify whether LVEDP is elevated (defined as > 18 mmHg) (Pahlevan and Matthews 2019, Pahlevan *et al* 2024, Shavelle *et al* 2026). The corresponding signals and outputs are transmitted to a computer tablet interface for (automated) processing and classification.

As described in the multicenter validation study in Shavelle *et al* (2026), these synchronized ECG and brachial waveform signals undergo standardized preprocessing, including noise filtering, cardiac-cycle identification, and detection of fiducial points. Features derived from the ECG include timing and morphology parameters corresponding to *P*-wave, *T*-wave, and QRS complex components. The brachial waveform is analyzed using techniques based on waveform derivatives in order to identify physiologically-relevant features including systolic and diastolic peaks, the foot of the waveform, notches, inflection points, and slope characteristics. ECG beats are matched to corresponding brachial pulse cycles by aligning the onset of the QRS complex with the foot of the brachial waveform within a physiologically-appropriate time window, ensuring accurate beat-to-beat correspondence. Only matched ECG-pulse cycle pairs are used for feature extraction, where the aforementioned features reflect ventricular preload, afterload, and electromechanical coupling (Shavelle *et al* 2026), which in turn influence brachial waveform morphology and ECG-arterial timing relationships. Since elevated LVEDP represents increased left ventricular filling pressure, corresponding alterations in these parameters provide a physiologically grounded basis for discriminating between normal and elevated filling pressures (Shavelle *et al* 2026).

From a physiological perspective, the approach is based on the principle that left ventricular filling pressure reflects the interaction between preload, afterload, and contractility, consistent with established relationships between ventricular loading conditions and cardiac performance. As described in the multicenter validation study (Shavelle *et al* 2026), features derived from the brachial pulse waveform capture aspects of arterial load and ventricular-arterial coupling, while ECG-derived timing features reflect electromechanical function. In the development study (Shavelle *et al* 2026), candidate features representing preload, afterload, and contractility were explicitly considered, and the final model incorporated a reduced set of features reflecting these physiological domains. Taken together, the simultaneous assessment of waveform morphology and ECG-arterial timing provides physiologically relevant information for identifying elevated LVEDP.

The classifier used in the present study was developed and validated in the aforementioned multicenter investigation (Shavelle *et al* 2026), in which elevated LVEDP was defined invasively as > 18 mmHg and used as the reference standard for supervised model training. For such training, Shavelle *et al* (2026) extracted 180 candidate features from synchronized ECG and brachial waveform data, including: pulse waveform-based timings, amplitudes, derivatives, and area-under-curve metrics; ECG morphologies and interval features; inter-signal timing features between the ECG and brachial waveforms; demographic and clinical characteristics; as well as certain nonlinear interaction terms. They performed feature

selection iteratively using distribution testing, correlation grouping, and backward elimination to minimize redundancy and reduce overfitting. They then trained a penalized logistic regression classifier with a log-F penalty using leave-one-subject-out cross-validation and subsequently frozen for independent validation (Shavelle *et al* 2026).

The objective of the present work is to analyze the use and performance of this system within a dedicated, outpatient screening workflow that further incorporates the KCCQ-12 questionnaire (which is described in what follows).

2.3. Health status assessment: KCCQ

The 12-item version (Spertus *et al* 2020) of the KCCQ-12 was incorporated into the Vivio System workflow and offered to individuals with an estimated elevated LVEDP in order to provide additional insight into their symptom severity and functional status. The KCCQ is a validated patient-reported outcome measure that evaluates and quantifies health status in four separate domains for individuals with HF: physical limitation, symptom frequency, quality of life, and social limitation. These can be integrated into an overall summary (OS) score that reflects a patient's overall HF-related health status. KCCQ-12 scores range from 0 to 100, with lower values indicating more severe impairment and higher values indicating better health status (Spertus *et al* 2020). Cross-sectional interpretation commonly uses 25-point groupings: 0–24 (very poor to poor), 25–49 (poor to fair), 50–74 (fair to good), and 75–100 (good to excellent). Since clinician grading can be variable, direct alignment with New York Heart Association (NYHA) functional classes is not perfect (Tran *et al* 2020), although KCCQ-OS ranges of 0–44, 45–59, 60–79, and $\geqslant$80 approximate NYHA classes IV, III, II, and I, respectively (Tran *et al* 2020, Greene *et al* 2021).

2.4. Statistical analysis

Demographic and clinical characteristics were compared between individuals with and without an estimated elevated LVEDP (determined by the Vivio System). In order to comply with Health Insurance Portability and Accountability Act (HIPAA) de-identification standards, ages >89 years were recorded to 90. Continuous variables were summarized as mean $\pm$ standard deviation (SD), and categorical variables as counts and percentages. Comparisons between groups were performed using independent-sample t-tests for continuous variables and χ^2 tests for categorical variables.

Among participants with available KCCQ-12 data, health status was described using both the OS score and four OS categories: 100, 80–99, 60–79, and <60, which approximate asymptomatic status and NYHA functional classes I, II, and III/IV, respectively. In addition to the OS score, the four KCCQ subdomains—physical limitation, symptom frequency, quality of life, and social limitation—were analyzed to further characterize the multidimensional nature of health status. Subdomain scores were summarized using the same descriptive conventions and examined across the OS categories to provide additional context regarding functional and quality-of-life differences.

All analyses were conducted using MATLAB 2024b (MathWorks) with standard statistical toolboxes and functions.

3. Results

A total of 1141 patient visits resulted in screenings that produced conclusive diagnostics (out of 1238 individuals that came in, for a success rate of 92.2%). Figure 1 presents an illustrative summary of this overall operational workflow. Of this cohort (mean age: 74.6 ± 6.2 years) were: 639 (56.0%) women; 527 (46.2%) with class 1 obesity or higher; 748 (65.6%) with DM; 499 (43.7%) with CKD; and 870 (76.3%) with hypertension. Table 1 presents the distribution of all these clinical characteristics across the total cohort, as well as across those estimated (by the Vivio System) to have elevated LVEDP or non-elevated LVEDP. Overall, 458 (40.1%) of patients were found to have an elevated LVEDP (65.1% of them women), with similar ages (74.7 ± 6.4 vs. 74.5 ± 6.1 years; $p = 0.609$; figure 2(a)) and with comparable BMI (29.8 ± 4.9 vs. $29.4 \pm 4.8\,\mathrm{kg\,m^{-2}}$; $p = 0.119$; figure 2(b)) to those found without, indicating no statistically significant differences for these characteristics. Comorbidity patterns differed between groups (figure 2(c)): patients with elevated LVEDP had a lower prevalence of DM but higher prevalences of CKD and hypertension (see table 1 for corresponding p-values).

A higher proportion of patients with elevated LVEDP were women compared to those without (65.1% vs. 49.9%; $p < 0.0001$). Indeed, the prevalence of elevated LVEDP was found to be higher in women than in men (46.6% vs. 31.9%; $p < 0.0001$), and this difference was also statistically significant. A multivariate logistic regression including both age and sex similarly found that while age was

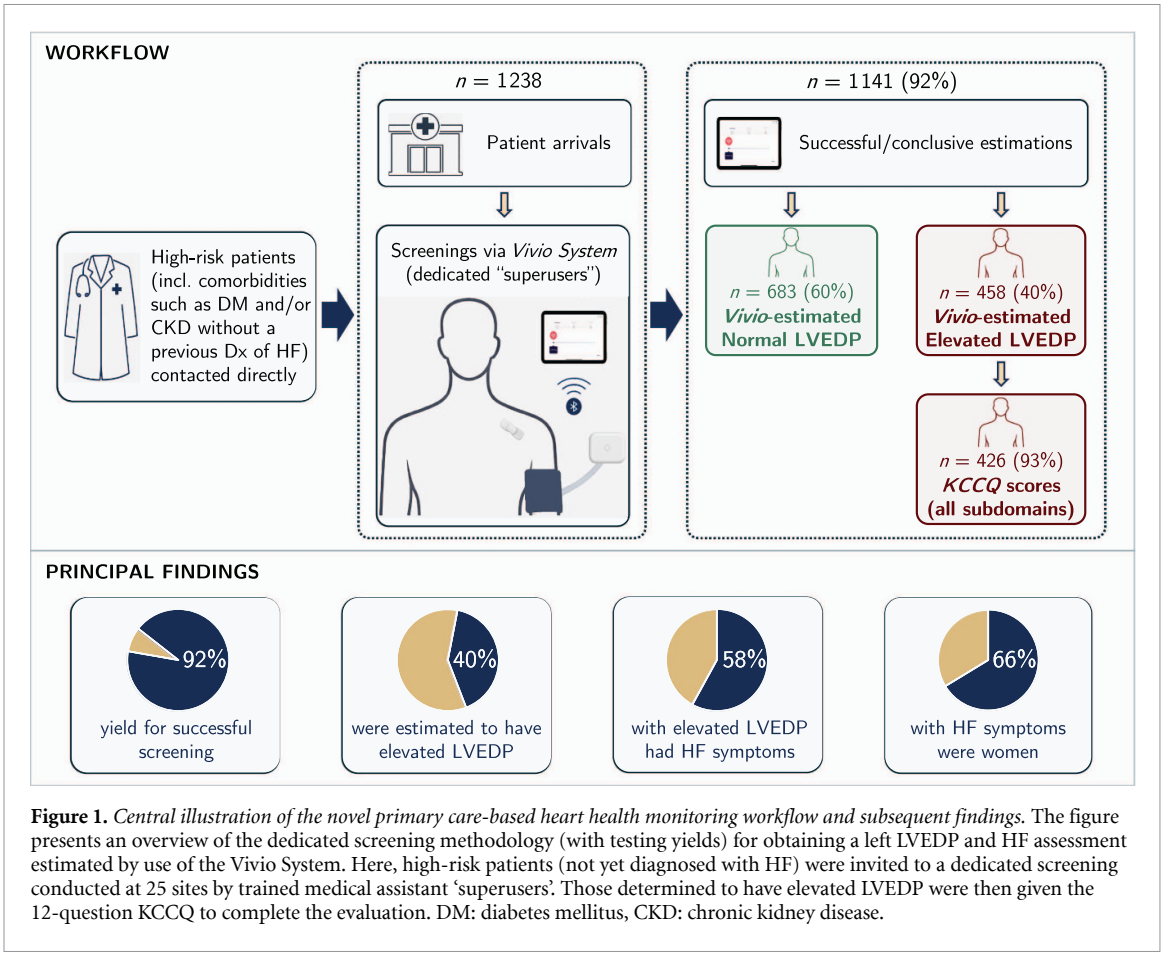

Figure 1. *Central illustration of the novel primary care-based heart health monitoring workflow and subsequent findings.* The figure presents an overview of the dedicated screening methodology (with testing yields) for obtaining a left LVEDP and HF assessment estimated by use of the Vivio System. Here, high-risk patients (not yet diagnosed with HF) were invited to a dedicated screening conducted at 25 sites by trained medical assistant 'superusers'. Those determined to have elevated LVEDP were then given the 12-question KCCQ to complete the evaluation. DM: diabetes mellitus, CKD: chronic kidney disease.

Table 1. Characteristics of patients comparing those with estimated elevated LVEDP and normal LVEDP.

	Overall ($n = 1141$)	Elevated LVEDP ($n = 458$, 40.1%)	Normal LVEDP ($n = 683$, 59.9%)	p-value
Age, mean (SD)[a]	74.6 (6.2)	74.7 (6.4)	74.5 (6.1)	0.609
Women, n (%)	639 (56.0%)	298 (65.1%)	341 (49.9%)	<0.001
BMI, mean (SD)	29.5 (4.9)	29.8 (4.9)	29.4 (4.8)	0.119
Blood pressure, mean (SD)[b]				
Systolic blood pressure	138.3 (18.1)	146.7 (17.5)	132.7 (16.2)	<0.001
Mean arterial blood pressure	98.7 (12.5)	104.9 (11.6)	94.5 (11.2)	<0.001
Diastolic blood pressure	80.1 (11.3)	85.4 (10.6)	76.5 (10.4)	<0.001
Comorbidities, n (%)				
DM	748 (65.6%)	275 (60.0%)	473 (69.3%)	<0.001
CKD	499 (43.7%)	220 (48.0%)	279 (40.8%)	<0.05
Hypertension	870 (76.3%)	366 (79.9%)	504 (73.8%)	<0.05

BMI: body mass index; DM: diabetes mellitus; CKD: chronic kidney disease; LVEDP: left ventricular end-diastolic pressure; SD: standard deviation.

[a] Patients with age >89 were recoded as 90 since the exact age was not available due to HIPAA privacy rules.

[b] Brachial blood pressure values taken with the Vivio System are not currently cleared by the FDA.

not significantly associated with elevated LVEDP after adjusting for sex ($p = 0.802$; 95% CI for age coefficient: −0.0168 to 0.0217), women in this population were strongly and independently associated with elevated LVEDP ($p < 0.0001$; 95% CI for sex coefficient: 0.3792 to 0.8673). In order to evaluate whether such an association was confounded by blood pressure or comorbidities, further analysis revealed that, among patients with elevated LVEDP, women and men had similar ages (75.0 ± 6.1 vs. 74.1 ± 6.8 years; $p = 0.172$; 95% CI for mean difference: −0.41 to 2.12) and systolic blood pressure values (147.7 ± 17.7 vs. 144.8 ± 17.0 mmHg; $p = 0.086$; 95% CI for mean difference: −0.38 to 6.26), with a modest difference observed in diastolic blood pressure (84.6 ± 10.5 vs. 87.0 ± 10.5 mmHg; $p = 0.023$;

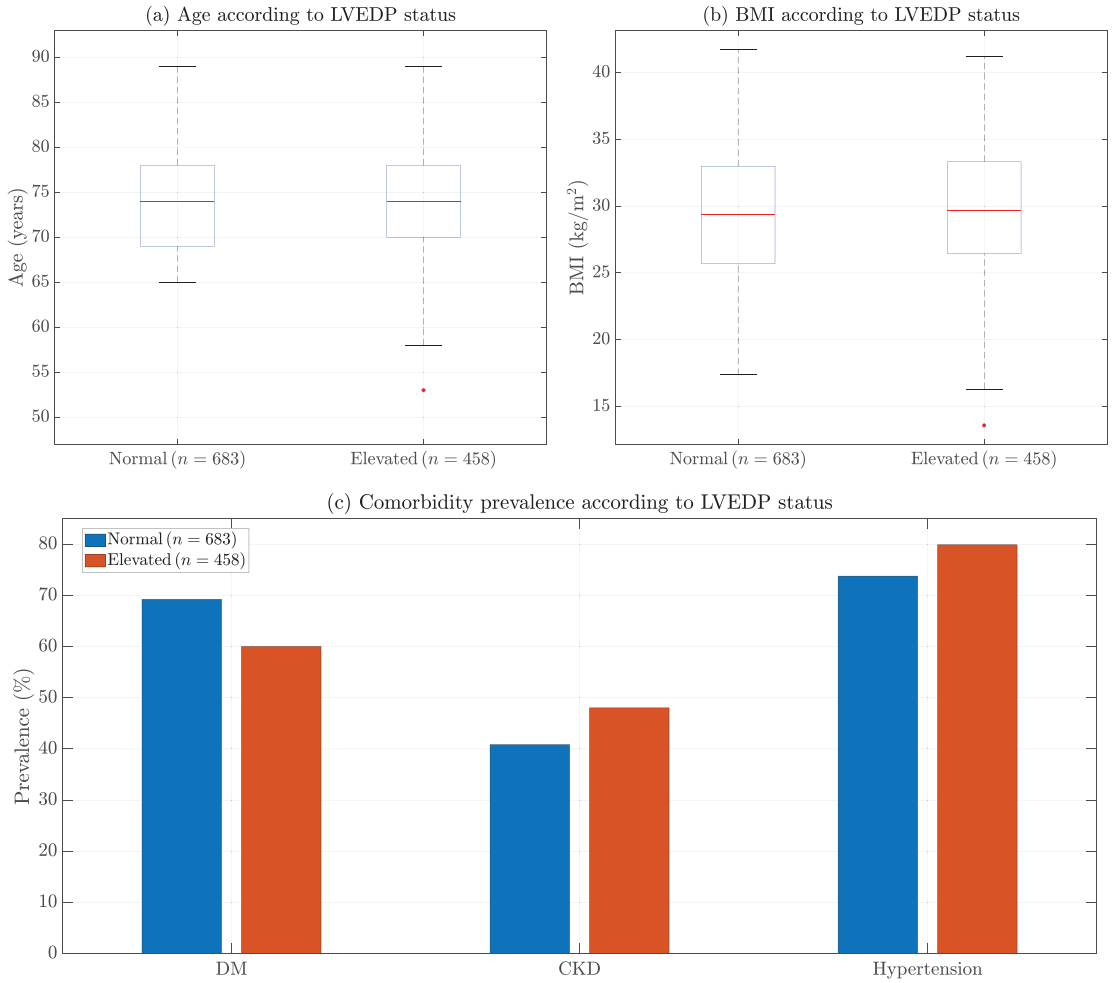

Figure 2. *Baseline clinical characteristics according to assessed LVEDP status.* Box plots depicting distributions of (a) age and (b) body mass index (BMI) among patients with normal versus elevated LVEDP. (c) The prevalence of diabetes mellitus (DM), CKD, and hypertension according to LVEDP status. Corresponding *p*-values for each between-group comparison are reported in table 1.

95% CI for mean difference: −4.39 to −0.33). For comorbidities, DM was less prevalent among women with elevated LVEDP compared to men (56.7% vs. 66.2%; $p = 0.047$; 95% CI for proportion difference: −0.188 to −0.003), while no statistically significant differences were observed for CKD (51.3% vs. 41.9%; $p = 0.053$; 95% CI for proportion difference: −0.001 to 0.190) or hypertension (78.2% vs. 83.1%; $p = 0.209$; 95% CI for proportion difference: −0.124 to 0.025). In a multivariate logistic regression including age, SBP, DM, CKD, and hypertension, female sex remained independently associated with elevated LVEDP ($p = 0.0002$; 95% CI for sex coefficient: 0.2392 to 0.7752).

Of those patients estimated by the Vivio System to have elevated LVEDP, a subgroup of 426 individuals (mean age: 74.4 ± 6.2 years) had completed all four subdomains in the corresponding KCCQ-12, a 93.0% rate. Table 2 presents the distribution of patient clinical characteristics across various resulting KCCQ-OS score groups. A total of 180 (42.3%) patients, which represents 15.8% of the complete cohort, were classified as Stage B HF (asymptomatic; KCCQ-OS = 100), 192 (45.1%) were classified as NYHA I (KCCQ-OS 80–99), 28 (6.6%) were classified as NYHA II (KCCQ-OS 60–79), and 26 (6.1%) were classified as NYHA III/IV (KCCQ-OS < 60). Women had significantly lower scores than men (90.2 ± 15.2 vs. 93.8 ± 12.4; $p < 0.05$; 95% CI for mean difference: −6.44 to −0.78), representing 60.6% of asymptomatic patients and 66.3% of symptomatic patients, with no statistically significant difference by sex ($p = 0.226$). A multivariate linear regression ($p < 0.005$) further found that higher age and BMI were associated with lower KCCQ-OS scores (decreasing by around 0.25 points per year of age; 95% CI for age coefficient: −0.47 to −0.03 and 0.35 points per kg m^{-2} increase; 95% CI for BMI coefficient: −0.64 to −0.06, respectively), and that being a woman remained an independent predictor of lower KCCQ-OS scores (on average 3.12 points lower than men after adjustment for age and BMI; 95% CI for sex coefficient: −5.96 to −0.30).

Table 2. Characteristics of patients with estimated elevated LVEDP across KCCQ-OS score groups.

	Overall ($n = 426$)	100 ($n = 180$, 42.3%)	80–99 ($n = 192$, 45.1%)	60–79 ($n = 28$, 6.6%)	< 60 ($n = 26$, 6.1%)
Age, mean (SD)[a]	74.4 (6.3)	73.9 (5.9)	74.5 (6.5)	76.9 (5.9)	75.1 (7.5)
Women, *n* (%)	272 (63.8%)	109 (60.6%)	119 (62.0%)	24 (85.7%)	20 (76.9%)
BMI, mean (SD)	29.8 (4.8)	29.3 (4.6)	29.9 (4.9)	31.5 (4.2)	30.4 (5.7)
Blood pressure, mean (SD)[b]					
Systolic blood pressure	146.4 (17.4)	147.1 (17.5)	145.3 (17.7)	148.7 (15.0)	146.7 (17.5)
Mean arterial blood pressure	104.8 (11.5)	105.9 (11.7)	103.7 (11.5)	103.9 (9.6)	105.5 (11.9)
Diastolic blood pressure	85.3 (10.5)	86.7 (10.5)	84.3 (10.6)	82.8 (9.2)	86.4 (11.0)
Comorbidities, *n* (%)					
DM	256 (60.1%)	114 (63.3%)	114 (59.4%)	17 (60.7%)	11 (42.3%)
CKD	205 (48.1%)	76 (42.2%)	95 (49.5%)	14 (50.0%)	20 (76.9%)
Hypertension	340 (79.8%)	143 (79.4%)	154 (80.2%)	24 (85.7%)	19 (73.1%)
KCCQ scores, mean (SD)					
Overall summary score	91.5 (14.4)	100.0 (0.0)	92.7 (5.1)	72.2 (6.2)	45.1 (8.8)
Physical limitation	91.4 (17.3)	100.0 (0.0)	92.4 (10.1)	70.4 (21.0)	46.0 (25.1)
Symptom frequency	92.3 (13.8)	100.0 (0.0)	92.2 (9.5)	77.1 (13.9)	56.7 (18.5)
Quality of life	88.8 (19.7)	100.0 (0.0)	89.1 (13.1)	66.1 (14.8)	33.7 (19.9)
Social limitation	93.4 (15.5)	100.0 (0.0)	96.7 (6.6)	75.0 (12.8)	43.9 (15.4)

BMI: body mass index; DM: diabetes mellitus; CKD: chronic kidney disease; KCCQ-OS: Kansas City Cardiomyopathy Questionnaire overall summary; LVEDP: left ventricular end-diastolic pressure; SD: standard deviation.

[a] Patients with age > 89 were recoded as 90 since the exact age was not available due to HIPAA privacy rules.

[b] Brachial blood pressure values taken with the Vivio System are not currently cleared by the FDA.

Mean subdomain scores were 91.4 ± 17.3 for physical limitation, 92.3 ± 13.8 for symptom frequency, 88.8 ± 19.7 for quality of life, and 93.4 ± 15.5 for social limitation. The proportions of patients with domain scores <80 were 14.8% for physical limitation, 12.9% for symptom frequency, 21.8% for quality of life, and 11.7% for social limitation. When stratified by age ranges (here, tertiles), subdomain score distributions were lower in the oldest age group across all four domains (figure 3). In contrast, higher BMI ranges were associated with lower subdomain scores primarily for physical limitation and symptom frequency, with less apparent differences across BMI groups for quality of life and social limitation (figure 4). Women had lower mean scores than men across multiple domains, with the largest and most statistically significant difference observed for physical limitation (89.5 ± 18.9 vs. 94.7 ± 13.3; $p < 0.005$; 95% CI for mean difference: -8.58 to -1.81) and social limitation (92.1 ± 16.6 vs. 95.7 ± 13.1; $p < 0.05$; 95% CI for mean difference: -6.64 to -0.53), followed by quality of life (87.4 ± 20.1 vs. 91.3 ± 18.7; $p < 0.05$; 95% CI for mean difference: -7.84 to -0.06); symptom frequency did not differ by sex (91.7 ± 14.9 vs. 93.4 ± 11.6; $p = 0.22$; 95% CI for mean difference: -4.43 to 1.04). A multivariate linear regression for physical limitation ($p < 0.0001$) further found that higher age and BMI were associated with lower scores (decreasing by around 0.23 points per year of age [95% CI for age coefficient: -0.49 to 0.04] and 0.61 points per kg m^{-2} increase [95% CI for BMI coefficient: -0.95 to -0.26], respectively), and that being a woman was an independent predictor of lower physical limitation scores (on average 4.48 points lower than men; $p < 0.01$; 95% CI for sex coefficient: -7.85 to -1.11). For symptom frequency ($p < 0.05$), higher age and BMI were similarly associated with lower scores (decreasing by around 0.16 points per year [95% CI for age coefficient: -0.37 to 0.05] and 0.35 points per kg m^{-2} [95% CI for BMI coefficient: -0.63 to -0.07], respectively), with no independent association observed for sex ($p = 0.36$; 95% CI for sex coefficient: -4.01 to 1.47). For quality of life ($p < 0.05$), higher age was associated with lower scores (decreasing by around 0.33 points per year [95% CI for age coefficient: -0.64 to -0.03]), while BMI was not significantly associated (95% CI for BMI coefficient: -0.61 to 0.18), and being a woman was associated with lower scores that did not reach statistical significance (on average 3.56 points lower than men; $p = 0.074$; 95% CI for sex coefficient: -7.46 to 0.35). For social limitation ($p < 0.01$), higher age was associated with lower scores (decreasing by around 0.28 points per year [95% CI for age coefficient: -0.52 to -0.04]), and being a woman again remained an independent predictor of lower scores (on average 3.21 points lower than men after adjustment for age and BMI; $p < 0.05$; 95% CI for sex coefficient: -6.27 to -0.15).

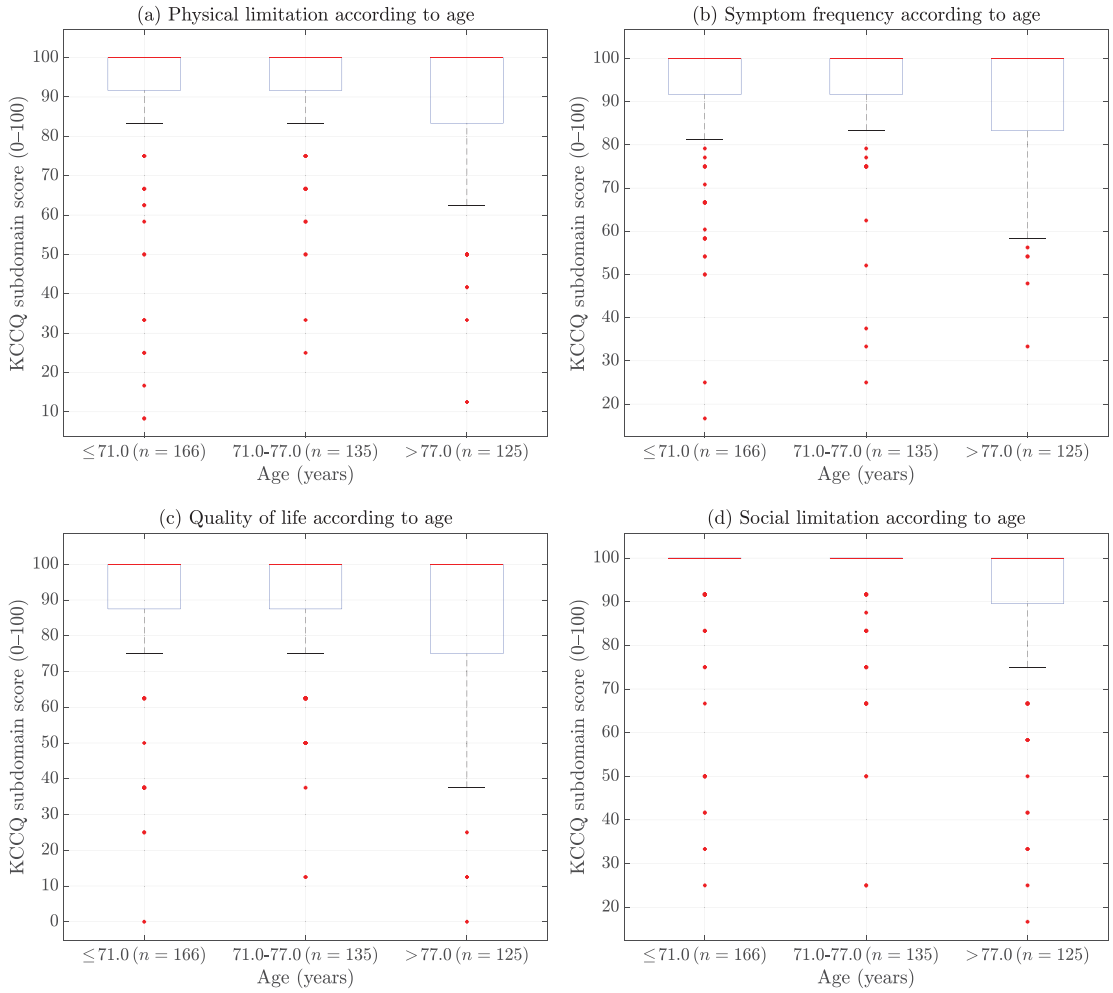

Figure 3. *KCCQ subdomain scores among patients with elevated LVEDP according to age.*Box plots depicting distributions of KCCQ subdomain scores for (a) physical limitation; (b) symptom frequency; (c) quality of life; and (d) social limitation. Age ranges are tertiles defined by the 33rd and 67th percentiles, corresponding to $\leqslant$ 71.0 years ($n = 166$), 71.0–77.0 years ($n = 135$), and $>$ 77.0 years ($n = 125$).

4. Discussion

This study evaluates the feasibility, throughput, and operational independence of the use of noninvasive LVEDP assessment (facilitated by the FDA-cleared noninvasive Vivio System) within a screening-oriented workflow aligned with population-based approaches for early HF identification. A primary finding is that conclusive noninvasive LVEDP estimations were successfully obtained in 92.2% of the screened cohort, demonstrating its suitability for more general population-based screening frameworks (Wang *et al* 2003, Bozkurt 2022). Among screened patients, those with an estimated elevated LVEDP had similar age and BMI compared with those without an elevated LVEDP, suggesting that successful identification occurred without introducing measurable selection bias across key demographic characteristics. Indeed, figure 2 further supports this interpretation, depicting substantial overlap in age and BMI between groups and reinforcing that elevated LVEDP identification was not driven by simple demographic stratification. Similarly, patterns across major comorbidities in figure 2(c) do not show a consistent increase in the elevated LVEDP group, indicating that differences in LVEDP status were not simply attributable to a greater overall burden of baseline disease. Overall, these results suggest that LVEDP classification in this cohort was not explained solely by routine demographic or clinical risk markers. Such observations are consistent with other multicenter validation studies that have also demonstrated similar outcomes for noninvasive LVEDP screening in at-risk patients, supporting its use in primary and community care settings (Cantu-Martinez *et al* 2025, Shavelle *et al* 2026). In a large outpatient cross-sectional study ($n = 2040$) employing the same Vivio device but a different clinical workflow (Cantu-Martinez *et al* 2025), 38.5% tested positive for elevated LVEDP of which 68.6% reported notable impairments

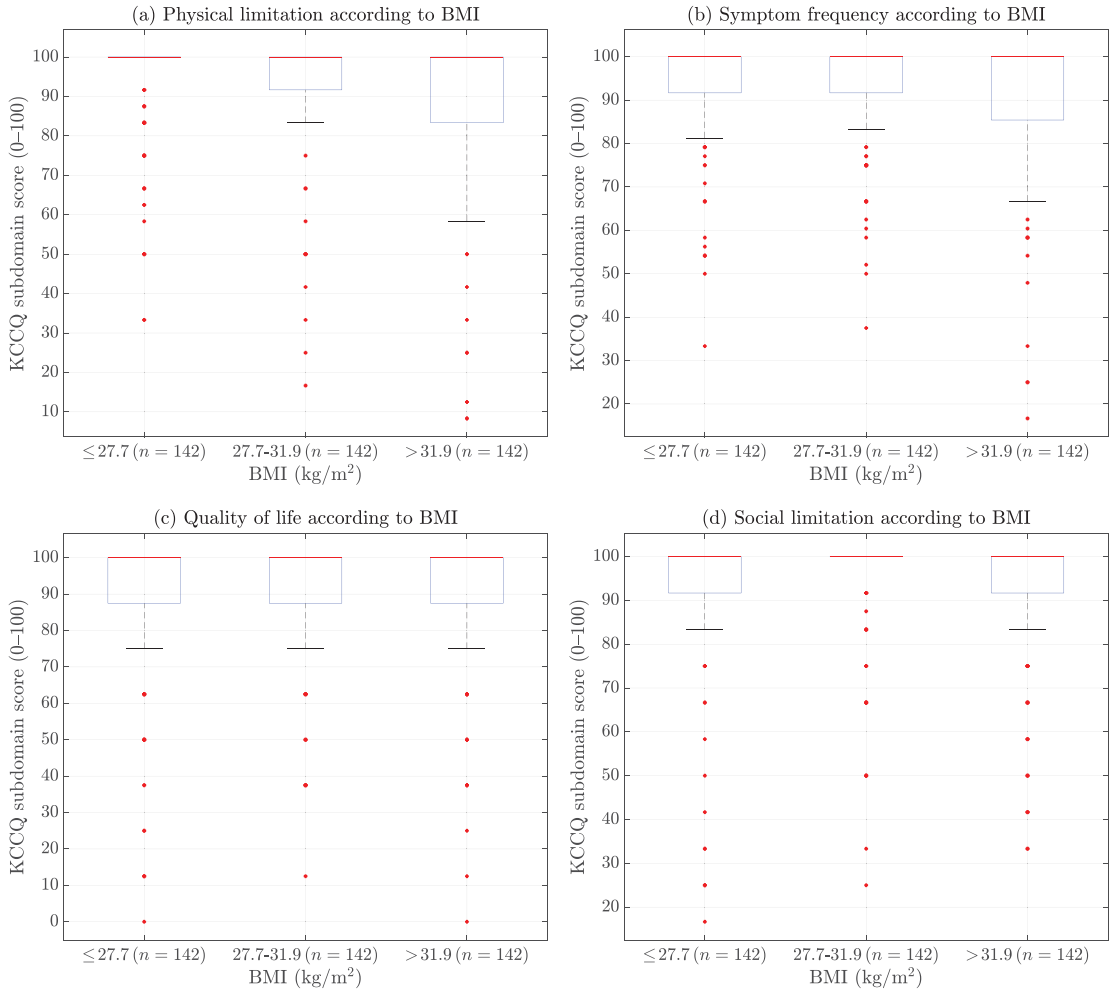

Figure 4. *KCCQ subdomain scores among patients with elevated LVEDP according to BMI.*Box plots depicting distributions of KCCQ subdomain scores for (a) physical limitation; (b) symptom frequency; (c) quality of life; and (d) social limitation. BMI ranges are tertiles defined by the 33rd and 67th percentiles, corresponding to $\leqslant 27.7$ kg m^{-2} ($n = 142$), 27.7–31.9 kg m^{-2} ($n = 142$), and > 31.9 kg m^{-2} ($n = 142$).

in their health status (Cantu-Martinez *et al* 2025). In the present study, for a different patient population and a novel workflow (dedicated clinic visit for LVEDP screening), results are found to be similar (40.1% and 57.8%, respectively), suggesting that adopting the proposed heart health clinic workflow does not induce any bias (numbers and percentages are consistent with other studies (Cantu-Martinez *et al* 2025) which, again, were conducted across different populations, care centers, and workflows). This further implies that noninvasive LVEDP assessment can be applied within diverse clinical settings without introducing measurable selection bias, supporting its evaluation as a component of scalable, population-level HF screening strategies (Wang *et al* 2003, Jafari *et al* 2020, Bozkurt 2022, Khan *et al* 2025).

Among individuals with estimated elevated LVEDP who completed the KCCQ-12, patient-reported health status was predominantly in the asymptomatic or mildly symptomatic range, with 42.3% (15.8% of the total at-risk, Stage A HF population) reclassified as Stage B (KCCQ-OS = 100). Of the symptomatic cases, NYHA I (KCCQ-OS 80–99) was the largest at 45.1% (16.8% of the total), and a further 12.7% (4.7% of the total) were found to be in the NYHA II and NYHA III/IV ranges. All such proportions are consistent with previous (larger cohort) studies (Bergamasco *et al* 2022, Bozkurt *et al* 2023, Cantu-Martinez *et al* 2025). This study also analyzed, for the first time, the subdomains of the KCCQ-12 in conjunction with the Vivio System (i.e. physical limitation, symptom frequency, quality of life, social limitation). In multivariate analysis, higher age and/or BMI were associated with lower KCCQ scores across multiple domains (as expected), supporting the feasibility of integrating this workflow into routine screening while preserving expected (van den Berge *et al* 2021, Siddiqi *et al* 2023) demographic distributions. Indeed, age-related differences were observed across all four subdomains (figure 3), whereas BMI-related differences (figure 4) were largely confined to physical limitation and symptom frequency.

The same analysis indicates that sex (but not age nor BMI after adjustment for sex) was independently associated with elevated LVEDP. This association persisted even after further adjustment for SBP and major comorbidities (DM, CKD, and hypertension), suggesting that the higher prevalence of elevated LVEDP observed in women was not explained by differences in baseline characteristics or disease burden. In this context, women comprised a majority of the elevated LVEDP group and had a higher prevalence of elevated LVEDP than men in the screened cohort of this study, consistent with prior observations that HF is frequently underrecognized and underdiagnosed in women (Sotomi *et al* 2021, Lala *et al* 2022, Rosano *et al* 2024, Tayal *et al* 2024). This finding may reflect known sex-based differences in cardiac structure and physiology, as women are more prone to diastolic dysfunction and HFpEF phenotypes, characterized by impaired left ventricular relaxation (Sotomi *et al* 2021) and often accompanied by structural changes such as concentric remodeling (Rosano *et al* 2024). These features are associated with higher left ventricular filling pressures, consistent with elevated LVEDP. Such alterations are linked to hypertension, obesity, and systemic inflammation, with these risk factors having a greater relative impact on HF risk in women (Sotomi *et al* 2021, Lala *et al* 2022). These differences may be further influenced by post-menopausal hormonal changes associated with systemic inflammation and increased susceptibility to coronary vasomotor disorders (Tayal *et al* 2024). In the present study, it was also observed that women reported lower KCCQ-OS and lower subdomain scores than men in unadjusted analyses, and, after adjustments for age and BMI, female sex was demonstrated to be an independent predictor of lower scores (most pronounced for physical limitation, with smaller differences observed in social limitation and quality of life, and none in symptom frequency). Overall, these findings suggest that among patients with elevated LVEDP, women experience a disproportionate burden of functional impairment (as also reported elsewhere (Rosano *et al* 2024, Tayal *et al* 2024)), particularly in terms of physical limitations (and to some extent, social function), even after accounting for differences in age and BMI.

4.1. Limitations

A number of limitations exist in the context of the present study. The retrospective observational cohort design may have introduced selection bias or residual confounding from unmeasured characteristics/variables. Furthermore, different racial and ethnic groups were not factored into this cohort. Although the Vivio System has been validated in large cohorts from multicenter studies against invasively-measured left heart catheterization (Shavelle *et al* 2026), a major limitation is that HF was not independently and clinically confirmed in all patients found to have elevated LVEDP, nor was the absence of HF independently and clinically confirmed in all patients found to have normal LVEDP. The KCCQ-12 was also administered only to patients classified as having elevated LVEDP per the predefined workflow design; inclusion of KCCQ-12 data in patients with normal LVEDP estimates could potentially strengthen the discrimination analysis. Finally, the operational variability of the dedicated 'superusers' against regular/routine users was not investigated in this study.

5. Conclusions

This study evaluates a novel primary care-based workflow and device (Vivio-facilitated screening-only 'heart health clinics') that generates interpretable noninvasive LVEDP assessments in over 92% of patients who were invited to their primary care clinic for LVEDP screening by 'superusers'. The proposed workflow does not produce any specific bias (elevated LVEDP prevalence and patient-reported health status distributions are similar to prior studies employing different workflows (Cantu-Martinez *et al* 2025)). Additionally, by looking at subdomains of the corresponding KCCQ-12 scores of participants with estimated elevated LVEDP, findings further highlight a greater symptom burden among women (particularly with respect to physical limitations). Indeed, the overall results demonstrate that the use of the novel workflow and device represents a promising avenue for improving HF diagnosis in primary care settings, particularly in women (and others) that are traditionally underdiagnosed (Sotomi *et al* 2021, Lala *et al* 2022, Tayal *et al* 2024).

Data availability statement

The data cannot be made publicly available upon publication because they contain sensitive personal information.

Disclosures

FA has a consulting agreement with Avicena LLC (Ventric Health). TC discloses providing consultative services to and incentive compensation with Ventric Health. RA declares no conflicts of interest.

Ethical statement

The study protocol was reviewed by the Advarra IRB and was determined to be exempt from human subject research requirements in accordance with applicable federal regulations (since it involved the analysis of existing, de-identified data).

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