

## Supplementary Table: Study population

The study population comprised two major cohorts: a development cohort of 20,768 patients from Peking University People's Hospital (Beijing, China) and a geographically independent external validation cohort of 16,621 patients from the Second Hospital of Tianjin Medical University (Tianjin, China). Detailed baseline characteristics are provided in Table 1.

Table 1: **Characteristics of multi-centre cohort.** LV/LA, left ventricular/atrial; RV/RA, right ventricular/atrial.

|                                              | PKUPH           | SHTMU           |
|----------------------------------------------|-----------------|-----------------|
| <b>Patients (<i>n</i>)</b>                   | 20,768          | 16,621          |
| <b>ECGs (<i>n</i>)</b>                       | 27,158          | 18,588          |
| <b>Age, years (Mean <math>\pm</math> SD)</b> | 61.6 $\pm$ 14.4 | 65.3 $\pm$ 13.7 |
| <b>Sex, <i>n</i> (%)</b>                     |                 |                 |
| Male                                         | 9,193 (45.3)    | 9,654 (59.1)    |
| <b>SHD prevalence, <i>n</i> (%)</b>          |                 |                 |
| Reduced LV systolic function                 | 573 (2.8)       | 1,478 (8.9)     |
| Pericardial effusion                         | 444 (2.1)       | 67 (0.4)        |
| LV enlargement                               | 942 (4.5)       | 26 (0.2)        |
| LA enlargement                               | 6,657 (32.1)    | 10,087 (60.7)   |
| RV enlargement                               | 189 (0.9)       | 41 (0.2)        |
| RA enlargement                               | 233 (1.1)       | 99 (0.6)        |
| Global heart enlargement                     | 83 (0.4)        | 289 (1.7)       |
| Ascending aortic dilation                    | 2,059 (9.9)     | 1,808 (10.9)    |
| Aortic regurgitation                         | 138 (0.5)       | 265 (1.6)       |
| Aortic stenosis                              | 73 (0.3)        | 11 (0.1)        |
| Tricuspid regurgitation                      | 195 (0.7)       | 535 (3.2)       |
| Mitral regurgitation                         | 294 (1.1)       | 531 (3.2)       |
| Mitral stenosis                              | 69 (0.3)        | 22 (0.1)        |

## Supplementary Table: Performance benchmarking using 12-lead ECG configurations

While the primary focus of this study is SHD screening via wearable-compatible single-lead ECGs, we evaluated the AnyECG-Echo framework using standard clinical 12-lead ECG inputs to establish a performance benchmark. As shown in Table 3, the transition to a 12-lead configuration provides a modest but consistent improvement in discrimination across nearly all SHD categories. This gain is most notable in conditions where multi-vector electrophysiological information is critical, such as valvular regurgitation and right heart remodeling. Crucially, the framework maintains high external generalizability even with the increased complexity of 12-lead inputs. These findings confirm that AnyECG-Echo effectively scales to different clinical hardware environments while maintaining the same hierarchical diagnostic patterns observed in the single-lead analysis.

A comparison of Table 2 and Table 3 further reveals that single-lead performance retained a consistently high proportion of 12-lead AUROC across all labels.

Table 2: Summary of AUROC performance with 1-lead ECG (including Positive/Negative counts).

| Cardiac condition            | Internal test |       |                | Temporal validation |       |                | External validation |       |                |
|------------------------------|---------------|-------|----------------|---------------------|-------|----------------|---------------------|-------|----------------|
|                              | N (P/N)       | AUROC | 95% CI         | N (P/N)             | AUROC | 95% CI         | N (P/N)             | AUROC | 95% CI         |
| Mitral stenosis              | 8/4070        | 0.836 | [0.685, 0.971] | 11/4512             | 0.889 | [0.735, 0.977] | 22/16599            | 0.906 | [0.837, 0.951] |
| Global heart enlargement     | 20/4058       | 0.931 | [0.880, 0.971] | 25/4498             | 0.929 | [0.883, 0.963] | 289/16332           | 0.877 | [0.860, 0.894] |
| Reduced LV systolic function | 110/3968      | 0.924 | [0.895, 0.950] | 139/4384            | 0.920 | [0.901, 0.936] | 1478/15143          | 0.866 | [0.858, 0.874] |
| Tricuspid regurgitation      | 28/4050       | 0.907 | [0.838, 0.962] | 32/4491             | 0.893 | [0.837, 0.936] | 535/16086           | 0.820 | [0.800, 0.837] |
| Mitral regurgitation         | 40/4038       | 0.808 | [0.739, 0.870] | 41/4482             | 0.842 | [0.786, 0.889] | 531/16090           | 0.806 | [0.788, 0.823] |
| RA enlargement               | 36/4042       | 0.914 | [0.871, 0.952] | 66/4457             | 0.913 | [0.887, 0.936] | 99/16522            | 0.803 | [0.762, 0.843] |
| Pericardial effusion         | 88/3990       | 0.728 | [0.676, 0.777] | 96/4427             | 0.691 | [0.646, 0.734] | 67/16554            | 0.832 | [0.790, 0.870] |
| RV enlargement               | 42/4036       | 0.882 | [0.833, 0.930] | 35/4488             | 0.771 | [0.689, 0.846] | 41/16580            | 0.748 | [0.670, 0.819] |
| LV enlargement               | 197/3881      | 0.868 | [0.843, 0.895] | 216/4307            | 0.838 | [0.812, 0.861] | 26/16595            | 0.698 | [0.605, 0.777] |
| Aortic stenosis              | 15/4063       | 0.835 | [0.734, 0.917] | 13/4510             | 0.756 | [0.616, 0.883] | 11/16610            | 0.714 | [0.576, 0.832] |
| Ascending aortic dilation    | 342/3736      | 0.685 | [0.658, 0.713] | 507/4016            | 0.677 | [0.657, 0.700] | 1808/14813          | 0.635 | [0.622, 0.648] |
| Aortic regurgitation         | 17/4061       | 0.928 | [0.841, 0.979] | 27/4496             | 0.807 | [0.721, 0.886] | 265/16356           | 0.639 | [0.609, 0.669] |
| LA enlargement               | 1289/2789     | 0.665 | [0.648, 0.680] | 1406/3117           | 0.657 | [0.641, 0.673] | 10087/6534          | 0.610 | [0.602, 0.618] |

Table 3: Summary of AUROC performance with 12-lead ECG (including Positive/Negative counts).

| Cardiac condition            | Internal test |       |                | Temporal validation |       |                | External validation |       |                |
|------------------------------|---------------|-------|----------------|---------------------|-------|----------------|---------------------|-------|----------------|
|                              | N (P/N)       | AUROC | 95% CI         | N (P/N)             | AUROC | 95% CI         | N (P/N)             | AUROC | 95% CI         |
| Mitral stenosis              | 8/4070        | 0.972 | [0.947, 0.983] | 11/4512             | 0.944 | [0.930, 0.987] | 22/16599            | 0.916 | [0.882, 0.959] |
| Global heart enlargement     | 20/4058       | 0.961 | [0.950, 0.980] | 25/4498             | 0.980 | [0.974, 0.987] | 289/16332           | 0.897 | [0.889, 0.904] |
| Reduced LV systolic function | 110/3968      | 0.937 | [0.929, 0.952] | 139/4384            | 0.930 | [0.921, 0.942] | 1478/15143          | 0.890 | [0.880, 0.895] |
| Tricuspid regurgitation      | 28/4050       | 0.953 | [0.916, 0.973] | 32/4491             | 0.948 | [0.934, 0.964] | 535/16086           | 0.841 | [0.834, 0.851] |
| Mitral regurgitation         | 40/4038       | 0.876 | [0.820, 0.920] | 41/4482             | 0.876 | [0.840, 0.908] | 531/16090           | 0.820 | [0.810, 0.835] |
| RA enlargement               | 36/4042       | 0.916 | [0.911, 0.943] | 66/4457             | 0.922 | [0.902, 0.943] | 99/16522            | 0.803 | [0.752, 0.829] |
| Pericardial effusion         | 88/3990       | 0.822 | [0.799, 0.857] | 96/4427             | 0.784 | [0.762, 0.811] | 67/16554            | 0.766 | [0.687, 0.778] |
| RV enlargement               | 42/4036       | 0.932 | [0.907, 0.955] | 35/4488             | 0.754 | [0.704, 0.798] | 41/16580            | 0.735 | [0.655, 0.779] |
| LV enlargement               | 197/3881      | 0.892 | [0.878, 0.907] | 216/4307            | 0.861 | [0.849, 0.887] | 26/16595            | 0.730 | [0.686, 0.794] |
| Aortic stenosis              | 15/4063       | 0.867 | [0.771, 0.943] | 13/4510             | 0.707 | [0.602, 0.793] | 11/16610            | 0.700 | [0.650, 0.828] |
| Ascending aortic dilation    | 342/3736      | 0.725 | [0.710, 0.744] | 507/4016            | 0.713 | [0.697, 0.726] | 1808/14813          | 0.674 | [0.668, 0.685] |
| Aortic regurgitation         | 17/4061       | 0.956 | [0.938, 0.968] | 27/4496             | 0.782 | [0.707, 0.833] | 265/16356           | 0.673 | [0.655, 0.686] |
| LA enlargement               | 1289/2789     | 0.725 | [0.718, 0.737] | 1406/3117           | 0.719 | [0.711, 0.724] | 10087/6534          | 0.642 | [0.637, 0.650] |

## Supplementary Table: Subgroup Analysis of Low-Prevalence SHD Subtypes

Supplementary Table 4 provides a comprehensive demographic breakdown for the remaining SHD subtypes in the external validation cohort. Due to the low prevalence of certain conditions within specific age and sex strata, several categories contained fewer than five positive cases and are consequently reported as N/A to ensure statistical reliability.

Despite the limited sample sizes in these sub-populations, AnyECG-Echo maintained robust discriminative performance across the calculable categories. Notably, for RV enlargement and Mitral stenosis, the model achieved AUROCs consistently exceeding 0.80 across most age groups, further demonstrating the framework’s ability to capture specific structural signatures even for less frequent pathologies. The performance across sex and age strata, where data were sufficient for calculation, remained generally consistent with the primary findings, suggesting that the model’s diagnostic utility extends to a broad spectrum of valvular and chamber-specific abnormalities without manifesting significant demographic bias.

**Table 4: Subgroup analysis of the remaining labels in the PKUPH cohort, stratified by age group and sex.** Values are AUROC (95% confidence interval). N/A indicates fewer than five positive cases in that specific stratum.

| Subgroup                 | <i>n</i><br>(pos/neg) | LA<br>enlargement    | RA<br>enlargement    | RV<br>enlargement    | Aortic<br>regurg.    | Aortic<br>stenosis   | Tricuspid<br>regurg. | Mitral<br>regurg.    | Mitral<br>stenosis   |
|--------------------------|-----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| <b>Age group (years)</b> |                       |                      |                      |                      |                      |                      |                      |                      |                      |
| <50                      | 142/280               | 0.617 [0.541, 0.688] | N/A                  | 0.856 [0.663, 0.981] | N/A                  | N/A                  | N/A                  | 0.787 [0.548, 0.963] | N/A                  |
| 50–64                    | 347/410               | 0.644 [0.600, 0.689] | N/A                  | 0.917 [0.792, 0.998] | 0.814 [0.515, 0.984] | N/A                  | 0.840 [0.672, 0.990] | 0.708 [0.553, 0.856] | 0.845 [0.640, 0.993] |
| 65–74                    | 342/248               | 0.634 [0.588, 0.680] | N/A                  | 0.953 [0.902, 0.992] | N/A                  | N/A                  | 0.973 [0.920, 0.999] | 0.880 [0.798, 0.949] | N/A                  |
| ≥75                      | 267/136               | 0.640 [0.587, 0.694] | 0.837 [0.681, 0.949] | N/A                  | N/A                  | N/A                  | N/A                  | N/A                  | N/A                  |
| <b>Sex</b>               |                       |                      |                      |                      |                      |                      |                      |                      |                      |
| Male                     | 858/571               | 0.641 [0.611, 0.670] | 0.868 [0.760, 0.948] | 0.906 [0.820, 0.976] | 0.844 [0.545, 0.977] | 0.903 [0.754, 0.978] | N/A                  | 0.838 [0.732, 0.923] | N/A                  |
| Female                   | 753/999               | 0.677 [0.649, 0.705] | 0.928 [0.867, 0.974] | 0.883 [0.802, 0.948] | N/A                  | 0.846 [0.734, 0.942] | 0.901 [0.812, 0.968] | 0.731 [0.598, 0.856] | 0.830 [0.673, 0.983] |

*n* = positive / negative ECG recordings per subgroup (SHD overall). AUROC values: point estimate [95% confidence interval], calculated via 2,000 bootstrap iterations. RV, Right ventricular; LA, Left atrial; RA, Right atrial; Regurg., Regurgitation.

## Supplementary Table: Community prevalence estimates used for NNS calculation

Community prevalence estimates were derived from published population-based echocardiographic screening studies. Where contemporary data were unavailable, we adopted conservative estimates from earlier landmark studies. Given the well-documented increase in SHD prevalence driven by population ageing<sup>1</sup>, these figures likely underestimate the true contemporary prevalence, rendering our NNS estimates conservative.

**Table 5: Community prevalence estimates for SHD subtypes used in number-needed-to-screen (NNS) calculations.** Estimates reflect the general adult population unless otherwise noted.

| Cardiac condition                 | Assumed prevalence | Reported range      | Source                                                                                                  |
|-----------------------------------|--------------------|---------------------|---------------------------------------------------------------------------------------------------------|
| Reduced LV systolic function      | 3.0%               | 2–6%                | Mosterd et al., <i>Eur Heart J</i> 1999 <sup>2</sup> ; Raymond et al., <i>Heart</i> 2003 <sup>3</sup>   |
| Pericardial effusion              | 1.0%               | 1–3%                | Morbach et al., <i>JAHA</i> 2024 <sup>4</sup>                                                           |
| Global heart enlargement          | 1.0%               | 0.4–1% <sup>†</sup> | Estimated from clinical series                                                                          |
| Left atrial enlargement           | 5.0%               | 2–10%               | Ou et al., <i>BMC Cardiovasc Disord</i> 2016 <sup>5</sup>                                               |
| LV enlargement                    | 2.0%               | 1–3% <sup>†</sup>   | Vasan et al., <i>Circulation</i> 1997 <sup>6</sup>                                                      |
| Right atrial enlargement          | 1.0%               | ~1% <sup>†</sup>    | Estimated from clinical series                                                                          |
| RV enlargement                    | 1.0%               | ~1% <sup>†</sup>    | Estimated from clinical series                                                                          |
| Ascending aortic dilation         | 3.0%               | 1.5–5%              | Nkomo et al., <i>The lancet</i> 2006 <sup>7</sup> ; d'Arcy et al., <i>Eur Heart J</i> 2016 <sup>8</sup> |
| Aortic regurgitation (mod–sev)    | 1.5%               | 1–2%                | Nkomo et al., <i>The lancet</i> 2006 <sup>7</sup> ; d'Arcy et al., <i>Eur Heart J</i> 2016 <sup>8</sup> |
| Aortic stenosis (mod–sev)         | 1.5%               | 1–2%                | Nkomo et al., <i>The lancet</i> 2006 <sup>7</sup> ; d'Arcy et al., <i>Eur Heart J</i> 2016 <sup>8</sup> |
| Tricuspid regurgitation (mod–sev) | 1.0%               | 0.5–1%              | Nkomo et al., <i>The lancet</i> 2006 <sup>7</sup> ; d'Arcy et al., <i>Eur Heart J</i> 2016 <sup>8</sup> |
| Mitral regurgitation (mod–sev)    | 2.0%               | 1–2%                | Nkomo et al., <i>The lancet</i> 2006 <sup>7</sup> ; d'Arcy et al., <i>Eur Heart J</i> 2016 <sup>8</sup> |
| Mitral stenosis (mod–sev)         | 0.5%               | 0.1–1% <sup>‡</sup> | Nkomo et al., <i>The lancet</i> 2006 <sup>7</sup> ; d'Arcy et al., <i>Eur Heart J</i> 2016 <sup>8</sup> |

<sup>†</sup>No large-scale population-based echocardiographic data available; estimate derived from disease-specific prevalence studies and clinical series.

<sup>‡</sup>Prevalence varies substantially by geography; rheumatic mitral stenosis is rare in high-income countries (<0.1%) but more common in low- and middle-income settings (1–2%).

## Supplementary Figure: Electrophysiological interpretation results

A distinct set of results characterizing the model’s sensitivity to subtle atrial signatures is summarized in Fig. 1. While AnyECG-Echo identifies P-mitrale patterns in mitral stenosis

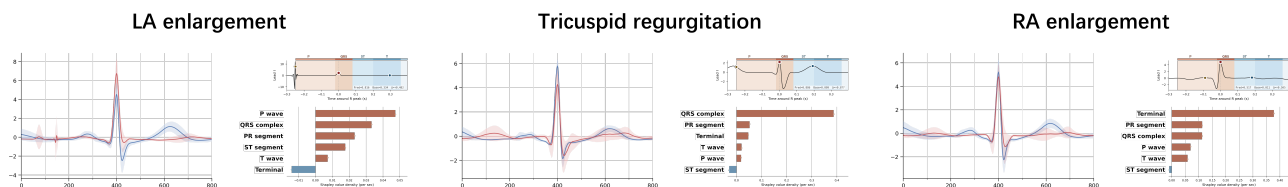


Figure 1: **Supplementary Electrophysiological interpretation of learned ECG features across SHD phenotypes.**

through combined P-wave and QRS complex attribution, its capture of isolated P-wave morphology remains incomplete. For conditions such as tricuspid regurgitation or right atrial enlargement, the P-wave broadening and amplitude shifts in Lead I are often too subtle for robust single-beat encoding. These findings suggest a technical nuance: the model's discrimination of atrial-related labels likely relies more heavily on co-occurring ventricular or hemodynamic features than on direct P-wave signatures. This limitation reflects the inherent constraints of single-lead, single-beat analysis in resolving subtle atrial structural changes.

## References

1. Mensah, G.A., Fuster, V., Murray, C.J., Roth, G.A., Abate, Y.H., Abbasian, M., Abd-Allah, F., Abdollahi, A., Abdollahi, M., Abdulah, D.M. et al. (2023). Global burden of cardiovascular diseases and risks, 1990-2022. *Journal of the American College of Cardiology* 82, 2350–2473.
2. Mosterd, A., Hoes, A., De Bruyne, M., Deckers, J., Linker, D., Hofman, A., and Grobbee, D. (1999). Prevalence of heart failure and left ventricular dysfunction in the general population; the rotterdam study. *European heart journal* 20, 447–455.
3. Raymond, I., Pedersen, F., Steensgaard-Hansen, F., Green, A., Busch-Sorensen, M., Tuxen, C., Appel, J., Jacobsen, J., Atar, D., and Hildebrandt, P. (2003). Prevalence of impaired left ventricular systolic function and heart failure in a middle aged and elderly urban population segment of copenhagen. *Heart* 89, 1422–1429.
4. Sahiti, F., Cejka, V., Schmidbauer, L., Albert, J., Kerwagen, F., Frantz, S., Gelbrich, G., Heuschmann, P.U., Störk, S., and Morbach, C. (2024). Prognostic utility of pericardial effusion in the general population: findings from the staab cohort study. *Journal of the American Heart Association* 13, e035549.
5. Ou, Q., Chen, Y., Yu, S., Guo, X., Zhao, H., and Sun, Y. (2016). Prevalence of left atrial enlargement and its risk factors in general chinese population. *BMC cardiovascular disorders* 16, 53.
6. Vasan, R.S., Larson, M.G., Benjamin, E.J., Evans, J.C., and Levy, D. (1997). Left ventricular dilatation and the risk of congestive heart failure in people without myocardial infarction. *New England Journal of Medicine* 336, 1350–1355.
7. Nkomo, V.T., Gardin, J.M., Skelton, T.N., Gottdiener, J.S., Scott, C.G., and Enriquez-Sarano, M. (2006). Burden of valvular heart diseases: a population-based study. *The lancet* 368, 1005–1011.

8. d'Arcy, J.L., Coffey, S., Loudon, M.A., Kennedy, A., Pearson-Stuttard, J., Birks, J., Frangou, E., Farmer, A.J., Mant, D., Wilson, J. et al. (2016). Large-scale community echocardiographic screening reveals a major burden of undiagnosed valvular heart disease in older people: the oxvalve population cohort study. *European heart journal* 37, 3515–3522.