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RAPID COMMUNICATION

Dynamic changes of artificial intelligence estimated electrocardiographic age and sex predicts recurrence after atrial fibrillation catheter ablation

Hanjin Park[1†], Oh-Seok Kwon [1†], Jaemin Shim [2*‡], Daehoon Kim [1], Je-Wook Park [1], Yun-Gi Kim [2], Hee Tae Yu [1], Tae-Hoon Kim [1], Jae-Sun Uhm [1], Jong-Il Choi [2], Boyoung Joung [1], Moon-Hyoung Lee [1], and Hui-Nam Pak [1*‡]

[1]Yonsei University College of Medicine, Yonsei University Health System, 50-1 Yonsei-ro, Seodaemun-gu, Seoul 120-752, Republic of Korea; and [2]Division of Cardiology, Department of Internal Medicine, Korea University Medical Center, 126-1 Anam-5ga Seungbuk-ku, Seoul 136-705, Republic of Korea

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Introduction

Artificial intelligence (AI)-derived electrocardiographic (ECG) age and sex are independent risk markers of atrial fibrillation (AF) recurrence after catheter ablation.[1,2] However, AI-ECG age and sex are dynamic parameters that might reflect effectiveness of the lesion formation and maintenance of sinus rhythm.[3] We hypothesized that dynamic changes in AI-ECG age and sex discordance after catheter ablation would predict reverse remodelling of left atrium (LA), functional recovery of left ventricle (LV), and risk of AF recurrence.

Methods

We developed a residual network-based model for AI-ECG age and sex prediction.[2] We then externally validated the model on two independent datasets unseen during pre-training. External validation cohorts consisted of a total of 819 408 ECGs; CODE-15% [$n = 345\,779$; $r = 0.78$ for AI-ECG age, area under the curve (AUC) 0.91 for AI-ECG sex] and MIMIC-IV ($n = 473\,629$; $r = 0.69$ for AI-ECG age, AUC 0.90 for AI-ECG sex) cohorts.[4,5] After validation, the model was tested on a pooled AF catheter ablation cohort (Yonsei University Health System and Korea University Anam Hospital; retrospective cohorts from tertiary medical centres in South Korea that included patients scheduled for AF catheter ablation from 2009 to 2024 and 2015 to 2022, respectively). Artificial intelligence (AI)-derived electrocardiographic (ECG) age and sex was predicted using 12-lead sinus rhythm ECGs sampled at 500 Hz and length of 10 s. Patients who met the following criteria were excluded; (i) underwent prior AF catheter ablation, (ii) history of mitral valve surgery or mitral stenosis, and (iii) without pre- and 3rd month post-procedural sinus rhythm ECG. Finally, a total of 5073 patients were analysed (59.5 ± 10.8 years; 27.0% female). The AFCA protocols were consistent across individuals as previously described.[1,2]

To investigate the effect of dynamic AI-ECG age and sex discordance change before and after catheter ablation on clinical recurrence, we defined ΔAI-ECG age and sex discordance as follows;

$$\text{(1) } \Delta\text{AI-ECG age} = \text{Post-procedural AI-ECG age} - \text{Pre-procedural AI-ECG age}$$

$$\begin{cases} \text{Increasing } \Delta\text{AI-ECG age} = \Delta\text{AI-ECG age} > 0 \text{ years} \\ \text{Decreasing } \Delta\text{AI-ECG age} = \Delta\text{AI-ECG age} \leq 0 \text{ years} \end{cases}$$

$$\text{(2) } \Delta\text{AI-ECG sex discordance} = \text{Post-procedural AI-ECG sex probability for the opposite sex} - \text{Pre-procedural ECG sex probability for the opposite sex}$$

$$\begin{cases} \text{Increasing } \Delta\text{AI-ECG sex discordance} = \Delta\text{AI-ECG sex discordance} > 0\ \% \\ \text{Decreasing } \Delta\text{AI-ECG sex discordance} = \Delta\text{AI-ECG sex discordance} \leq 0\ \% \end{cases}$$

Post-procedural AI-ECG age and sex were evaluated at 1 to 3rd month after the index procedure given that post-procedural transient local inflammatory state[6] might affect AI-ECG age and sex prediction rather than reflecting true effect of the procedure. We obtained 24-h Holter recordings at 3 and 6 months and every 6 months thereafter. Atrial fibrillation recurrence was defined as any episode of AF or atrial tachycardia of at least 30 s after 3 months blanking period.

* Corresponding authors. Tel: +82-2-2228-8459; fax: +82-2-2227-7732. *E-mail address*: hnpak@yuhs.ac (H.-N.P.); Tel: +82-2-920-5445; fax: +82-2-927-1478. *E-mail address*: jaemins@korea.ac.kr (J.S.)

† These two authors contributed equally to this work.

‡ Joint senior authors.

Hazard ratios (adjusted for clinical risk factors; AF type, chronological age, sex, body mass index, hypertension, diabetes, vascular disease, heart failure, LV ejection fraction, LA diameter, and E/e') and 5-year cumulative event rates of recurrence were calculated according to ΔAI-ECG age and ΔAI-ECG sex discordance.

All participants provided written informed consent. The study protocol adhered to the principles of the Declaration of Helsinki and was approved by the Institutional Review Board of the Yonsei University Health System.

Results

Increasing ΔAI-ECG age was associated with significantly less PR interval and LA diameter decrease and increasing ΔAI-ECG sex discordance with significantly greater QTc interval and less LV ejection fraction increase. Compared to those with decreasing ΔAI-ECG age and sex discordance, individuals with increasing ΔAI-ECG age and sex discordance were associated with a hazard ratio of 1.24 [95% confidence interval (CI) 1.11–1.37] and 1.20 (95% CI 1.08–1.33) for AF recurrence, respectively.

Compared to individuals with decreasing ΔAI-ECG age and ΔAI-ECG sex discordance, the hazard ratios for AF recurrence were 1.23 (95% CI 1.06–1.42), 1.26 (95% CI 1.09–1.26), and 1.47 (95% CI 1.24–1.66) for those with decreasing ΔAI-ECG age and increasing ΔAI-ECG sex discordance, increasing ΔAI-ECG age and decreasing ΔAI-ECG sex discordance, and increasing ΔAI-ECG age and ΔAI-ECG sex discordance, respectively. The trends for 5-year cumulative event rates showed consistent findings. There was no significant interaction with baseline chronological age, sex, AF type, or LA diameter (P for interaction >0.05).

Discussion

Many scientific efforts on the application of AI on 12-lead ECGs have been limited by using a 'static' approach, in which AI-enabled single baseline ECG predicts an outcome. However, ECG is a dynamic parameter that changes over time depending on the condition of the heart, which is particularly true in cases when an individual undergoes an interventional procedure such as AF catheter ablation. To our knowledge, this is the first study to introduce the novel concept of 'dynamic' changes in AI-ECG age and sex discordance. We found that that 'dynamic' AI-ECG age and sex discordance change after catheter ablation might be a simple, in-office risk marker for clinical recurrence that reflect reverse remodelling of the LA and functional recovery of LV.

Several potential mechanisms by which ΔAI-ECG age and sex discordance predicts AF recurrence can be suggested. First, ΔAI-ECG age increase might be associated with ineffective post-procedural atrial reverse remodelling, given the association with less PR interval and LA diameter decrease, that might have translated into increased risk of recurrence.[7] Second, ΔAI-ECG sex discordance increase was associated with increase in QTc intervals, and QTc prolongation is reportedly a risk marker for recurrence that reflect intrinsic cardiac electrophysiology and susceptibility to 'atrial torsade de pointes'.[8,9] Third, ΔAI-ECG sex discordance increase was associated with less LV functional recovery, and the associated elevated diastolic filling pressure might have translated into increased risk of recurrence.

Several clinical implications of ΔAI-ECG age and sex discordance can be considered. First, individuals planned for AF catheter ablation would benefit from re-assessing AI-ECG age and sex post-procedure. Second, clinicians might offer lifestyle interventions and anti-arrhythmic drug maintenance to reduce the risk of recurrence and adverse events whose ΔAI-ECG age and sex discordance increase post-procedure. Third, ΔAI-ECG sex discordance estimation might be useful in assessing LV functional recovery response after AF catheter ablations given its mortality benefit in patients with heart failure.[10]

Conclusions

Dynamic AI-ECG age and sex discordance changes after catheter ablations are useful risk markers for clinical recurrence of AF that reflect LA reverse remodelling and LV functional recovery.

Author contributions

H.J.P. contributed to conceptualization, data curation, formal analysis, methodology, and writing-original draft. O.S.K. contributed to investigation, methodology, software, validation, visualization. J.M.S. and Y.G.K. contributed to project administration, resources, supervision, and validation. D.H.K., J.W.P., H.T.Y., and T.H.K. contributed to investigation, methodology, project administration, and supervision. J.S.U., J.I.C., B.Y.J., and M.H.L. contributed to methodology, supervision, validation. J.I.C. contributed to project administration, supervision, validation, visualization. H.N.P. contributed to conceptualization, funding acquisition, methodology, supervision, validation, and writing-review and editing.

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Conflict of interest: none declared.

Data availability

Yonsei University Health System and Korea University Anam Hospital datasets are not publicly available due to institutional and ethical regulations. External validation was performed using two open-access datasets: the CODE-15% dataset (https://zenodo.org/records/4916206) and the MIMIC-IV ECG dataset (https://physionet.org/content/mimic-iv-ecg/1.0/). Both datasets are publicly accessible from the respective repositories. The code and pre-trained weights used in this study are available upon reasonable request from the corresponding author.

References

1. Park H, Kwon OS, Shim J, Kim D, Park JW, Kim YG *et al.* Artificial intelligence estimated electrocardiographic age as a recurrence predictor after atrial fibrillation catheter ablation. *NPJ Digit Med* 2024;**7**:234.
2. Park H, Kwon OS, Shim J, Kim D, Park JW, Kim YG *et al.* Artificial intelligence-estimated electrocardiographic sex as a recurrence predictor after atrial fibrillation catheter ablation. *Eur Heart J Digit Health* 2025;**6**:624–34.
3. Reant P, Lafitte S, Jais P, Serri K, Weerasooriya R, Hocini M *et al.* Reverse remodeling of the left cardiac chambers after catheter ablation after 1 year in a series of patients with isolated atrial fibrillation. *Circulation* 2005;**112**:2896–903.
4. Ribeiro ALP, Paixao GMM, Gomes PR, Ribeiro MH, Ribeiro AH, Canazart JA *et al.* Tele-electrocardiography and bigdata: the CODE (clinical outcomes in digital electrocardiography) study. *J Electrocardiol* 2019;**57**:S75–8.
5. Johnson AEW, Bulgarelli L, Shen L, Gayles A, Shammout A, Horng S *et al.* MIMIC-IV, a freely accessible electronic health record dataset. Sci Data 2023;10:1.
6. Willems S, Khairy P, Andrade JG, Hoffmann BA, Levesque S, Verma A *et al.* Redefining the blanking period after catheter ablation for paroxysmal atrial fibrillation: insights from the ADVICE (adenosine following pulmonary vein isolation to target dormant conduction elimination) trial. *Circ Arrhythm Electrophysiol* 2016;**9**:e003909.
7. Intzes S, Zagoridis K, Symeonidou M, Spanoudakis E, Arya A, Dinov B *et al.* P-wave duration and atrial fibrillation recurrence after catheter ablation: a systematic review and meta-analysis. *Europace* 2023;**25**:450–9.
8. Liu N, Wen S-N, Ruan Y-F, Zhang T, Li S-N, Wu J-H *et al.* QTc interval prolongation predicts the ablation outcome in hypertensive patients with paroxysmal atrial fibrillation. *Eur Heart J Suppl* 2015;**17**:B32–8.
9. Nielsen JB, Graff C, Pietersen A, Lind B, Struijk JJ, Olesen MS *et al.* J-shaped association between QTc interval duration and the risk of atrial fibrillation: results from the Copenhagen ECG study. *J Am Coll Cardiol* 2013;**61**:2557–64.
10. Marrouche NF, Brachmann J, Andresen D, Siebels J, Boersma L, Jordaens L *et al.* Catheter ablation for atrial fibrillation with heart failure. *N Engl J Med* 2018;**378**:417–27.