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Rubén Molero, Olivier Meste, Ralf Peeters, Joël Karel, Pietro Bonizzi, et al.. Complexity and recurrence of body surface electrocardiograms correlate with estimated reentrant atrial activity using electrocardiographic imaging in atrial fibrillation patients. *BMC Cardiovascular Disorders*, 2025, 25 (1), pp.23. 10.1186/s12872-025-04483-4 . hal-04889927

**HAL Id: hal-04889927**

**<https://hal.science/hal-04889927v1>**

Submitted on 15 Jan 2025

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# Complexity and recurrence of body surface electrocardiograms correlate with estimated reentrant atrial activity using electrocardiographic imaging in atrial fibrillation patients

Rubén Molero<sup>1,2\*</sup>, Olivier Meste<sup>3</sup>, Ralf Peeters<sup>4</sup>, Joël Karel<sup>4</sup>, Pietro Bonizzi<sup>4†</sup> and María S. Guillem<sup>1,2†</sup>

## Abstract

**Background** Complexity and signal recurrence metrics obtained from body surface potential mapping (BSPM) allow quantifying atrial fibrillation (AF) substrate complexity. This study aims to correlate electrocardiographic imaging (ECGI) detected reentrant patterns with BSPM-calculated signal complexity and recurrence metrics.

**Methods** BSPM signals were recorded from 28 AF patients (17 male, 11 women,  $62.69 \pm 8.09$  y.o.), followed by ECGI calculation. Signal complexity and recurrence metrics were computed on BSPM and ECGI signals. Rotors per second and rotor duration were computed on ECGI signals for each atrium and the whole atrial surface. Correlation between BSPM metrics and ECGI reentrant patterns for the entire atrial surface and for left atrium (LA) and right atrium (RA) were analyzed.

**Results** Atrial complexity and recurrence metrics strongly correlated when computed on BSPM and ECGI. Higher sample entropy and relative harmonic energy (RHE) correlated with rotors of short duration. The highest dominant frequency of the ECGI signals did not correlate with the reentrant activity of the ECGI. Higher short- and long-term recurrence of BSPM signals correlated with longer duration rotors, particularly for long-term recurrence ( $r_{LA}=0.74$  vs.  $r_{RA}=0.42$ ). Only ECGI-based reentrant parameters showed higher LA complexity compared to RA ( $p < 0.05$ ).

**Conclusions** BSPM metrics strongly correlate with metrics measured on ECGI signals. BSPM metrics indicate a more elevated atrial electro-structural remodeling aligned with more short-duration rotors from ECGI computations. Although BSPM delivers qualitative AF reentry data, ECGI remains essential for identifying regional substrate complexity.

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**Keywords** Atrial fibrillation, Electrocardiographic imaging, Body surface potential mapping, Electrical complexity, Reentrant activity

## Background

Atrial fibrillation (AF) is the most prevalent cardiac arrhythmia in adults, which is linked to higher morbidity and mortality rates [1]. The electrocardiogram (ECG) is a widely used diagnostic tool for AF and has been used for the estimation of the morbidity and maintenance of AF [2]. Body surface potential mapping (BSPM) is a non-invasive method used to assess the electrical activity of the heart by means of a large number of electrodes distributed over the torso surface of a patient, which provides higher spatial resolution and more information about the arrhythmia than the standard 12-lead ECG [3].

High AF substrate complexity typically suggests advanced electro-structural remodeling and more disorganized spatio-temporal propagation patterns, often associated with persistent AF and more challenging management, whereas low complexity corresponds to more organized arrhythmias that may respond better to interventions. Several studies have systematically analyzed the electrical properties of BSPM signals during AF, in order to extract relevant information about AF substrate complexity and link it to the electrostructural remodeling, the disease progression and treatment outcome of this arrhythmia [4–6]. For instance, previous research demonstrated that BSPM can be used to non-invasively localize sites of the dominant frequency (DF) in atrial activity [7]. Other studies have examined AF complexity by evaluating the short- and long-term recurrent behavior of atrial activity propagation on BSPM signals [8]. These findings suggest that the variability in the recurrent behavior of the atrial activity is due mostly to an uncoordinated propagation of waveforms on the atrial surface. Additionally, AF surface complexity has been shown to influence the short-term repetitive behavior of atrial propagation [8].

At the same time, it is still unclear to what extent BSPM signals can be used to characterize and localize AF propagation patterns. In this respect, electrocardiographic imaging (ECGI) has been used to non-invasively reconstruct epicardial potentials starting from BSPM signals and information about the geometry of the heart and the torso. Moreover, ECGI can serve as a valuable tool to confirm and correlate the information captured by BSPM signals on the torso with the substrate complexity measured on the heart's surface. Although ECGI requires more information from the patient and it is consequently more burdensome to obtain ECGI maps compared to BSPM, it has been shown in the past to be helpful for the evaluation of drivers that initiate and maintain AF [9–11]. This comparison could help validate BSPM as a practical,

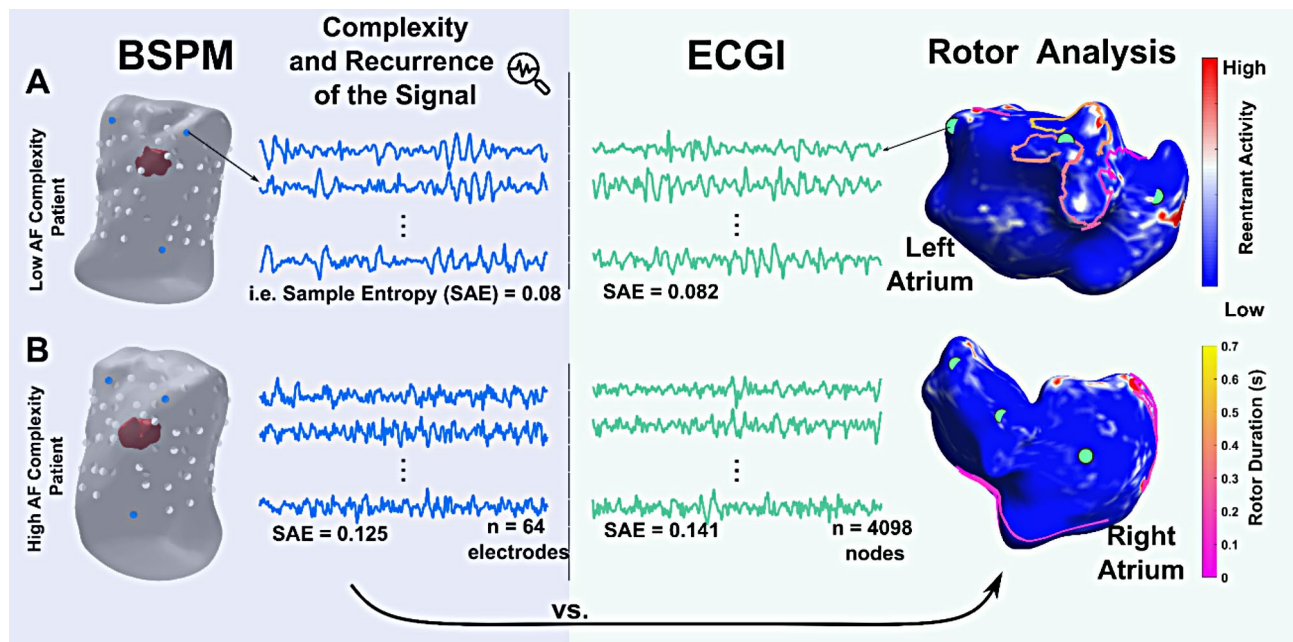
non-invasive approach to evaluate AF substrates in clinical settings, thereby enhancing diagnostic accessibility for AF management, before moving to ECGI if needed, or when ECGI is not possible to use. In addition, it has been proved that AF drivers detected through ECGI signals presented a good correlation with intracardiac mapping in AF patients [12, 13]. ECGI has also been proven to be a reliable tool for locating and characterizing atrial rotors [11, 14], which are one of the hypothesized mechanisms of AF generation and maintenance [15, 16].

The purpose of this study is to investigate the relationship of BSPM-derived metrics that quantify AF substrate complexity and AF propagation recurrence with properties such as the number and duration of reentrant atrial patterns assessed on ECGI signals. While ECGI provides detailed insights into the atrial substrate, a systematic exploration of the correlation between ECGI-derived metrics and BSPM signals in the context of AF has not yet been conducted. The hypothesis of this study is that BSPM- and ECGI-derived metrics will exhibit similar trends. Specifically, BSPM metrics for AF substrate complexity and propagation recurrence are expected to provide insights into the properties of atrial reentrant activity (rotors) and rotor duration, as observed through ECGI. Additionally, metrics were evaluated for each atrium (left and right) to determine if BSPM could offer specific information about AF substrate characteristics unique to each atrium. A graphical representation of the present study is shown in Fig. 1.

## Methods

### Data acquisition and processing

A population of 28 AF patients (11 female, 17 male,  $62.69 \pm 8.09$  years old) was studied prior to pulmonary vein isolation (PVI). Nine patients were diagnosed with paroxysmal AF and 19 with persistent AF prior to the PVI. The protocol was authorized by the Spanish Agency of Medicines and Medical Devices (AEMPS), code: FAT-ANT-2018-01 after patients provided informed consent. BSPM signals from 64 electrodes were recorded before PVI at a sampling frequency of 1 kHz. The electrodes were distributed in the torso 24 on the front, 24 on the back, and 8 on each side of the torso. The geometry of each of the patient's torso and the electrode positions were obtained using photogrammetry [17]. This method allows for a precise 3D mapping of the torso and electrode locations using a camera, eliminating the need for CT or MRI imaging. Each patient's atrial anatomy was derived from an MRI-segmented atria database based on the patient's torso similarity and placed on patient's torso



**Fig. 1** Graphical overview of the study. Panel **A** represents a patient with low AF substrate complexity and panel **A** a patient with high AF substrate complexity. In blue, atrial activity body surface potential signals (BSPM) and the value of sample entropy illustrating the quantified complexity (SAE). The  $n=64$  indicates the number of electrodes that registered BSPM signals. Dots represented on the torso are the location of the electrodes in the torso of the patient, blue dots represent electrodes of the illustrated signals in the figure. In green, electrocardiographic imaging (ECGI) atrial activity signals and their SAE. The  $n=4098$  represents the nodes of the atrial geometries where the ECGI signals were calculated. At the right, the rotor histograms are represented together with the detected rotors, and their duration over atrial geometries (pink-lines). Dots represented in the atria are the location of the green represented signals in the figure. The pink line in the atrial maps represents the trajectory and duration of a moving rotor. This figure illustrates the methodology of this paper comparing the complexity and recurrence of the signals on BSPM with the reentrant atrial activity evaluated on ECGI

reconstruction [18]. Atrial geometries were segmented into regions differentiating left (LA) and right atrium (RA) using Autodesk Meshmixer [19]. Each geometry was visually inspected, and the left and right atria were identified and labeled. These labels were assigned to the corresponding nodes in the atrial model, which were then used to compute the metrics specific to each atrium.

Signal processing involved baseline correction and band-pass filtering to eliminate noise while preserving atrial activity. Specifically, a 10th-order Butterworth band-pass filter with a range of 2–45 Hz was applied to the BSPM signals to remove baseline wander and high-frequency noise, ensuring the retention of clinically relevant components of the signal. Ventricular activity was eliminated using a single-lead Principal Component Analysis (PCA) approach, isolating the atrial component of the signals. Since for all patients 8 s of recordings are available, two successive signals per patient were selected, each with a length of 4s, to increase robustness [20]. ECGI signals were calculated by solving the inverse problem with the zero-order Tikhonov method and L-curve optimization [21]. The inverse problem in ECGI refers to reconstructing epicardial potentials from body surface recordings by combining BSPM data with a patient-specific torso geometry. This process requires solving a mathematical problem that links the electrical

signals measured on the torso with their corresponding sources on the heart's surface [22].

## Assessment of AF substrate complexity and AF propagation recurrence on body surface potential mapping

### AF substrate complexity

In the present article, the assessment of the atrial substrate complexity on BSPM is based on metrics compiled in a previous systematic analysis by Bonizzi et al. 2014 [4]. The explored metrics were computed based on the analysis of the principal components, the spatial complexity, the spectral concentration, and the organization of the signals. In the following lines, the most relevant analyzed metrics are described:

- Highest dominant frequency (HDF): dominant frequency of ECGI signals is defined as the most relevant activation rate of the atrial activity [23], with lower values related to more organized AF. Highest DF, is a derived metric computed as the 98th percentile of the dominant frequencies of all leads or ECGI signals obtained from the maximum power spectral density using Welch's method [7, 24]. HDF is computed in order to estimate the frequency that defines the arrhythmia.

- Sample entropy (SAE) is a statistical method used to quantify the amount of regularity or irregularity in a signal by measuring the similarity between epochs within the signal. SAE attributes a positive value to the signal, where higher values indicate greater variability. It is expected that more organized atrial fibrillation propagation patterns are associated with lower values of SAE [25].
- Relative harmonic energy (RHE) is computed as the relative energy of the sub-bands from the first and second harmonics of the dominant atrial fibrillation frequency [4]. More organized atrial fibrillation propagation patterns are expected to be associated with lower values of RHE [26].

### AF propagation recurrence

The analysis of AF propagation recurrence on BSPM was computed based on the characterization of the atrial signal dynamics [8]. The recurrent behavior of AF was studied by looking at the short- and long-term spatial variability of the atrial activity propagation as exhibited on BSPM signals [8]. This analysis is based on multivariate autocorrelation function of the atrial activity from body surface signals [27]. The signals were resampled to 256 Hz. The multivariable autocorrelation function is defined as a square matrix  $R$  of dimensions  $M \times M$ , obtained by calculating:

$$R_{i,j} = \frac{x(i)^T x(i+j-1)}{\|x(i)\|_2 \|x(i+j-1)\|_2}, \text{ with } i, j = 1 \dots, M,$$

Where  $x(i)$  is a vector containing the BSPM samples from all 64 electrodes at a given time instant  $i$ , and  $M$  represents the window size used for the analysis [8]. Autocorrelation is therefore measured using a cosine distance ( $R_{i,j} = \cos(x(i), x(i+j-1))$ ), where each element in the matrix  $R$  is the cosine of the angle between two vectors (with column  $j$  including correlation at lag  $p=j-1$ ). By averaging each column (for each lag), a multivariate spatial autocorrelation function can be generated for the atrial fibrillation oscillatory patterns across lags  $p=0, \dots, M-1$ .

According to [8], the following descriptive characteristics of the AF propagation recurrence were calculated for each multivariable autocorrelation function and averaged per patient:

- Long-term recurrence (LTR): calculated as the mean absolute value of the recurrence signals with lags between 150 and 450. LTR is defined as a metric of the patient's long-term recurrent atrial activity propagation behavior, and it is linked with the overall complexity of the AF substrate. A smaller level of

electro-structural remodeling correlates with a greater LTR value.

- Short-term recurrence ( $|P_1|$  and  $P_2$ ): computed utilizing the absolute value of the first negative peak ( $|P_1|$ ) and the first positive peak ( $P_2$ ) in the multivariable autocorrelation function. Higher values of  $|P_1|$  and  $P_2$  are associated with a lower degree of electro-structural remodeling.  $|P_1|$  is correlated with half of the AF cycle length and  $P_2$  with the complete AF cycle length.

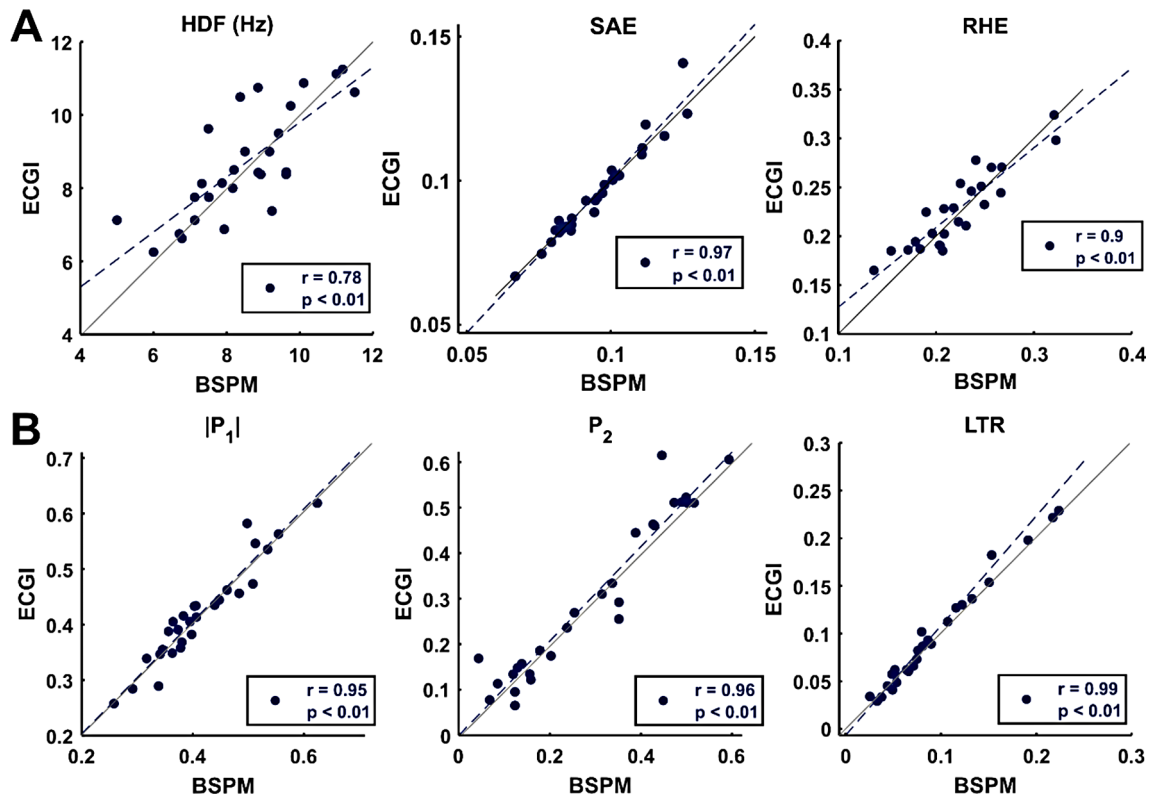
### Reentrant atrial activity analysis from ECGI signals

Reentrant atrial activity was analyzed by identifying rotors from the ECGI signals. Rotors were calculated. First, the phase of the inverse electrograms was calculated using the Hilbert transform. Singularity points (SPs) were then detected as stable locations where the phase rotated continuously from  $-\pi$  to  $+\pi$  [28, 29]. Candidate SPs were identified if they completed one full phase progression around their center of rotation, ensuring the detection of consistent reentrant patterns [28, 29]. Next, the SPs were connected spatiotemporally to form rotors, allowing for the exclusion of transient or isolated phase singularities [11].

To characterize the reentrant atrial activity, state-of-the-art metrics for SP characterization and rotor detection were computed [9, 26]. The number of SPs per second was calculated by scaling the total count of detected singularities by the signal duration. Rotor count per second (rotors/s) was determined by identifying phase singularities that completed at least one full rotation and spatially connected these into stable reentrant patterns. Mean rotor duration was computed as the average time (in seconds) during which a rotor remained stable in the signal. Finally, the Shannon spatial entropy of the SP histogram was calculated to quantify the spatial distribution of phase singularities. This methodology ensures robust assessment of reentrant atrial activity, as detailed in [10]. Furthermore, the above metrics were computed per atrium. To consider a rotor as located in one atrium (left or right), it had to be the 70% of its duration detected in that atrium. Rotors that were not detected for more than 70% of their duration in a specific atrium were discarded from the atrium specific analysis.

### Statistical analysis

The metrics extracted from both 4s segments of the signal were averaged to reduce the variability and are presented as mean  $\pm$  standard deviation. Correlation between BSPM-based and ECGI-based AF substrate complexity and AF propagation recurrence metrics was computed by using Pearson's correlation. Correlation between BSPM-based metrics and rotors properties and their duration was also investigated for each atrium. Normality of all



**Fig. 2** Correlations of metrics computed on the body surface electrocardiograms (BSPM) and on the ECGI solution. **(A)** AF substrate complexity metrics: highest dominant frequency (HDF), sample entropy (SAE), and relative harmonic energy (RHE). **(B)** AF propagation recurrence metrics: short-term ( $|P_1|$  and  $P_2$ ) and long-term (LTR) recurrence. The values of  $r$  represent the Pearson's correlation coefficient (and its  $p$ -value). In each plot, the line of best fits (dashed line) is also shown together with the line of identity

metrics was tested by via the Kolmogorov-Smirnov test. Student's t-test was used to evaluate differences between the left and right atrium for normally distributed metrics. Alternatively, the Wilcoxon rank-sum test was used. A  $p$ -value below 0.05 was deemed statistically significant. Outliers were identified and removed using the interquartile range (IQR) method, excluding values outside 1.5 times the IQR. This step minimizes the impact of extreme values likely caused by noise or artifacts, ensuring that the correlations reflect meaningful biological trends without being skewed by anomalies. We have included in the supplemental material all the figures presented in the manuscript with outliers, along with their corresponding statistical analyses, to provide a complete representation of the data included in the study.

**Results**

**BSPM-based versus ECGI-based AF substrate complexity and AF propagation recurrence**

Figure 2 shows the correlations between the three BSPM-based and ECGI-based AF substrate complexity metrics introduced in the methods section (HDF, SAE, RHE; top row), and three BSPM-based and ECGI-based AF propagation recurrence ( $|P_1|$ ,  $P_2$ , and LTR; bottom row). Most

**Table 1** Mean and standard deviation values of the metrics reflecting AF complexity and propagation recurrence measured in BSPM and ECGI. Correlation values between them and statistical significance of the correlation are presented

Metric	BSPM	ECGI	Correlation BSPM - ECGI	$P$ -value
HDF (Hz)	$8.48 \pm 1.54$	$8.66 \pm 1.49$	0.78	$10^{-6}$
SAE	$0.1 \pm 0.02$	$0.1 \pm 0.02$	0.97	$10^{-16}$
RHE	$0.22 \pm 0.04$	$0.23 \pm 0.04$	0.9	$5.2 \cdot 10^{-10}$
$ P_1 $	$0.41 \pm 0.07$	$0.41 \pm 0.08$	0.95	$1.44 \cdot 10^{13}$
$P_2$	$0.29 \pm 0.16$	$0.3 \pm 0.18$	0.96	$1.13 \cdot 10^{-15}$
LTR	$0.09 \pm 0.05$	$0.1 \pm 0.06$	0.99	$2.5 \cdot 10^{-23}$

analyses showed high correlations between BSPM- and ECGI-based metrics, thus suggesting that the overall estimation of substrate complexity is comparable if performed on BSPM or ECGI signals. Strong correlations were also observed for LTR and short- and long-term recurrence, with  $r > 0.99$ . A summary of the metrics is also reported in Table 1.

**BSPM-based AF substrate complexity and AF propagation recurrence vs. ECGI-based reentrant atrial activity**

To attempt a physiological interpretation of the AF complexity and recurrence as reflected on the body surface in

terms of the underlying reentrant activity inside the atria, BSPM-based AF substrate complexity and AF propagation recurrence metrics were compared with ECGI-based reentrant atrial activity metrics. Figure 3 illustrates the results of the comparison between the HDF, SAE and RHE of surface electrocardiograms and rotors per second and the duration of the rotors estimated on reconstructed electrograms through ECGI. Poor correlation between HDF, SAE and RHE and the number of rotors/s was observed ( $p > 0.05$ ). Nevertheless, SAE and RHE showed a significant inverse correlation with the duration of rotors, indicating that more complex surface atrial activity correlates with the presence of AF rotors of shorter duration ( $r = -0.71, p < 0.01$ ). HDF showed poor correlation with mean rotor duration ( $r = -0.34, p > 0.05$ ).

Figure 4 shows the results of the comparison between the three AF propagation recurrence metrics ( $P_1$ ,  $P_2$ , and LTR) and rotors/s and the duration of the rotors estimated on reconstructed electrograms through ECGI. Short- and long-term recurrence presented an inverse correlation with the number of rotors/s, which was significant only for the recurrent behavior at the complete AF cycle ( $P_2$ ). Significant correlations ( $p < 0.01$ ) were also found between the three metrics and the duration of rotors, showing that more repetitiveness at short- and long-term correlate with rotors of longer duration.

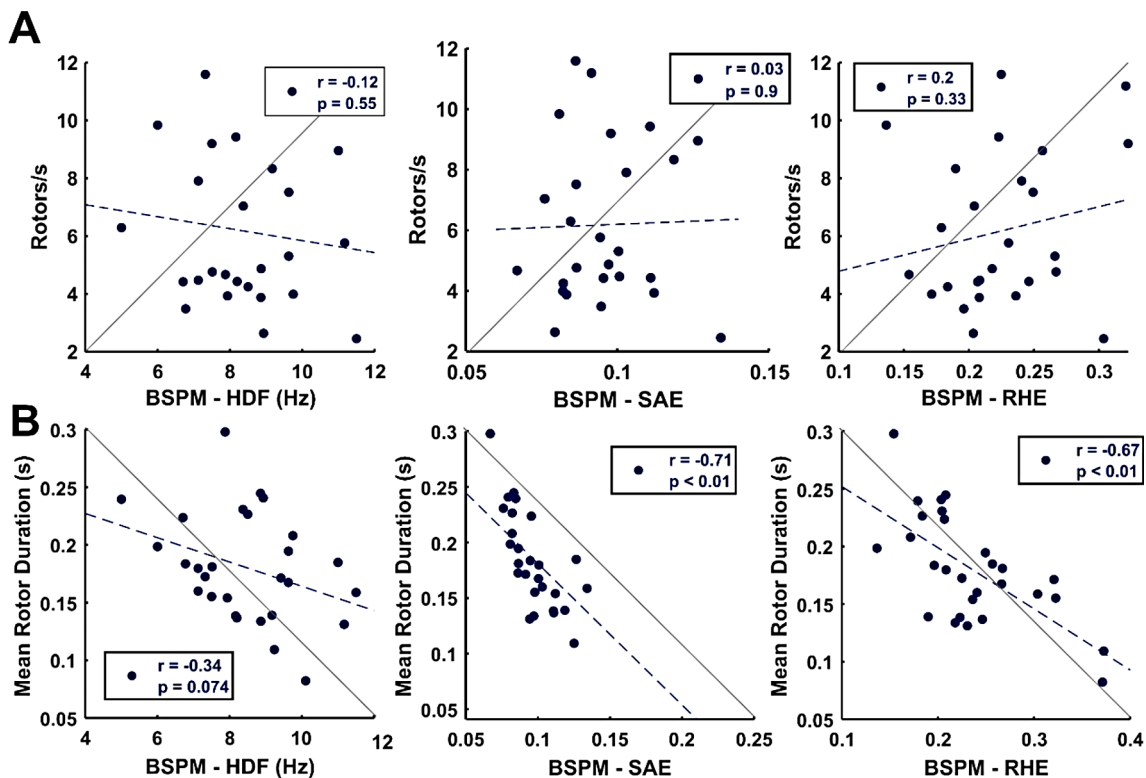
**Assessment of left and right atrium differences**

Figure 5 shows violin plots of the ECGI-based AF substrate complexity and AF propagation recurrence metrics on the left (blue) and right atrium (red). None of those metrics was able to capture significant differences between the two atria. Median values of the metrics were higher on the LA but not significant ( $p > 0.05$ ).

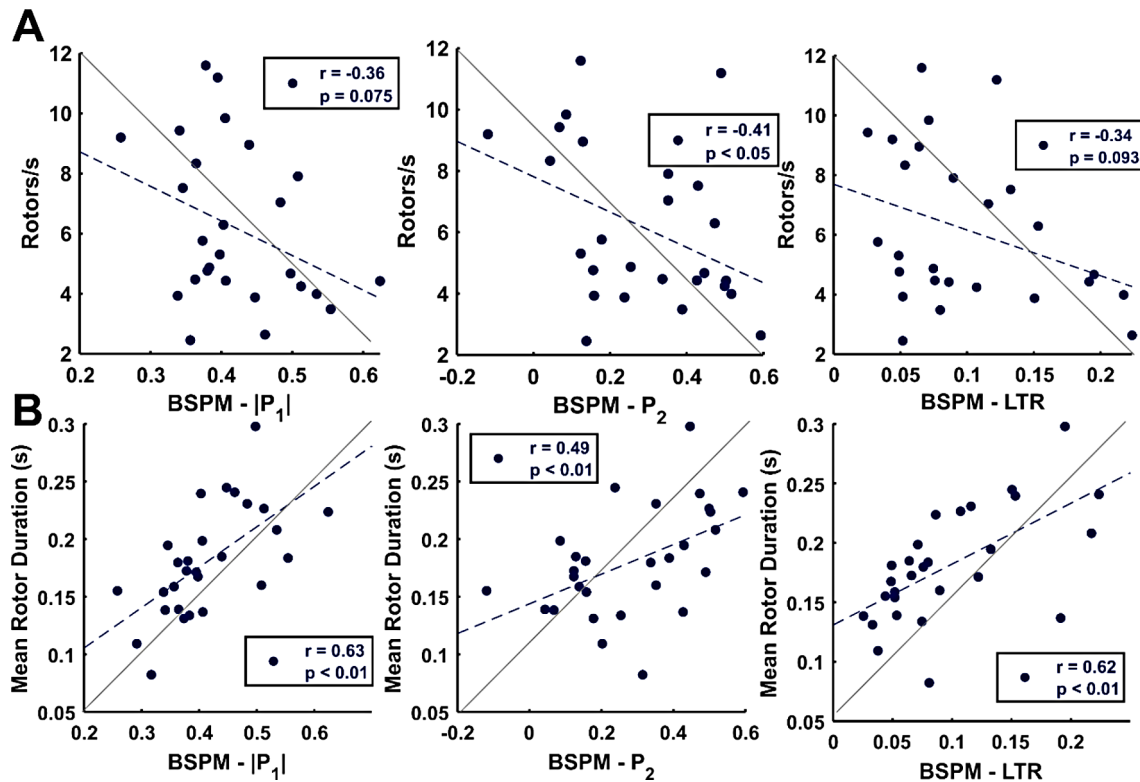
In contrast, ECGI-based metrics characterizing SPs and rotor properties were able to capture significant differences between the two atria (as illustrated in Fig. 6). SP per second, rotors/s, and the spatial entropy of the SP histogram were significantly higher ( $p < 0.01$ ) on the left atrium, showing a stronger reentrant activity in this atrium and possibly a more extended electro-structural remodeling of the underlying AF substrate. Mean rotor duration was significantly different between the two atria, meaning that rotors in the LA lasted more compared to the ones in the RA.

**BSPM-based AF substrate complexity and AF propagation recurrence vs. ECGI-based reentrant atrial activity per atrium**

In Fig. 7 it is shown the correlation of the rotors/s (A) and mean rotor duration (B) with HDF, SAE and RHE for the LA and the RA separately. No significant correlations were observed between HDF and any of the metrics



**Fig. 3** Correlations between AF substrate complexity metrics obtained on body surface (HDF, SAE, and RHE) electrocardiograms and the number of rotors per second (A) and mean rotor duration (B). The values of r represent the Pearson's correlation coefficient (and its p-value). In each plot, the line of best fits (dashed line) is also shown together with the line of identity



**Fig. 4** Correlations between AF propagation recurrence metrics obtained on the body surface (short ( $|P_1|$ ,  $P_2$ ) and long-term (LTR) recurrence) and the number of rotors per second (A) and mean rotor duration (B). The values of  $r$  represent the Pearson's correlation coefficient (and its  $p$ -value). In each plot, the line of best fits (dashed line) is also shown together with the line of identity

computed for either atrium. In contrast, SAE showed a significant correlation with mean rotor duration in both atria. Similarly, RHE was inversely correlated with mean rotor duration, with a stronger inverse correlation observed in the LA compared to the RA (RHE, LA: -0.63,  $p < 0.01$ , RA: -0.40,  $p < 0.05$ ). Significant correlations were also observed between RHE and number of rotors/s in both atria (both  $p < 0.05$ ).

Figure 8 shows the correlation of the rotors/s (A) and mean rotor duration (B) with  $|P_1|$ ,  $P_2$ , and LTR. Short- ( $|P_1|$  and  $P_2$ ) and long-term recurrence (LTR) metrics did not show a strong correlation with rotors/s computed per atrium, although the correlation in the LA was higher and significant ( $p < 0.05$ ) for  $|P_1|$  and  $P_2$  compared to the RA. Mean rotor duration showed higher correlations with these metrics in the LA compared to the RA, especially for the LTR (LA: 0.74,  $p < 0.01$ , RA: 0.42,  $p < 0.05$ ).

## Discussion

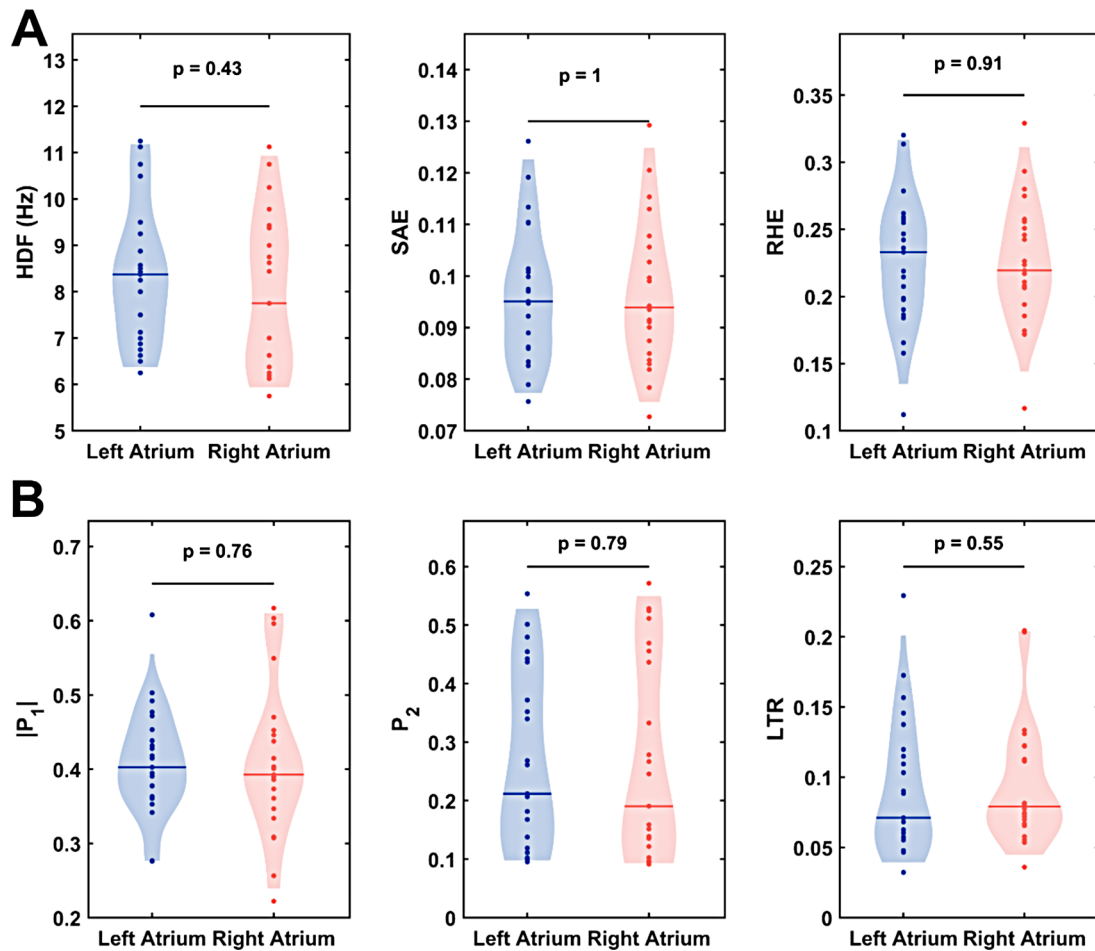
This study compared state-of-the-art BSPM metrics designed to evaluate the complexity and recurrence of AF with corresponding metrics computed from epicardial signals reconstructed using ECGI. This comparison was performed with the objective to improve the understanding of how and to what extent surface electrocardiogram

recordings relate to reentrant atrial activity on the epicardium.

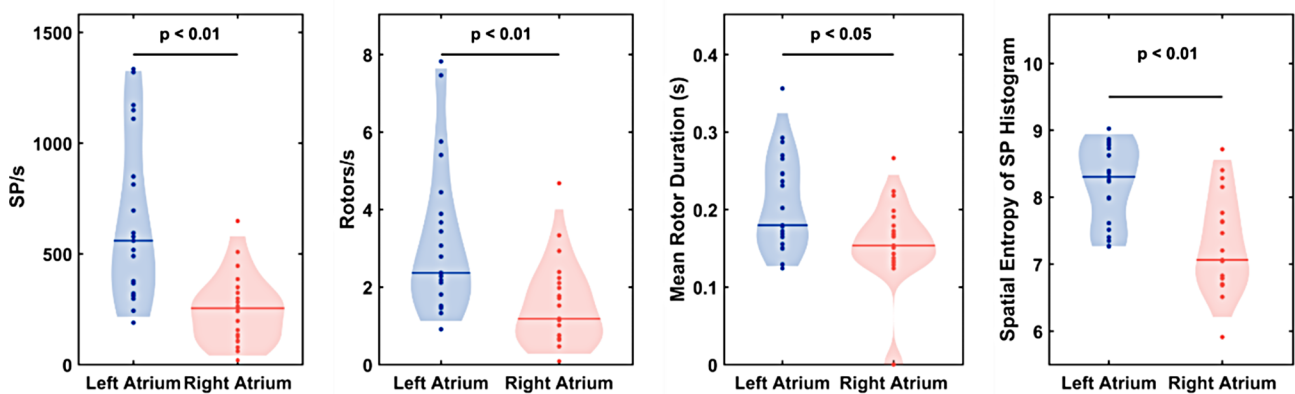
## The main findings of this study are summarized as follows

- BSPM metrics evaluating AF complexity and recurrence showed significant correlations with corresponding ECGI-derived metrics, improving understanding of how surface electrocardiograms relate to reentrant atrial activity.
- Metrics analyzing entropy (SAE) and energy (RHE) of BSPM signals were associated with reentrant atrial activity duration.
- Short- ( $|P_1|$  and  $P_2$ ) and long-term (LTR) recurrence metrics derived from BSPM signals correlated with ECGI-estimated reentrant activity duration.  $P_2$  was correlated significantly with the number of rotors per second.
- BSPM metrics demonstrated stronger inverse correlations with the duration of rotors observed in the left atrium, indicating that atrial regions with higher complexity are partially reflected in BSPM recordings.





**Fig. 5** Violin plots of AF substrate complexity (A) and AF propagation recurrence metrics (B) measured in the left (blue) and the right (red) atrium. The p-value of each statistical comparison is shown on the top of each graph, the line represents the median of the metric

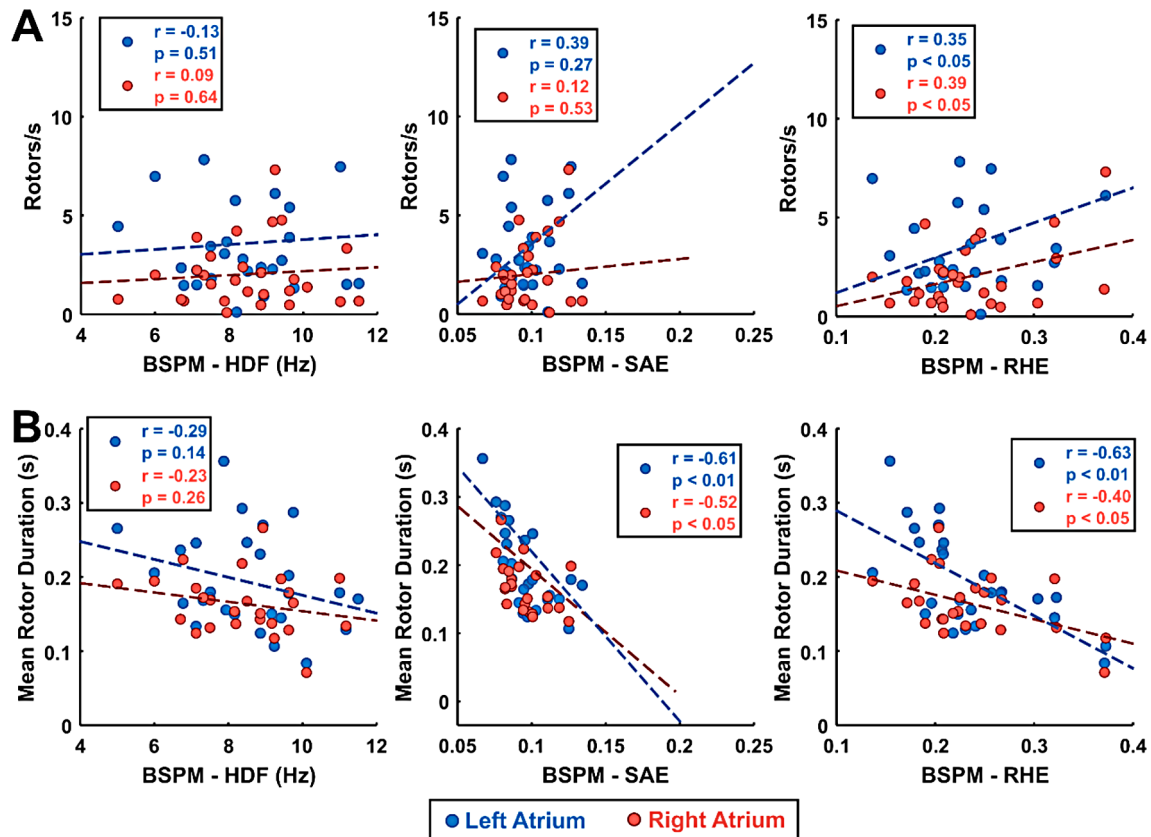


**Fig. 6** Violin plots of reentrant metrics measured at the left (blue) and right (red) atrium. The p-value of each statistical comparison is shown on the top of each graph, the line represents the median of the metric

**Relationship between BSPM and ECGI AF substrate complexity and propagation metrics**

In this study, a significant correlation was found between BSPM metrics evaluating signal complexity and AF

propagation recurrence and the same metrics derived from ECGI signals. While ECGI signals are indeed reconstructed from BSPM data and provide a spatial representation over the heart’s geometry, the observed high



**Fig. 7** Correlation of BSPM-based AF substrate complexity metrics with the number of rotors per second (A) and mean rotor duration (B) for rotors in the left (blue dots) and in the right (red dots) atrium, respectively. The values of r represent the Pearson's correlation coefficient and its p-value of the adjusted regression lines

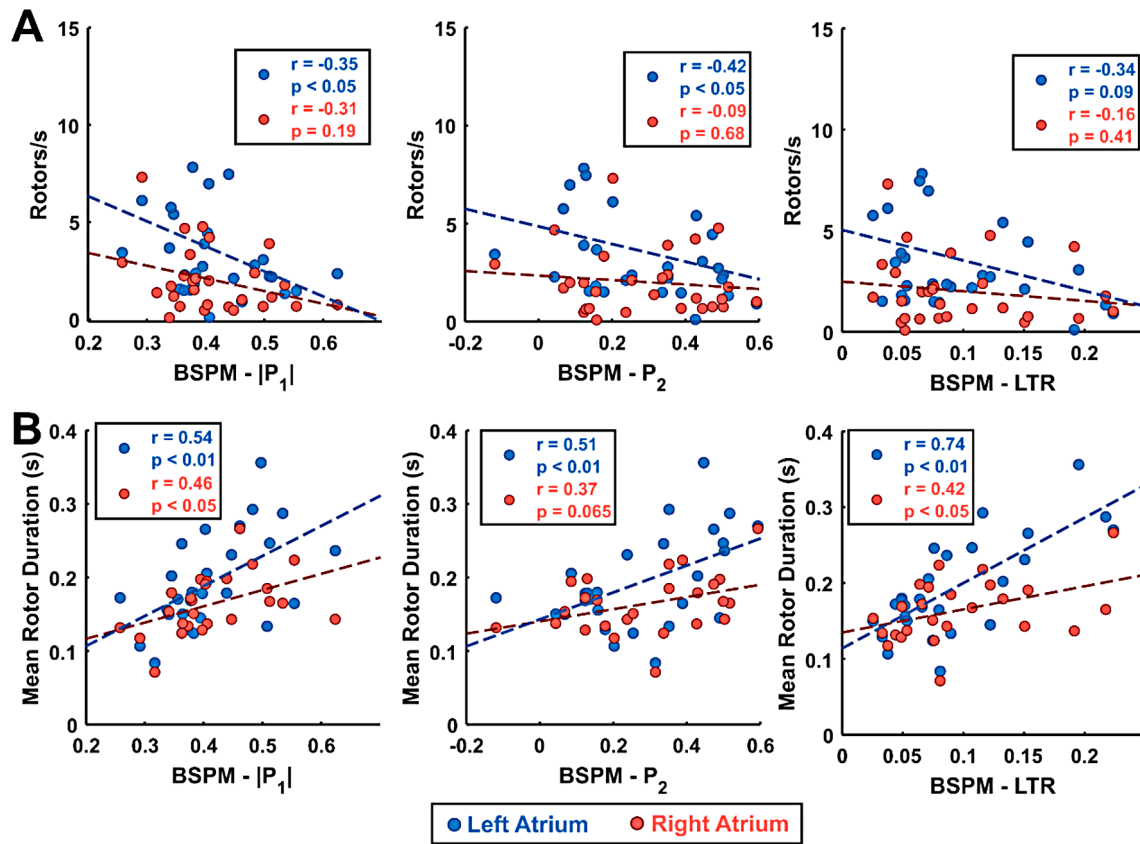
correlations were not entirely expected due to the nature of the inverse problem. The inverse problem of electrocardiography is well-documented as an ill-posed problem, meaning small variations in the BSPM domain can lead to amplified inaccuracies in the ECGI solution [21]. To address this, ECGI signals in the present study were reconstructed using zero-order Tikhonov regularization combined with L-curve optimization, which inherently smooths the electrograms to minimize the impact of noise in BSPM data. Despite this regularization, the strong correlations observed indicate that ECGI reliably preserves essential features of AF complexity and propagation, and conversely, that sufficient information is transferred from the heart surface to the body surface in terms of atrial substrate complexity during AF, and that BSPM metrics can serve as a reliable proxy for epicardial activity.

It is also important to highlight that BSPM and ECGI metrics capture distinct aspects of atrial activity. BSPM metrics measure surface potentials directly, whereas ECGI metrics provide spatially resolved epicardial activity across the atrial geometry. The observed correlations suggest that surface measurements reflect underlying

epicardial dynamics effectively, making BSPM a valuable tool for non-invasive assessments.

**Relationship between reentrant activity and BSPM-based AF complexity and AF propagation recurrence**

In previous studies, it has been demonstrated that BSPM signals do reflect the local activation rates (or dominant frequencies) in the atria [7]. More recently, it has been evaluated the ability of BSPM signals to identify the presence and location of AF rotors using neural networks [30], but no previous studies have reported a relationship of reentrant activity during AF and its duration and AF substrate complexity metrics derived from body surface recordings. In [4], it was shown that higher SAE and RHE computed on epicardial recordings during AF were associated with a more complex and less organized AF. In this study, both SAE and RHE computed on surface recordings inversely correlated with rotors of shorter duration as measured by ECGI. These results together confirm that information about AF substrate complexity of atrial activity patterns during AF is, to a certain degree, reflected on the body surface. At the same time, although previous studies have linked the presence of rotors to AF dominant frequency measured on the body surface



**Fig. 8** Correlation of BSPM-based AF propagation recurrence metrics with the number of rotors per second (A) and mean rotor duration (B) for rotors in the left (blue dots) and in the right (red dots) atrium, respectively. The values of r represent the Pearson’s correlation coefficient and its p-value of the adjusted regression lines

[31], statistically significant correlations were not found between BSPM-based HDF and the number and duration of rotors computed on ECGI.

In the same direction, the AF propagation recurrence computed on the BSPM signals was shown to be correlated with rotors of shorter duration as measured on ECGI signals. A higher number of rotors has been associated with more atrial electro-structural remodeling [32] and fibrosis [33], and this may be a physiological explanation of lower values of parameters as short- and long-term recurrence, which is indicative of a greater AF substrate complexity. Especially, LTR, associated with long-term AF recurrence, presented a significant correlation with rotor duration. This suggests a link between reentrant atrial activity during AF and recurrence of BSPM-derived atrial signals, which could provide helpful information to electrophysiologists prior to ablation or other treatment without the need for estimating ECGI potentials and relying just on the BSPM data.

**Left and right atrium assessment of AF substrate complexity**

Estimating AF substrate complexity from a surface ECG can be challenging, especially in determining the

differences in AF complexity between the atria. While the analysis of BSPM signals provides a broader view of AF progression [4, 8], it may still be difficult to distinguish the different properties of the two atria without invasive intracardiac recordings. ECGI has been shown to be a valuable tool in assessing the atrial substrate, and in this study, a strong correlation was found between AF substrate complexity metrics measured on both BSPM and ECGI signals. However, no statistical differences in these metrics were found when computed on the left and right atrium through ECGI, respectively, suggesting that AF complexity and AF propagation recurrence metrics are not sufficiently accurate to capture differences in AF substrate complexity between the atria.

On the other hand, the quantification of ECGI-based atrial reentrant activity computed on the left and right atrium showed significant differences. A more complex AF substrate with more and shorter rotational activity was observed on the left than in the right atrium. This is expected in AF patients since pulmonary veins are usually the primary source of AF episodes and are the main target in ablation procedures. The presented findings are consistent with other studies that also reported a greater reentrant activity in the left atrium (more SP and rotors

per second,  $p=10^{-3}$  and  $6\cdot 10^{-3}$  respectively) [34]. This highlights the importance of utilizing ECGI and measuring rotors for a more comprehensive and specific evaluation of AF, particularly for patients undergoing ablation.

Moreover, in the studied patient population, body-surface metrics showed higher correlations with rotational activity in the left atrium. However, it remains unclear whether this relationship is due to a higher complexity in the LA (as revealed by reentrant analysis), which is better captured on BSPM signals overshadowing the RA, or because the left atrial activity is better reflected on BSPM independently of its substrate complexity.

### Clinical impact

This study highlights the clinical importance of combining and linking BSPM and ECGI to better understand AF mechanisms like substrate complexity and reentrant activity. BSPM offers a non-invasive, accessible way to analyze surface-level electrical activity, while ECGI provides detailed epicardial mapping, linking surface signals to atrial substrate characteristics. Together, these tools can guide more precise, personalized treatments such as catheter ablation.

Validating BSPM metrics with ECGI strengthens its potential for identifying patients who may benefit from standard ablation versus those requiring targeted AF driver-based procedures. Particularly, BSPM's ability to infer rotor duration in the left atrium adds a valuable dimension. Further research is needed to refine ablation strategies based on non-invasive assessments of AF substrate complexity.

### Limitations

This study represents an initial exploration of how BSPM signals can be used to interpret atrial reentrant activity and AF substrate complexity. While the findings suggest promising correlations between BSPM and ECGI-derived metrics, there are limitations that must be addressed.

First, the study included a relatively small sample size, with 68% of the patients presenting persistent AF. This distribution may not fully capture the variability in AF mechanisms between paroxysmal and persistent AF cases, but the inclusion of both types of AF patients allowed us to examine a wider range of AF substrate complexity. Further research with larger and more balanced cohorts is essential to confirm these findings and assess the clinical utility of BSPM metrics.

Second, this study lacks intracardiac ground truth data to directly validate the ECGI-derived maps. However, rotor detection using ECGI has been clinically validated in previous studies, demonstrating its reliability when compared with intracavitary data [13]. Despite this limitation, the correlations observed between BSPM and ECGI metrics remain a relevant finding (assuming

the presence of reentrant activity), and provide valuable knowledge into the potential non-invasive assessment of atrial substrate complexity and reentrant activity duration.

### Conclusion

This study highlights a strong correlation between BSPM-derived AF substrate complexity and recurrence metrics and reentrant atrial activity estimated through ECGI. The findings demonstrate that BSPM metrics reliably reflect atrial electro-structural remodeling, as evidenced by their correlation with reentrant ECGI metrics, especially the ones relative to rotor duration. This work emphasizes the importance of BSPM as a non-invasive tool that aligns well with detailed epicardial assessments and its potential clinical applications in managing atrial fibrillation. Additionally, it highlights the continued necessity of ECGI for detailed, regional, non-invasive mapping of AF substrates.

### Abbreviations

AF	Atrial Fibrillation
BSPM	Body Surface Potential Mapping
ECG	Electrocardiogram
ECGI	Electrocardiographic Imaging
HDF	Highest Dominant Frequency
LA	Left Atrium
LTR	Long-term Recurrence
MRI	Magnetic Resonance Imaging
$ P_1 $	Short-term recurrence at half AF cycle
$P_2$	Short-term recurrence at full AF cycle
PVI	Pulmonary Vein Isolation
RA	Right Atrium
RHE	Relative Harmonic Energy
SAE	Sample Entropy
SP	Singularity Point

### Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12872-025-04483-4>.

Supplementary Material 1

### Acknowledgements

This manuscript is based on work included in the doctoral thesis of Rubén Molero, submitted to the Universitat Politècnica de València.

### Author contributions

R.M. conceptualization, data curation, formal analysis, investigation, visualization, writing-original draft. O.M., R.P. J.K., supervision, writing-review & editing. P.B. and M.S.G. investigation, resources, supervision, writing-review & editing.

### Funding

This work was supported by: Instituto de Salud Carlos III (supported by FEDER Fondo Europeo de Desarrollo Regional P117/01106), Generalitat Valenciana and European Social Fund (ACIF/2020/265, BEFPI/2021/062, CIAICO/2022/020), Agencia Estatal de Investigación PID2020-119364RB-I00, PID2023-149812OB-I00 and CPP2021-008562 by "European Union NextGenerationEU/PRTR". This research has received funding from the European Institute of Innovation and Technology (EIT) under grant agreement No 220385. This European body receives support from the Horizon 2020 research and innovation programme.

### Data availability

All data generated or analysed during this study are included in this published article.

### Declarations

#### Ethics approval and consent to participate

Written informed consent was obtained from the participants. The protocol for data collection was approved by the Spanish Agency of Medicines and Medical Devices (AEMPS) and the ethical committee from Hospital General Universitario Gregorio Marañón, Madrid, Spain, code: FAT-ANT-2018-01.

#### Consent for publication

Not applicable.

#### Competing interests

R. Molero receives honoraria from Corify Care SL. MS Guillem is co-founder and shareholder of Corify Care SL. O.M., R.P, J.K, and P.B. declare no conflict of interests.

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Received: 9 May 2024 / Accepted: 6 January 2025

Published online: 15 January 2025

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