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Current progress of computational modeling for guiding clinical atrial fibrillation ablation

Key words: Atrial fibrillation; Catheter ablation; Computational modeling; Atrial fibrosis

Research Summary

This review summarizes three-dimensional computational modeling simulations of catheter ablation for atrial fibrillation, from the early-stage attempts such as Maze III or circumferential pulmonary vein isolation to the latest advances based on personalized substrate-guided ablation. Finally, we summarize current developments and challenges and provide our perspectives and suggestions for future directions.

Innovation points

Table 1 3D geometrical atrial models

Reference	Number	Image source	Geometry	Atrial myocyte model	Fiber orientation	Numerical solution	Ablation patterns
Dang et al., 2005	1	MRI	Monolayer, bi-atrial	Modified Luo–Rudy model	No	FVM	Maze, Modified maze
Ruchat et al., 2007(a,b,c)	1	MRI	Monolayer, bi-atrial	Modified Luo–Rudy model	No	FVM	Maze, Modified maze
Rotter et al, 2007	1	MRI	Monolayer, dilated bi-atrial	Modified Luo–Rudy model	No	FVM	PVI, Linear ablation
Reumann et al., 2008	1	Visible female	Multilayer, bi-atrial	Cellular automaton	Visible female data	FEM	PVI, Linear ablation, Maze
Gong et al., 2015	1	Heart specimen	Bilayer, bi-atrial	Modified Courtemanche model	Image-based	FDM	Maze, Modified maze

PVI, pulmonary vein isolation; MRI, magnetic resonance imaging; FVM, finite volume method; FEM, finite element method; FDM; finite difference method.

Table 1｜ Early-stage 3D computational modeling for AF ablation is briefly summarized

Table 2 Patient-specific models of AF and their properties

Reference	Number	Image data	Geometry	Cell model	Fibrosis distribution	Fiber orientation	Numerical solution	Ablation patterns	Guide for clinical
Hwang et al., 2014	20	CT	Monolayer left atrial	Modified Courtemanche model	No	No	FEM	PVI, Linear ablation, CFAE	No
Hwang et al., 2016	1	CT	Monolayer left atrial	Modified Courtemanche model	No	No	FEM	PS-based, ShEn-based, DF-based, CFAE	No
Lim et al., 2017	10	CT	Monolayer left atrial	Modified Courtemanche model	No	No	FEM	DF-based, PS-based	No
Shim et al., 2017	108	CT	Monolayer left atrial	Modified Courtemanche model	No	No	FEM	PVI, Linear ablation, CFAE	Yes
Kim et al., 2019	118	CT	Monolayer left atrial	Modified Courtemanche model	No	No	FDM	PVI, Linear ablation, CFAE	Yes
Lim et al., 2020a	27	CT	Monolayer left atrial	Modified Courtemanche model+fibroblasts	Clinical voltage map-based	Atlas-based	FDM	PS-based, DF-based	Yes
Lim et al., 2020b	10	CT	Monolayer bi-atrial	Modified Courtemanche model+fibroblasts	Clinical voltage map-based	Atlas-based	FDM	PVI, IACs-based	No
McDowell et al., 2015	4	MRI	Bilayer left atrial	Krummen Model+fibroblasts	Threshold-based	Atlas-based	FEM	PS-based	No
Zahid et al., 2016	10	MRI	Bilayer bi-atrial	Modified Courtemanche model+fibroblasts	Threshold-based	Atlas-based	FEM	Graph-based	No
Deng et al., 2017	12	MRI	Bilayer bi-atrial	Modified Courtemanche model+fibroblasts	Threshold-based	Atlas-based	FEM	RD-based	No
Hakim et al., 2018	12	MRI	Bilayer bi-atrial	Modified Courtemanche model+fibroblasts	Threshold-based	Atlas-based	FEM	RD-based	No
Boyle et al., 2018a	11	MRI	Bilayer bi-atrial	Modified Courtemanche model+fibroblasts	Threshold-based	Atlas-based	FEM	RD-based	No

Table 2｜ provides an overview of the published patient-specific models of AF and their properties

Table 2 continued

Reference	Number	Image data	Geometry	Cell model	Fibrosis distribution	Fiber orientation	Numerical solution	Ablation patterns	Guide for clinical
Boyle et al., 2018b	12	MRI	Bilayer bi-atrial	Modified Courtemanche model+fibroblasts	Threshold-based	Atlas-based	FEM	RD-based	No
Boyle et al., 2019	10	MRI	Bilayer bi-atrial	Modified Courtemanche model+fibroblasts	Threshold-based	Atlas-based	FEM	RD-based	Yes
Ali et al., 2019	12	MRI	Bilayer bi-atrial	Modified Courtemanche model+fibroblasts	Threshold-based	Atlas-based	FEM	PVI, RD-based	No
Shade et al., 2020	32	MRI	Bilayer bi-atrial	Modified Courtemanche model+fibroblasts	Threshold-based	Atlas-based	FEM	RD-based	No
Bayer et al., 2016	1	CT	Bilayer bi-atrial	Modified Courtemanche model+fibroblasts	Possibility method	Rule-based	FEM	PVI, Linear ablation, AS-based, PS-based	No
Roney et al., 2018	12	MRI	Bilayer bi-atrial	Modified Courtemanche model+fibroblasts	Possibility method, Threshold-based	Atlas-based	FEM	PVI, IACs-based	No
Roney et al., 2020	50	MRI	Bilayer left atrial	Modified Courtemanche model+fibroblasts	Threshold-based	DTMRI-based	FEM	PVI, Linear ablation, PS-based	No
Alessandrini et al., 2018	1	MRI	Bilayer left atrial	Modified Courtemanche model	No	Rule-based	FEM	Basket catheter-based	No
Roy et al., 2020	6	MRI	Bilayer left atrial	Fenton-Karma model	Threshold-based	No	FDM	PVI, Linear ablation, RD-based	No
Gharaviri et al., 2021	1	MRI	Bilayer bi-atrial	Modified Courtemanche model	Possibility method	DTMRI-based	FDM	PVI, Linear ablation, LAAI	No

CT, computed tomography; MRI, magnetic resonance imaging; PVI, pulmonary vein isolation; DTMRI, diffusion tensor magnetic resonance imaging; FDM, finite difference method; FEM, finite element method; PS, phase singularity; DF, dominant frequency; ShEn, Shannon entropy; CFAE, complex fractionated atrial electrogram; AS, activation sequences; IACs, interatrial connections; LAAI, left atrial appendage isolation.

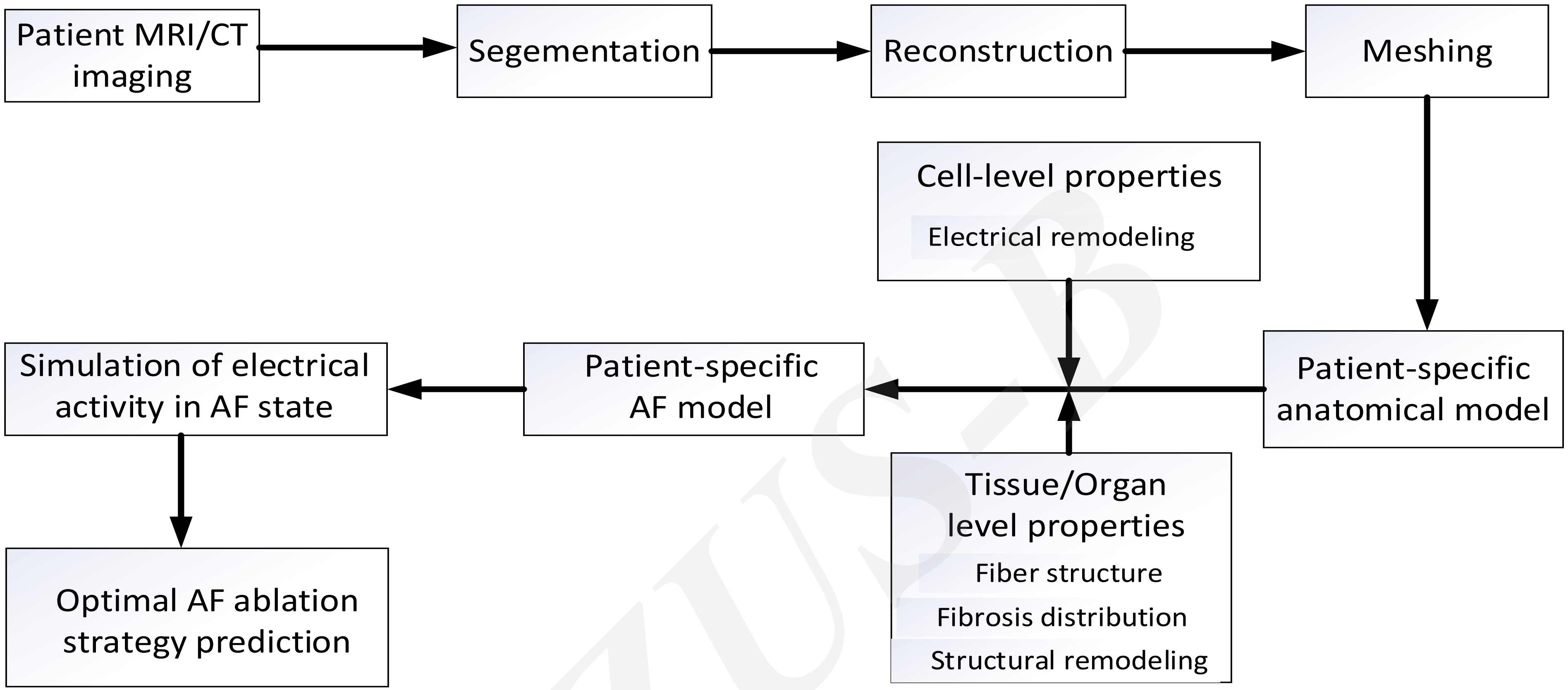

Fig.1 Workflow for a patient-specific model to predict the optimal AF ablation strategy

LGE-MRI or CT images from individual patients with AF are processed to segment, reconstruct, and mesh a patient-specific anatomical model. Next, cell/tissue/organ-level properties are assigned to the anatomical model to create a patient-specific AF model and personalized simulations are conducted to determine the optimal ablation strategy.