Supplementary Material

Development and validation of a clinical diagnostic model for myocardial ischemia in borderline coronary lesions based on optical pumped magnetometer magnetocardiography: a prospective observational cohort study

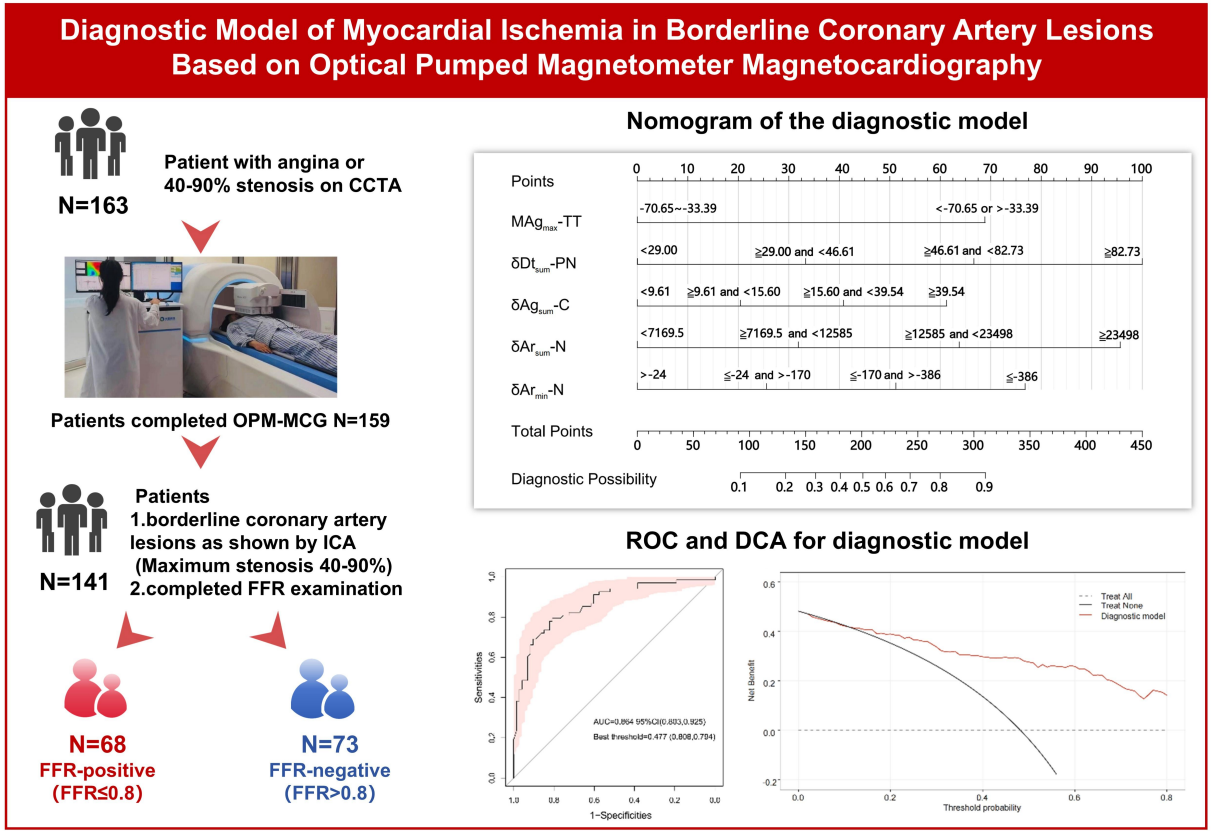
Contents

Optical pumped magnetometer magnetocardiography (OPM-MCG) post-processing steps

The post-processing process of OPM-MCG signals is as follows. Firstly, a composite gradient magnetometer array is constructed using a separate environmental monitoring channel, and the common mode projection components of the monitoring channel are subtracted from the OPM-MCG detection array channels, effectively suppressing environmental magnetic field drift and power frequency interference. Then, notching the 50Hz power frequency and its harmonic components of the data, and performing a 1-40Hz bandpass filter to further remove power frequency interference and limit the bandpass frequency to the main frequency range of the MCG. Finally, the denoised data is subjected to R-peak detection and recognition, with an average heartbeat cycle of 90 seconds as the length of the slice time, and the identified R-peak point is used as the time alignment point to slice the data and overlay it for average

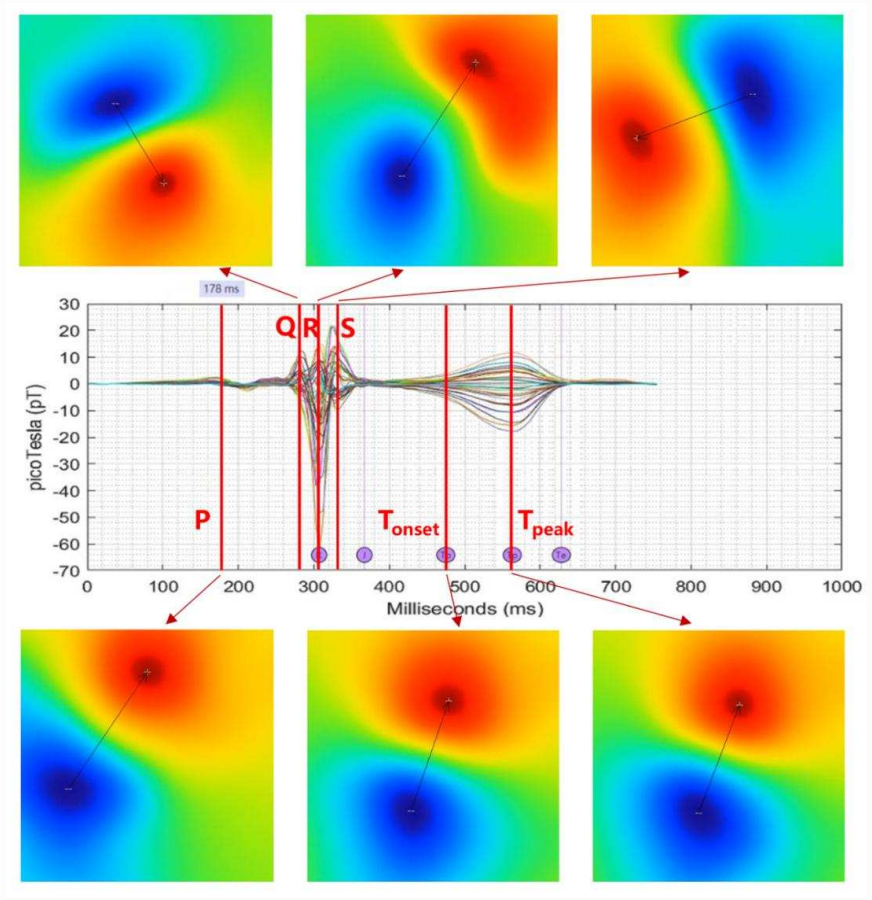
Yang S, *et al. BMJ Open* 2024; 14:e086433. doi: 10.1136/bmjopen-2024-086433

Supplementary Table and Figures

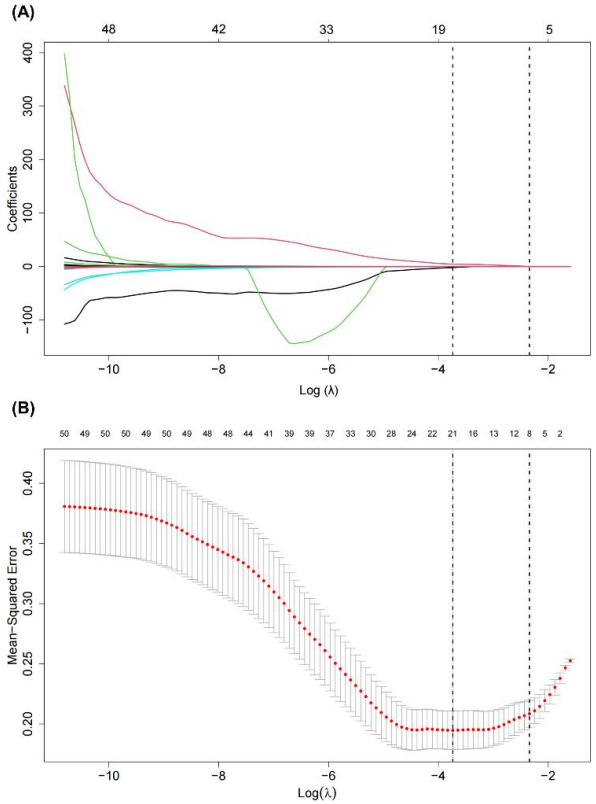


Supplementary Figure 1 Graphical Abstracts: Diagnostic Model of Myocardial Ischemia in Borderline Coronary Artery Lesions Based on OPM-MCG

CCTA= coronary computed tomography angiography; OPM-MCG=optical pumped magnetometer magnetocardiography; ICA= invasive coronary angiography; FFR=fractional flow reserve; PCI= percutaneous coronary intervention; DCA=decision curve analysis.

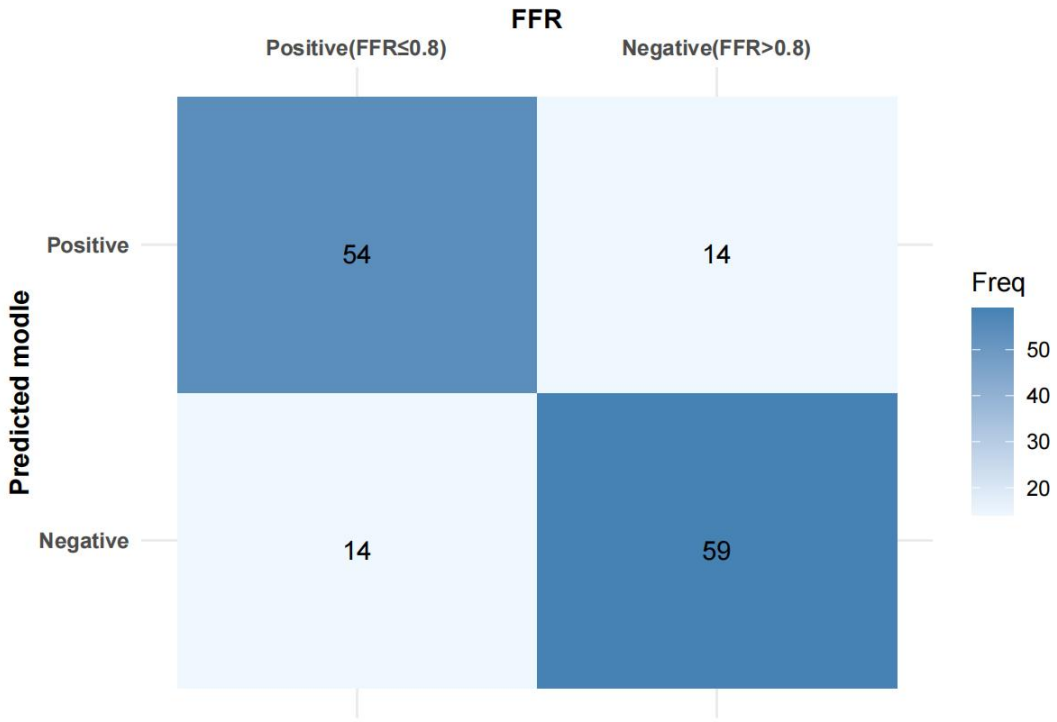


Supplementary Figure 2 The Magnetic Field Distributions (MFDs) of Key Points (P, QRS, and T onset and T peak) in the Cardiac Cycle of Healthy Individuals



Supplementary Figure 3 Least Absolute Shrinkage and Selection Operator (LASSO) Regression

Figure legend :(A) LASSO model coefficient profiles of the 50 candidate parameters. As log λ increases, the regression coefficients continue to converge, and there are fewer parameters with non-zero regression coefficients.(B) Tuning parameter selection by cross-validation in the LASSO model. The solid vertical lines represent the partial likelihood deviance standard error (SE). The red dotted line indicates the cross-validation curve. The vertical dashed lines are drawn at the optimal values on the basis of the minimum criteria and 1-SE criteria. Considering the reasonableness of the variables included in this model, with the λ value of 0.02380779 was chosen.



Supplementary Figure 4 Confusion Matrix for the Diagnostic Model

Figure Legend: The confusion matrix compares the FFR diagnostic results with those from the predictive model. The color intensity represents the frequency of occurrences, with darker shades indicating higher frequencies.

Supplementary Table 1 OPM-MCG Parameters and Definitions

Parameters	Definition
δ Ag_{max}-M	The maximum value of changes in magnetic field angle at intervals of a certain time τ within TT segment
δ Ag_{min}-M	The minimum value of changes in magnetic field angle at intervals of a certain time τ within TT segment
δ Ag_{std}-M	The standard deviation of changes in magnetic field angle at intervals of a certain time τ within TT segment
δ Ag_{sum}-M	The sum of changes in magnetic field angle at intervals of a certain time τ within TT segment
δ Dt_{max}-PN	The maximum value of changes in magnetic pole distance at intervals of a certain time τ within TT segment
δ Dt_{min}-PN	The minimum value of changes in magnetic pole distance at intervals of a certain time τ within TT segment
δ Dt_{std}-PN	The standard deviation of changes in magnetic pole distance at intervals of a certain time τ within TT segment
δ Dt_{sum}-PN	The sum of changes in magnetic pole distance at intervals of a certain time τ within TT segment
δ Ag_{max}-C	The maximum value of changes in current angle at intervals of a certain time τ within TT segment
δ Ag_{min}-C	The minimum value of changes in current angle at intervals of a certain time τ within TT segment
δ Ag_{std}-C	The standard deviation of changes in current angle at intervals of a certain time τ within TT segment
δ Ag_{sum}-C	The sum of changes in current angle at intervals of a certain time τ within TT segment
δ Ps_{max}-C	The maximum value of changes in the position of the current angle at intervals of a certain time τ within TT segment
δ Ps_{std}-C	The standard deviation of changes in the position of the current angle at intervals of a certain time τ within TT segment
δ Ps_{sum}-C	The sum of changes in the position of the current angle at intervals of a certain time τ within TT segment
δ Ar_{max}-NP	The maximum value of changes in negative pole point area at intervals of a certain time τ within TT segment
δ Ar_{min}-NP	The minimum value of changes in negative pole point area at intervals of a certain time τ within TT segment
δ Ar_{std}-NP	The standard deviation of changes in negative pole point area at intervals of a certain time τ within TT segment
δ Ar_{sum}-NP	The sum of changes in negative pole point area at intervals of a certain time τ within TT segment
δ Ar_{bp}-NP	The change in negative pole point area between T-begin and T-peak
Ar_{max}-NP	The maximum value of the negative pole point area at intervals of a certain time τ within TT segment
Ar_{min}-NP	The minimum value of the negative pole point area at intervals of a certain time τ within TT segment
δ Ps_{max}-NP	The maximum value of changes in the position of the negative pole point at intervals of a certain time τ within TT segment
δ Ps_{std}-NP	The standard deviation of changes in the negative of the positive pole point at intervals of a certain time τ within TT segment
δ Ps_{sum}-NP	The sum of changes in the position of the negative pole point at intervals of a certain time τ within TT segment
δ Ar_{max}-N	The maximum value of changes in negative pole area at intervals of a certain time τ within TT segment

Parameters	Definition
δ Ag_{max}-M	The maximum value of changes in magnetic field angle at intervals of a certain time τ within TT segment
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δ Ar_{sum}-N	The sum of changes in negative pole area at intervals of a certain time τ within TT segment
δ Ar_{bp}-N	The change in nagative pole area between T-begin and T-peak
Ar_{max}-N	The maximum value of the negative pole area at intervals of a certain time τ within TT segment
Ar_{min}-N	The minimum value of the negative pole area at intervals of a certain time τ within TT segment
δ $ArRto_{max}$-PN	The maximum value of changes in the ratio of positive and negative pole area at intervals of a certain time τ within TT segment
δ $ArRto_{min}$-PN	The minimum value of changes in the ratio of positive and negative pole area at intervals of a certain time τ within TT segment
δ $ArRto_{std}$-PN	The standard deviation of changes in the ratio of positive and negative pole area at intervals of a certain time τ within TT segment
δ $ArRto_{sum}$-PN	The sum of changes in the ratio of positive and negative pole area at intervals of a certain time τ within TT segment
δ Ar_{max}-PP	The maximum value of changes in positive pole point area at intervals of a certain time τ within TT segment
δ Ar_{min}-PP	The minimum value of changes in positive pole point area at intervals of a certain time τ within TT segment
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δ Ps_{max}-PP	The maximum value of changes in the position of the positive pole point at intervals of a certain time τ within TT segment
δ Ps_{std}-PP	The standard deviation of changes in the position of the positive pole point at intervals of a certain time τ within TT segment
δ Ps_{sum}-PP	The sum of changes in the position of the positive pole point at intervals of a certain time τ within TT segment
δ Ar_{max}-P	The maximum value of changes in positive pole area at intervals of a certain time τ within TT segment
δ Ar_{min}-P	The minimum value of changes in positive pole area at intervals of a certain time τ within TT segment
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δ Ar_{sum}-P	The sum of changes in positive pole area at intervals of a certain time τ within TT segment
δ Ar_{bp}-P	The change in positive pole area between T-begin and T-peak
Ar_{max}-P	The maximum value of the positive pole area at intervals of a certain time τ within TT segment
Ar_{min}-P	The minimum value of the positive pole area at intervals of a certain time τ within TT segment
MAg_{max}-TT	The maximum magnetic field angle at intervals of a certain time τ within TT segment
CAg_{max}-TT	The maximum current angle at intervals of a certain time τ within TT segment
MAg_{min}-TT	The minimum magnetic field angle at intervals of a certain time τ within TT segment
CAg_{min}-TT	The minimum current angle at intervals of a certain time τ within TT segment
MAg-Rp	The magnetic field angle of the R-peak
RtoAm-R_pT_pN	The ratio of magnetic field amplitude at R-peak and the negative amplitude at T-peak
RtoAm-R_pT_pP	The ratio o magnetic field amplitude at R-peak and the positive amplitude at T-peak
RtoAm-R_pT_p	The ratio of magnetic field amplitudes at R-peak and T-peak
MAg-RpTp	The magnetic field angle between R-peak and T-peak
MAg-Tp	The magnetic field angle of the T-peak
CAg_{max}-Tp	The maximum current angle at T-peak
RtoAm-Tp	The ratio of positive to negative magnetic field amplitude at T-peak
TT	The interval from the beginning of the T-wave to its peak within the cardiac cycle

Dt = Distance, Ps = Position, Ag = Angle, Am = Magnitude, Ar = Area, Rto = Ratio, P = Positive, Positive Pole = PP, N = Negative, NP = Negative Pole, M = Magnetic Field, C = Current, max = Maximum, min = Minimum, sum=Sum of all, std = Standard deviation, δ = Change value, TT= TT segment (the position from one-third of the T max amplitude (T onset) to T max (T peak)), R_p=R peak, T_p=T peak

Supplementary Table 2 OPM-MCG Parameters of Univariable Logistic Regression Model P < 0.1

Parameters	FFR-Positive N=68	FFR-Negative N=73	Odds Ratio (95%CI)	P value	BH-adjusted p-value
δ Ag_{max}-M	0.77 (0.47,5.76)	0.54 (0.43,0.72)	1.077(1.023-1.163)	0.021	0.034
δ Ag_{min}-M	-0.42 (-0.82,-0.28)	-0.26 (-0.42,-0.14)	0.964(0.924-0.992)	0.034	0.045
δ Ag_{std}-M	0.28 (0.14,2.06)	0.14 (0.10,0.20)	1.594(1.213-2.313)	0.004	0.009
δ Ag_{sum}-M	20.2 (9.88,45.5)	8.28 (4.55,11.8)	1.064(1.037-1.1)	<0.001	<0.001
δ Dt_{max}-PN	3.51 (2.16,12.9)	2.22 (1.89,3.16)	1.014(1.001-1.032)	0.063	0.071
δ Dt_{min}-PN	-2.38 (-4.70,-1.91)	-2.00 (-2.80,-1.63)	0.971(0.94-0.991)	0.023	0.035
δ Dt_{std}-PN	0.82 (0.63,3.45)	0.63 (0.52,0.89)	1.158(1.031-1.332)	0.024	0.035
δ Dt_{sum}-PN	66.6 (42.0,110)	33.3 (25.7,48.6)	1.026(1.015-1.039)	<0.001	<0.001
δ Ag_{max}-C	1.79 (1.27,9.10)	1.52 (1.16,2.98)	1.009(1-1.022)	0.089	0.091
δ Ag_{min}-C	-1.70 (-8.89,-1.01)	-0.91 (-1.75,0.00)	0.983(0.962-0.997)	0.051	0.063
δ Ag_{std}-C	0.80 (0.37,3.16)	0.45 (0.34,0.70)	1.117(1.026-1.252)	0.025	0.035
δ Ag_{sum}-C	29.8 (13.5,71.6)	11.9 (7.79,17.5)	1.014(1.006-1.025)	0.003	0.009
δ Ps_{max}-C	33.0 (1.41,125)	31.0 (1.00,34.0)	1.008(1.003-1.015)	0.004	0.009
δ Ps_{std}-C	3.57 (0.29,11.7)	3.20 (0.24,4.86)	1.073(1.019-1.14)	0.013	0.025
δ Ps_{sum}-C	74.4 (8.31,161)	33.4 (4.00,66.0)	1.01(1.005-1.015)	<0.001	<0.001
δ Ar_{max}-NP	182 (102,314)	105 (59.0,180)	1.002 (1.0002,1.003)	0.027	0.036
δ Ar_{std}-NP	31.7 (23.4,70.1)	25.7 (17.1,41.4)	1.004 (1.000,1.010)	0.067	0.073
δ Ar_{sum}-NP	3369 (2230,5728)	1672 (1277,2987)	1.00020 (1.00006, 1.00034)	0.005	0.011
Ar_{max}-NP	4269 (3260,6056)	3828 (2894,5406)	1.000101 (0.999989, 1.000213)	0.077	0.080
δ Ps_{sum}-NP	59.8 (39.8,104)	26.4 (20.1,51.1)	1.013(1.006-1.021)	0.001	0.005
δ Ar_{max}-N	539 (269,990)	404 (221,526)	1.001(1-1.002)	0.022	0.034
δ Ar_{min}-N	-267.00 (-565.25,-108.75)	-79.00 (-224.00,-15.00)	0.998(0.996-0.999)	0.002	0.008
δ Ar_{std}-N	160 (90.5,273)	114 (74.6,158)	1.005(1.002-1.008)	0.003	0.009
δ Ar_{sum}-N	19058 (10208,29054)	9520 (6202,15009)	1.000084 (1.000046, 1.000122)	<0.001	<0.001
Ar_{max}-N	56546 (44597,77766)	51431 (38201,58878)	1.000014 (1.000002, 1.000026)	0.025	0.035
δ $ArRto_{max}$-PN	0.01 (0.00,0.03)	0.00 (0.00,0.01)	4.494e+10(5.890e+2,3.427+29)	0.008	0.016

Parameters	FFR-Positive N=68	FFR-Negative N=73	Odds Ratio (95%CI)	P value	BH-adjusted p-value
δ $ArRto_{min}$-PN	-0.02 (-0.07,-0.01)	-0.02 (-0.04,-0.01)	<0.001 (0,0.062)	0.014	0.026
δ $ArRto_{std}$-PN	0.01 (0.00,0.02)	0.01 (0.00,0.01)	3.177e+16(1.758e+3,5.740e+29)	0.015	0.027
δ $ArRto_{sum}$-PN	0.85 (0.39,2.36)	0.58 (0.29,0.88)	1.539 (1.175,2.117)	0.004	0.009
δ Ar_{max}-PP	281 (141,704)	153 (111,286)	1.001 (1.001,1.003)	0.004	0.009
δ Ar_{min}-PP	-196.00 (-563.75,-109.50)	-153.00 (-226.00,-104.00)	0.998 (0.996,0.999)	0.003	0.009
δ Ar_{std}-PP	77.3 (35.5,167)	43.7 (32.1,79.7)	1.007 (1.003,1.012)	0.004	0.009
δ Ar_{sum}-PP	6608 (3410,14024)	3487 (2556,5786)	1.00012(1.000053, 1.000187)	<0.001	<0.001
Ar_{min}-PP	4626 (2618,6928)	5754 (3719,8258)	0.999933 (0.999933, 1.000003)	0.06	0.071
δ Ps_{max}-PP	3.61 (3.00,100)	3.00 (2.24,3.61)	1.011(1.005-1.019)	0.002	0.008
δ Ps_{std}-PP	0.98 (0.66,8.50)	0.75 (0.57,0.90)	1.117(1.05-1.221)	0.003	0.009
δ Ps_{sum}-PP	73.8 (29.9,195)	32.8 (21.7,54.2)	1.012(1.006-1.019)	<0.001	<0.001
δ Ar_{max}-P	312 (150,692)	172 (70.0,362)	1.001(1-1.002)	0.007	0.015
δ Ar_{std}-P	135 (82.3,267)	109 (75.7,159)	1.002(1-1.005)	0.07	0.074
δ Ar_{sum}-P	15787 (7938,28576)	9566 (5985,15629)	1.000046 (1.000017, 1.000074)	0.001	0.005
MAg_{max}-TT	-48.00 (-66.89,15.5)	-67.39 (-72.03,-53.13)	1.019(1.009-1.029)	<0.001	<0.001
CAg_{max}-TT	58.2 (39.2,118)	43.1 (32.0,51.1)	1.018(1.009-1.028)	<0.001	<0.001
MAg_{min}-TT	-68.28 (-75.62,-41.24)	-71.98 (-77.61,-64.94)	1.009(1.000-1.018)	0.052	0.063
MAg-R_p	-53.44 (-70.66,-38.24)	-65.92 (-71.78,-50.54)	1.015(1.003-1.028)	0.017	0.028
RtoAm-R_pT_pN	7.35 (4.92,10.4)	5.68 (3.71,8.14)	1.055(1.005-1.126)	0.064	0.071
RtoAm-R_pT_pP	8.66 (6.03,12.9)	7.69 (5.56,11.1)	1.06(1.004-1.133)	0.061	0.071
RtoAm-R_pT_p	4.13 (3.08,5.01)	3.28 (2.36,4.50)	1.217(1.047-1.445)	0.016	0.028
MAg-T_p	-55.82 (-70.28,-12.79)	-67.91 (-72.69,-53.13)	1.015(1.006-1.026)	0.002	0.008
CAg_{max}-T_p	45.0 (27.6,74.7)	42.2 (30.7,46.9)	1.009(1.001-1.017)	0.037	0.047
RtoAm-T_p	0.81 (0.52,1.22)	0.75 (0.57,0.98)	1.519(0.978-2.618)	0.095	0.095

Dt = Distance, Ps = Position, Ag = Angle, Am = Magnitude, Ar = Area, Rto = Ratio, P = Positive, Positive Pole = PP, N = Negative, NP = Negative Pole, M = Magnetic Field, C = Current, max = Maximum, min = Minimum, sum=Sum of all, std = Standard deviation, δ = Change value, TT= TT segment (the position from one-third of the T max amplitude (T onset) to T max (T peak)), R_p=R peak, T_p=T peak

Supplementary Table 3 Diagnostic Model for Assessment of Myocardial Ischemia in Borderline Coronary Artery Lesions

Parameters	Diagnostic model			
	B	OR	95%CI	P value
MAg_{max}-TT	1.385	3.995	(1.592-10.023)	0.003
δDt_{sum}-PN	0.671	1.956	(1.270-3.012)	0.002
δAg_{sum}-C	0.411	1.508	(0.989-2.298)	0.056
δAr_{sum}-N	0.641	1.899	(1.251-2.883)	0.003
δAr_{min}-N	0.515	1.674	(1.121-2.500)	0.012

M= Magnetic Field; Ag= Angle; TT= from T onset to T peak; δ= Change value; DT= Distance; PN= Positive Pole to Negative Pole; C=Current; Ar= Area; N= Negative Pole; ; τ= one tenth of the time interval between TT segment.