Direct and Indirect Mapping of Intramural Space in Ventricular Tachycardia

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Running title: Prevalence of Intramural Ventricular Tachycardia

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Abstract

Background: Ventricular tachycardia (VT) circuit is often assumed to be located in the endocardium or epicardium. The plateauing success rate of VT ablation warrants re-evaluation of this mapping paradigm.

Objective: To resolve the intramural components of VT circuits, mapping was performed in human hearts.

Methods: Panoramic simultaneous endo/epicardial mapping (SEEM) during intraoperative mapping (IOM) was performed in human subjects. In explanted hearts (EH), SEEM and intramural multi-electrode plunge needle mapping (NM) of the left ventricle were performed. Overall, 37 VTs (26 ICM, 11 NICM) were studied in 32 patients. Intra-operative SEEM was performed in 16 patients (ICM = 16). Additionally, 16 explanted myopathic human hearts (NICM = 9, ICM= 7) were studied in the Langendorf set up. Predominant intramural location of the VT was imputed by the absence of significant endo-epi activation during intraoperative mapping (using SEEM & no NM) or by the presence of intramural activation spanning the entire cycle length (including mid diastole) in explanted hearts (SEEM and NM).

Results:

Intra Operative Mapping (SEEM)- Predominant endocardial activation (entire TCL including mid- diastolic activation) was present in 10/18 VTs (55%). In 8/18 VTs (44%) the VT circuit was presumed to be intramural due to incomplete diastolic activation in endocardium and epicardium.

Explanted Hearts (SEEM and NM)- VT location was predominantly intramural, endocardial and epicardial in 8/19(42%), 5/19(26%) and 1/19(5%) respectively.

Conclusion: In a significant proportion of both ischemic and non-ischemic ventricular tachycardias the predominant activation was located in the intramural space.

Introduction

Despite advances in mapping and understanding the arrhythmia mechanisms, ventricular tachycardia (VT) ablation strategies often assume the reentrant circuit to be planar, located either on the endocardium or epicardium. Although the knowledge of diastolic paths was developed from mapping studies of both endocardium and epicardium, for long the limitations in accessibility and mapping tools have defined our contemporary mapping paradigms. The role of the intra- mural three- dimensional space, which is inaccessible to mapping, has largely been ignored and consequently has rarely been evaluated. This final frontier space might hold the key to improved ablation success.

Ischemic cardiomyopathy (ICM) is assumed to be located in the sub-endocardium, [1] and non-ischemic cardiomyopathy (NICM) in the epicardium. [2] To improve success rates of VT ablation, increasing number of combined endo-epicardial ablation procedures is being undertaken with reasonable success. [3] However, the plateauing of success in VT ablation necessitates re-evaluation of the mapping paradigm, especially the role of intramural circuits in the left ventricle (LV).[4] A much-needed systematic study to explore the prevalence of intramural VT circuits has not been undertaken.

To resolve activation in the conventionally unmapped intramural space in the LV, we examined panoramic intra-operative simultaneous endo-epicardial VT activation maps (Simultaneous endo-epicardial mapping- SEEM) to indirectly

deduce the activation of the intramural space. Additionally, to further substantiate our deductions, in a different set of hearts the intramural space during VT was directly mapped with intramural plunge needles (Needle mapping- NM) in a human ex-vivo Langendorf set up.

Methods

Intra-operative and explanted heart mapping of recurrent VT refractory to medical therapy, which included both ICM and NICM were analyzed, table 1. Reentrant VTs with complete and partially mapped diastolic paths were included. Our local institutional review committee approved the study. Written informed consent was obtained from the patients.

Intraoperative Simultaneous Endocardial And Epicardial Mapping

A. Intra-operative mapping

The technique of intraoperative SEEM has been described before.[5, 6] In short, during cardiopulmonary bypass the LV endocardial balloon was placed via a left atriotomy incision. The balloon was filled with saline to maintain optimal endocardial contact. There were 14 splines of electrodes on the balloon. Each spline hosted 8 pairs of electrodes totaling 112 bipoles and each bipole had 2 electrodes separated by 1 mm distance. The adjacent bipoles were 1-3cms apart. The first row of spline was aligned to the anterior inter-ventricular groove. The

epicardial sock with 112 pairs of button electrodes was sutured to maintain position. The alignment was similar to the endocardial balloon, fig 1. A custom made mapping system that has been described previously was used. The bipolar local electrograms (Bi_{EGM}) were amplified, filtered and recorded. Filter settings were 28 - 750 Hz, with signal amplification up to 20,000 times. For optimal mapping of small diastolic signals higher gains were chosen. The minimal separation between the bipoles enabled higher signal resolution, even in detecting local potentials in the range of 0.05 - 0.1mV. Electrograms were then digitized to 2 kilo-samples/s and stored on a computer for offline analysis.

Ventricular Tachycardia induction

VT was induced with programmed ventricular stimulation using 1-3 extra-systoles (S2-4) upto refractoriness on 400-600ms base train (S1) after positioning the endocardial balloon array and epicardial sock in a stable position. The induced VT was compared to the clinical VT to establish significance.

Activation map during VT

Maximum dV/dt of each Bi_{EGM} was taken as the local activation time (LAT). In the case of long fragmented Bi_{EGM}, activation at adjacent sites were also taken onto account. When ≥50% of the VT cycle length was mapped, the isthmus region was defined as areas with activity during mid-diastolic phase of the tachycardia cycle. Pacing maneuvers were not used to discriminate bystander sites from isthmus

sites. Instead, since the entire endocardium was mapped simultaneously. fig: 2.

Direct Intramural Plunge needle VT Mapping In Explanted Hearts

Patients

Written informed consent was received from patients undergoing cardiac transplantation. Sixteen human hearts from patients diagnosed with both ICM and NICM were studied in the Langendorf set up using the global transmural plunge needle mapping protocol, fig 1.

B. Human Langendorff

Cold tyrode solution was used to preserve and flush the heart. Selective perfusion to the left and right coronary arteries was administered. Coronary perfusion pressure was maintained approximately 60-65 mm Hg with a flow rate of 0.9-1.1 L/min and the temperature was regulated to 37°C. After initial 5/10-minute stabilization, the protocol was completed within 30 minutes.

Mapping

Twenty-five 21-gauge plunge needles were used to directly map the intramural region of the LV. Each needle measured 13 mm in length and hosted four 36-gauge silver electrodes (0.24 mm in diameter) with 3 mm spacing, fig 1. An epicardial sock array was first applied, similar to intraoperative mapping, to provide an anatomical reference for the placement of needles. Needles were then inserted in a 5 x 5 array starting between rows 1 and 2 of the epicardial sock and terminating between rows 5 and 6. The innermost and outermost electrodes were kept in close proximity to the sub-endocardium and sub-epicardium respectively. The two electrodes between the innermost and outermost electrodes were situated in the mid-myocardium (2^{nd} and 3^{rd} electrodes). The electrograms recorded from the intramural needles were unipolar in nature. As surface QRS was not feasible in Langendorf set up the far field electrograms from the needles and the endo- epicardial electrodes were considered for timing. Our engineer used epicardial sock data to accomplish this. All apical EGMs (spline 5-8 of each spline) were analysed and calculated their rectified values (average sum of their squares). This estimated an average signal from the apex (64 EGMs combined to one). This was repeated for the basal EGMs. (electrodes on spline 1-4). Then the apical EGM was subtracted from the basal EGMs to obtain surface ECG of lead II/III. VT was considered to be predominantly located intramurally only if the whole TCL was activated in the mid myocardial electrodes (2 & 3). Hence systole and diastole in relation to surface ECG need not be accurately defined.

The endocardial balloon and epicardial sock similar to intraoperative mapping were placed. Unipolar EGMs from these electrodes were recorded simultaneously with the intramural EGMs.

VT induction

Two hook electrodes fixed at the posterior right ventricular epicardium were used to induce VT using programmed stimulation. A sustained ventricular arrhythmia with cycle length > 200 ms and stable morphology was diagnosed as VT.

Activation map during VT

The maximum negative dv/dt of the unipolar signal was used as the LAT. In needles where LAT was difficult to assess, surrounding activation times were taken into account.

Definitions

a) Systolic activation site: site with activation during the duration of surface QRS of each tachycardia cycle.
b) Diastolic activation site: site with activation during the post-QRS period of each tachycardia cycle.
c) Mid-diastolic site: The site, which is activated at mid-diastole.

d) Predominant zone of reentry (endocardium, myocardium or epicardium): activation of 100% of TCL on a particular zone.

e) Intramural VT: The presence of entire CL of VT in intramural electrodes 2 & 3 during NM or the absence of mid diastolic activation during simultaneous endocardial and epicardial mapping during VT.

Results

Patient characteristics

Thirty-two hearts (ICM-23, NICM-9) were studied using intraoperative SEEM in 16 and explanted heart NM & SEEM in 16 patients. All intraoperative SEEM patients (males 81%) suffered ICM, severe LV dysfunction, intractable VT without previous catheter ablation. They underwent surgical cryoablation 9 ± 5 years after myocardial infarction. The outcomes of surgery (LV aneurysm resection) were reported previously.[7]

The explanted heart NM & SEEM studies were performed in 16 hearts (males 60%) of which 9 were of NICM and 7 ICM patients. The NICM were of idiopathic etiology except for post partum cardiomyopathy and Sarcoidosis in one patient each. All patients suffered severe LV dysfunction and none of them underwent VT ablation in the past.

Intra Operative Mapping

IOM was performed only in ICM patients. In 10/18(55%) the activation was complete in endocardium and partial in epicardium. In all the VTs the activation was only partial in the epicardium. In 8/18 VTs the circuit was presumed to be intramural (44%) due to the absence of significant diastolic activation in endocardium and epicardium. These VT could have been located intramural in the septum as well, table 2, fig 3, supplementary video 1.

In intramural VTs the mean TCL was 358 ± 38 ms. The missing activation time (predominantly mid-diastolic) in endocardium and epicardium which is presumed to be located intramurally was 96 ± 39 ms, constituted 27 ± 11 % of the TCL. However the combined endocardial- epicardial activation covered 73 ± 11 % of TCL. There was significant overlap in the activation of the surfaces.
For the endocardial VTs the mean TCL was 325 ± 92 ms of which 100% activation was mapped in the endocardium.

Explanted hearts

The predominant VT location was in the intramural space in 8/19(42%), endocardial in 5/19(26%) and epicardial in 1/19(5%), table 3.

In predominant intramural VTs, the entire TCL (100%) including the mid-diastolic activation could be mapped in the mid-myocardial electrodes. However there was a significant overlap in activation of the other surfaces. In

257 predominant intramural VTs, endocardium was activated for 46 ± 22% of TCL in
258 ICM and 55 ± 15% in NICM and epicardium for 54 ± 26% of TCL in ICM and 82 ±
259 10% in NICM. Combined epicardial and endocardial activation was 81 ± 19% of
260 TCL, fig 3, table 3 and supplementary video 2.
261
262 In predominantly epicardial and predominantly endocardial VTs the mean
263 activation time recorded in the intramural space was 39 ± 15 % of the TCL.
264 Combined epicardial and endocardial activation was 100% of TCL. (Significant
265 overlap in the activation was present), table 3.
266
267 *Partially (incompletely) mapped VTs in explanted hearts:* In explanted hearts,
268 5/19 VTs could not be entirely mapped despite SEEM and NM of which 3 were
269 NICM and 2 were ICM. The mean TCL was 516 ± 78 ms. Intramural activation
270 accounted for 47 ± 20 % of TCL. Combined endocardial-epicardial activation
271 amounted to 35 ± 14% of TCL. The combined activation in the intramural,
272 epicardium and endocardium was nearing 100% in some VTs. This was due to
273 the significant overlap in activation in the early and late diastolic period. The
274 mid-diastolic EGMs were not mapped in any zone. Hence they have been
275 classified as partially mapped VTs. These VTs could be located in the septum
276 where intramural needles could not be placed, or the RV endocardium where
277 mapping was not done. table 3.
278
279 *Cardiomyopathy type:* In total the VT circuit was predominantly located intra-
280 murally in 16/37(43%) VTs. In ICM the VT circuit was predominantly located

intramurally in 11/26(42%), endocardium in 13/26(50%) and none in the epicardium. In NICM the VT circuit was predominantly located intramurally in 5/11(45%), endocardium in 2/11(18%) and epicardium in 1/11(9%) VTs.

Discussion

Predominant intramural activation was observed in 40% of VTs with similar occurrence in both ICM and NICM.

The success rate of VT ablation is moderate at best. Upto 50% recurrence in one-year has been reported. [8, 9] The reasons could be multifactorial, of which the intramural location of VT is a forerunner. [3] The presence of intramural circuits is more relevant in the current era of early reperfusion strategies. It was demonstrated previously in human autopsy specimens that patients who received early reperfusion therapy had non-transmural infarcts and consequently more surviving intra-myocardial fibers. This predisposed to less dense scar and faster VTs.[10]

Similar study of intraoperative VT mapping conducted by Pogwitz at al included ICM patients only.[11] Intramural reentry was identified as the mechanism of VT in half of the patients, which is similar to our results. In the other half of the cohort, focal VT was sited as the mechanism originating from the endocardium. This could have been micro-reentry, which the recording system was insensitive to

pick up. They used intramural needle recordings to characterize the VT circuit and endocardial mapping was not done. This could explain the difference in the findings as lack of comprehensive endocardial mapping could have missed a part of endocardial activation. Similar to our study, Kaltenbrunner et al observed that in half of the ICM VTs, the entire TCL could not be mapped in both endocardium and epicardium and hence it was presumed to be located intra-murally.[12] Using entrainment mapping Kokovic et al noted that the diastolic isolated isthmus signals were absent in half of ICM VT cases.[13] The reasons for the paucity of these diastolic and small amplitude signals could be multifactorial. Even though a deeper location of the circuit could be the most probable reason. Narrow isthmus, wave front-electrode angle, slow conduction velocity and thus low amplitude obscured under the noise floor also needs consideration. However in defense of our intraoperative mapping technique, the signal was gained upto 25,000 times, which has the best chance of recording deeper signals.

The VT substrate, even though often depicted as planar by contemporary electro-anatomical mapping systems is indeed a three-dimensional structure, which harbors the scar and islands of viable myocardium. [14] It is only logical to assume that the VT circuit would follow the scars and extend into the mid-myocardium towards the epicardium. This has been confirmed by imaging studies.[4, 15] Bogun et al demonstrated that 30% of NICM patients had intramural scar.[16] The ICM scar is considered to be a pyramidal structure with the base in the endocardium and a variable, often transmural, endo to epicardium distribution [14] The epicardial scar was reported to be a third in area to that of endocardial scar in

ICM and the critical components of the VT circuit were located in areas of more than 25% scar transmurality. [4, 17] The sub-epicardial space harbored 16-35% of border zone conducting channels as demonstrated with the help of cMRI.[17]

Multiple studies have shown that a combined endocardial- epicardial ablation enjoyed better success in both NICM and ICM. [3, 18, 19] This could be an indirect evidence of intramural circuits. Di Biase et al reported that 40% of ICM patients required epicardial VT ablation and thus improved freedom from arrhythmia recurrence. [9] Tung et al reported that in 24% of ICM VT, isthmus was located in the epicardium which could be successfully ablated.[20] Epicardial substrate including local abnormal ventricular activation (LAVA) was more common in NICM.[21, 22]

The depth at which the sub-endocardial intramural circuit, becomes unmappable with conventional endocardial electrodes, is unknown. [14] This could be a shallow depth amenable to endocardial ablation or it could be deep and inaccessible, which is more likely. There is clear evidence that the mapping catheters even while recording bipolar EGMs could encounter significant contamination from far-field signals. It is hardly possible to distinguish the electrograms if it is from adjacent tissue on the same plane or from tissue at a deeper plane. We currently lack the tools, to delineate that. Hence, in order to improve the success rate of VT ablation, deep intramural circuits have to be considered in both ICM and NICM VTs and techniques for deeper ablation such as intramural needle and bipolar ablation will have to be further explored. [23, 24]

Our findings show that during VT, activation simultaneously occurs in all three zones especially in systole and occasionally in early and late diastole. However the zone of predominant activation harbours the mid-diastolic electrograms.

Limitations

Lack of entrainment limits the identification of critical sites of VT circuit. However we report the predominant zone of activation instead of critical sites. The inter-electrode spacing in our intraoperative mapping is similar to the novel mapping catheters with 1mm inter-electrode distance. This enables higher resolution of local electrograms. However, this bipole has the characteristic of a smaller antenna as compared to larger inter-electrode distance of an ablation catheter. A larger inter-electrode distance might help to record deeper intramural signals at the cost of a lower mapping resolution. However, in such a scenario it would be difficult to differentiate endocardial from intramural signals. The use of unipolar instead of bipolar EGMs in explanted hearts and variability in techniques used in the study is a limitation. However only near field electrograms were used for analysis.

The absence of RV endocardial and outflow is a limitation. NM was performed only in the LV free wall. Due to access and stability of the heart preparation the intramural septum was not mapped in both IOM and EH study. This could have underestimated the prevalence of intramural VTs. Imaging data was also not

available to correlate the myocardial thickness especially in intramural VTs. Lack of autonomic inputs during VT induction in explanted hearts could have induced non clinical VTs. Our study only demonstrates that the intramural diastolic activation of VT is prevalent. This does not prove that they are critical, nor are they mappable with our current techniques.

Conclusion

In significant proportion of ischemic and non-ischemic hearts the VT circuit was predominantly located intra-murally. Strategies for intra-mural ablation need to be explored to augment the success of VT ablation.

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401 **Reference**

402

403 **1.** Sapp JL, Cooper JM, Soejima K, et al. Deep Myocardial Ablation Lesions
404 Can Be Created with a Retractable Needle-Tipped Catheter. Pacing and
405 Clinical Electrophysiology 2004;27:594-599.

406 **2.** Dinov B, Fiedler L, Schönbauer R, et al. Outcomes in catheter ablation of
407 ventricular tachycardia in dilated nonischemic cardiomyopathy compared
408 with ischemic cardiomyopathy: results from the Prospective Heart Centre
409 of Leipzig VT (HELP-VT) Study. Circulation 2014;129:728-736.

410 **3.** Chae S, Oral H, Good E, et al. Atrial tachycardia after circumferential
411 pulmonary vein ablation of atrial fibrillation: mechanistic insights, results
412 of catheter ablation, and risk factors for recurrence. Journal of the
413 American College of Cardiology 2007;50:1781-1787.

414 **4.** Deno DC, Balachandran R, Morgan D, Ahmad F, Massé S, Nanthakumar K.
415 Orientation-Independent Catheter-Based Characterization of Myocardial
416 Activation. IEEE Transactions on Biomedical Engineering 2017;64:1067-
417 1077.

418 **5.** Downar E, Parson ID, Mickleborough LL, Cameron DA, Yao LC, Waxman
419 MB. On-line epicardial mapping of intraoperative ventricular
420 arrhythmias: initial clinical experience. Journal of the American College of
421 Cardiology 1984;4:703-714.

422 **6.** Downar E, Harris L, Mickleborough LL, Shaikh N, Parson ID. Endocardial
423 mapping of ventricular tachycardia in the intact human ventricle:

evidence for reentrant mechanisms. Journal of the American College of Cardiology 1988;11:783-791.

7. Mickleborough LL, Mizuno S-i, Downar E, Gray GC. Late results of operation for ventricular tachycardia. The Annals of thoracic surgery 1992;54:832-839.

8. Di Biase L, Burkhardt JD, Lakkireddy D, et al. Ablation of stable VTs versus substrate ablation in ischemic cardiomyopathy: the VISTA randomized multicenter trial. Journal of the American College of Cardiology 2015;66:2872-2882.

9. Di Biase L, Santangeli P, Burkhardt DJ, et al. Endo-epicardial homogenization of the scar versus limited substrate ablation for the treatment of electrical storms in patients with ischemic cardiomyopathy. Journal of the American College of Cardiology 2012;60:132-141.

10. Wijnmaalen AP, Schalij MJ, Thüsen JHvd, Klautz RJM, Zeppenfeld K. Early Reperfusion During Acute Myocardial Infarction Affects Ventricular Tachycardia Characteristics and the Chronic Electroanatomic and Histological Substrate. Circulation 2010;121:1887-1895.

11. Pogwizd SM, Hoyt RH, Saffitz JE, Corr PB, Cox JL, Cain ME. Reentrant and focal mechanisms underlying ventricular tachycardia in the human heart. Circulation 1992;86:1872-1887.

12. Kaltenbrunner W, Cardinal R, Dubuc M, et al. Epicardial and endocardial mapping of ventricular tachycardia in patients with myocardial infarction. Is the origin of the tachycardia always subendocardially localized? Circulation 1991;84:1058-1071.

13. Kocovic DZ, Harada T, Friedman PL, Stevenson WG. Characteristics of electrograms recorded at reentry circuit sites and bystanders during ventricular tachycardia after myocardial infarction. Journal of the American College of Cardiology 1999;34:381-388.

14. Fernández-Armenta J, Berruezo A, Andreu D, et al. Three-dimensional architecture of scar and conducting channels based on high resolution ce-CMR: insights for ventricular tachycardia ablation. Circulation: Arrhythmia and Electrophysiology 2013CIRCEP. 113.000264.

15. Bogun F, Crawford T. Ablation for ventricular tachycardia: is more always better? How much more is too much?: Journal of the American College of Cardiology; 2012.

16. Bogun FM, Desjardins B, Good E, et al. Delayed-enhanced magnetic resonance imaging in nonischemic cardiomyopathy: utility for identifying the ventricular arrhythmia substrate. Journal of the American College of Cardiology 2009;53:1138-1145.

17. Sasaki T, Miller CF, Hansford R, et al. Myocardial structural associations with local electrograms: a study of post-infarct ventricular tachycardia pathophysiology and magnetic resonance based non-invasive mapping. Circulation Arrhythmia and electrophysiology 2012;5:1081.

18. Romero J, Cerrud-Rodriguez RC, Di Biase L, et al. Combined Endocardial-Epicardial Versus Endocardial Catheter Ablation Alone for Ventricular Tachycardia in Structural Heart Disease: A Systematic Review and Meta-Analysis. JACC: Clinical Electrophysiology 2018.

19. Gökoğlan Y, Mohanty S, Gianni C, et al. Scar homogenization versus limited-substrate ablation in patients with nonischemic cardiomyopathy and ventricular tachycardia. Journal of the American College of Cardiology 2016;68:1990-1998.

20. Tung R, Michowitz Y, Yu R, et al. Epicardial ablation of ventricular tachycardia: an institutional experience of safety and efficacy. Heart Rhythm 2013;10:490-498.

21. Sapp JL, Cooper JM, Zei P, Stevenson WG. Large Radiofrequency Ablation Lesions Can Be Created with a Retractable Infusion-Needle Catheter. Journal of Cardiovascular Electrophysiology 2006;17:657-661.

22. Soejima K, Stevenson WG, Sapp JL, Selwyn AP, Couper G, Epstein LM. Endocardial and epicardial radiofrequency ablation of ventricular tachycardia associated with dilated cardiomyopathy: the importance of low-voltage scars. Journal of the American College of Cardiology 2004;43:1834-1842.

23. Sapp JL, Beeckler C, Pike R, et al. Initial human feasibility of infusion needle catheter ablation for refractory ventricular tachycardia. Circulation 2013CIRCULATIONAHA. 113.003423.

24. KOTLER MN, TABATZNIK B, MOWER MM, TOMINAGA S. Prognostic Significance of Ventricular Ectopic Beats with Respect to Sudden Death in the Late Postinfarction Period. Circulation 1973;47:959-966.

Figure Legends

Fig 1 (a) Epicardial electrode sock and LV endocardial balloon (b) Epicardial sock on explanted heart (c) Endocardial balloon in explanted heart (d) schematic representation of intramural needle in LV free wall.

Fig 2 (a-f), The diastolic path, endocardial and epicardial electrograms of VT in six patients are illustrated. The upper panel shows endocardial VTs with the entire diastolic path mapped in the endocardium. The lower panel shows VTs with probable mid-diastolic intramural activation, where activation was incomplete in endocardium and epicardium during VT.

Fig 3 Chromatic representation of VT cycle length (CL) divided in seven segments- 18 VTs illustrated. Simultaneous endocardial-epicardial Intraoperative mapping (a-l) and simultaneous endocardial-epicardial with needle intramural mapping in explanted hearts (m-r). In endocardial VTs the whole TCL could be mapped in the endocardium and only partially mapped in epicardium, (a-f). In presumed intramural VTs the activation gaps in endocardial and epicardial mapping is evident, (g-i). In explanted hearts, combined endocardial-epicardial and intramural needle mapping, showing intramural VT (m-o) and partially (incompletely) mapped VTs in (p-r). The partially

(incompletely) mapped VTs could also be located intramurally in the septum, which was not mapped.

Study summary

Study set-up	Mapped regions	Study cohort	Cardiomyopathy type
Human Intra-operative Mapping (IOM)	Simultaneous endocardial epicardial mapping (SEEM)	16 patients with 18 VTs	ICM- 16 patients
Human explanted hearts (EH)	Simultaneous endocardial epicardial mapping (SEEM) & Needle Mapping (NM)	16 patients with 19 VTs	NICM- 9 patients, ICM- 7 patients

Table 1: Study summary

VT Characteristics Intraoperative mapping

Presumed intramural VT				
VT no:	**Mapping Endo-epi (IOM)**	**TCL (ms)**	**Presumed intramyocardial act. in ms (% of TCL)**	**Measured endo. & epi. act. in ms(% of TCL)**
1	Yes	350	158(45)	192(55)
2	Yes	350	147(42)	203(58)
3	Yes	390	90(23)	300(77)
4	Yes	340	61(18)	279(82)
5	Yes	340	82(24)	258(76)
6	Yes	280	42(15)	238(85)
7	Yes	380	103(27)	277(73)
8	Yes	400	88(22)	312(78)
Mean ± SD		358 ± 37	96 ± 39 (27 ± 11)	257 ± 44 (73 ± 11)
Non-Intramural (Predominantly endocardial) VT				
VT	**Mapping Endo-epi (IOM)**	**TCL(ms)**		**Endo (%)Act.**
1	Yes	320		100
2	Yes	220		100
3	Yes	390		100
4	Yes	210		100
5	Yes	500		100
6	Yes	270		100
7	Yes	400		100
8	Yes	370		100
9	Yes	320		100
10	Yes	250		100
Mean ± SD		325 ± 92		

Myo. Act.- Intramural activation time. Myo/TCL- Intramural activation time represented as a fraction of tachycardia cycle length. Epi. Act.- Epicardial activation time. Endo. Act.- Endocardial activation time

IOM- Intra-operative mapping. EH- Explanted Heart

Table 2: VT characteristics- Intraoperative mapping of Ischemic Cardiomyopathy. Simultaneous endocardial and epicardial mapping (SEEM) performed without intramural mapping. During SEEM the missing activation in endocardium and epicardium was presumed to be located intramurally. In all cases of presumed intramural VT the mid-diastolic activation was absent in SEEM.

Explanted Hearts- VT characteristics

Predominantly Intramural VT				
VT no:	Diagnosis	TCL	Intramural act. in ms (% of TCL)	Total epi-endo act., in ms (% of TCL)
1	DCM	570	570(100)	460(81)
2	PPCM	260	260(100)	235(90)
3	DCM	290	290(100)	260(90)
4	DCM	280	280(100)	250(90)
5	DCM	520	520(100)	280(54)
6	ICM	290	290(100)	195(67)
7	ICM	200	200(100)	180(90)
8	ICM	370	370(100)	150(40)
Mean ± SD		348 ± 131	348 ± 131(100)	251 ± 95(75 ± 20)
Predominantly epicardial, endocardial & partially mapped VTs				
1	DCM	590	120(20)	190(32)
2	DCM	580	380(66)	320(55)
3	DCM	400	185(46)	100(25)
4	DCM	310	100(32)	310(100)
5	SCM	310	120(38)	310(100)
6	SCM	340	140(41)	340(100)
7	ICM	480	170(35)	130(27)
8	ICM	530	350(66)	160(30)
9	ICM	360	90(25)	360(100)
10	ICM	310	70(23)	310(100)
11	ICM	280	120(43)	280(100)
Mean ± SD		408 ± 116	167 ± 103 (39 ±15)	306 ± 124 (81 ± 32)

DCM- Dilated Cardiomyopathy, PPCM- Post partum Cardiomyopathy, ICM- Ischemic Cardiomyopathy, SCM- Sarcoid Cardiomyopathy. Predominant intramural/endocardial/epicardial VT- Entire TCL including the mid-diastolic EGM is mapped in the respective zone. Partially (incompletely) mapped VT- Entire TCL could not be mapped in any zone.

Table 3: VT characteristics- Intramural needle, endocardial and epicardial mapping in explanted Hearts. A significant proportion of VTs were located in the intramural space in both ICM and NICM. Partially mapped VTs have the serial numbers 1,2,3,7 and 8.

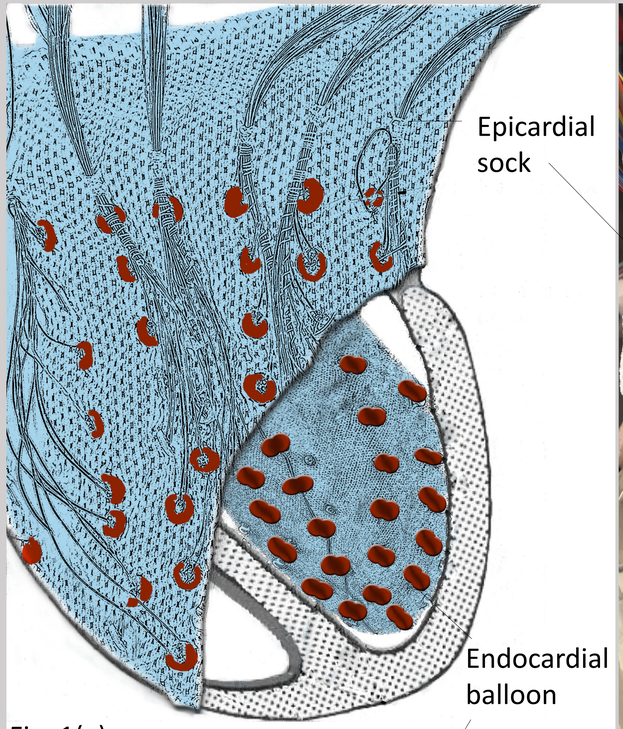
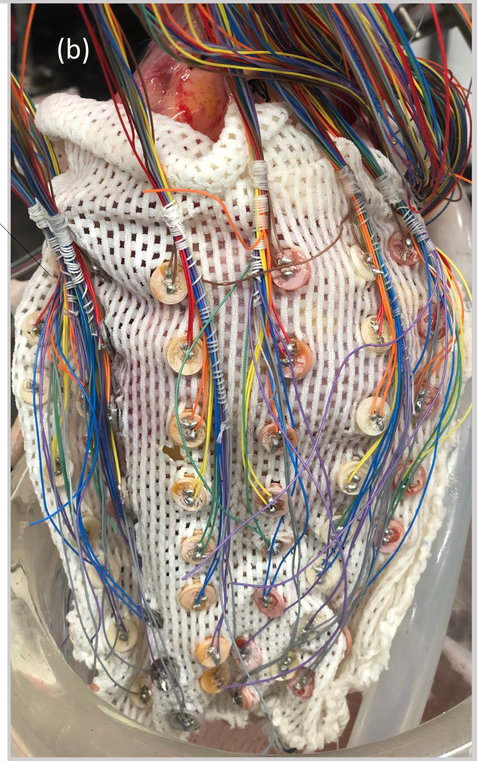
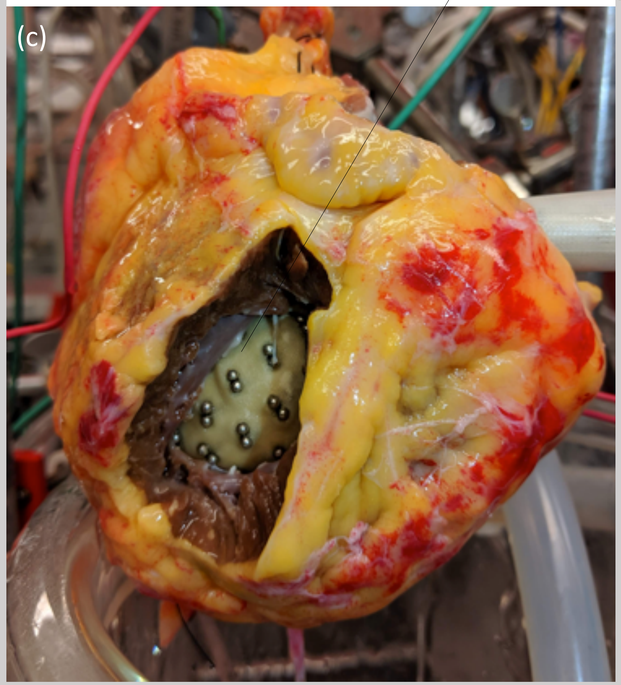
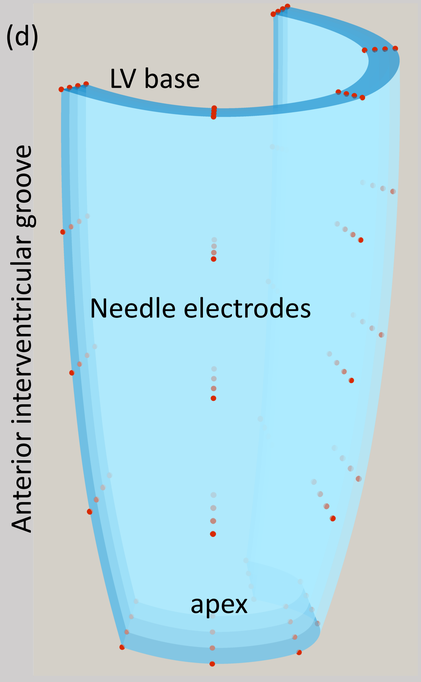

Epicardial
sock
Endocardial
balloon

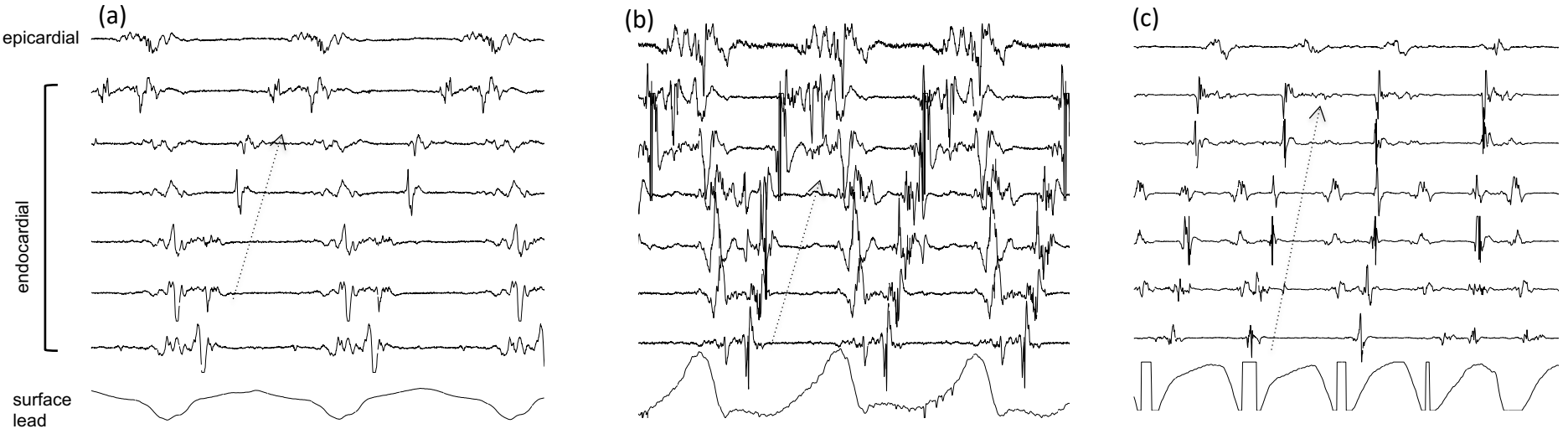
Fig: 1(a)


(b)


(c)

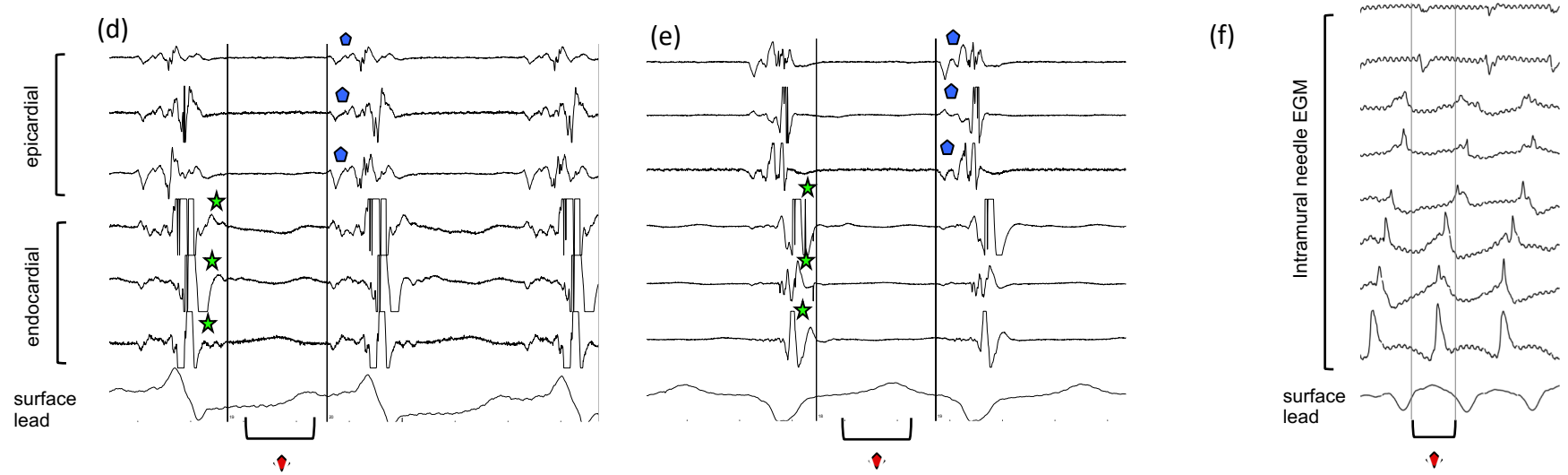

(d)
LV base
Anterior interventricular groove
Needle electrodes
apex

VTs with entire diastolic path mapped in the endocardium (entire LV endo and epi mapped simultaneously in intraoperative mapping)



VTs with mid-diastolic intra-mural activation
(entire LV endo and epi mapped simultaneously in intraoperative mapping)

VT with intra-mural activation
(needle mapping in explanted heart)



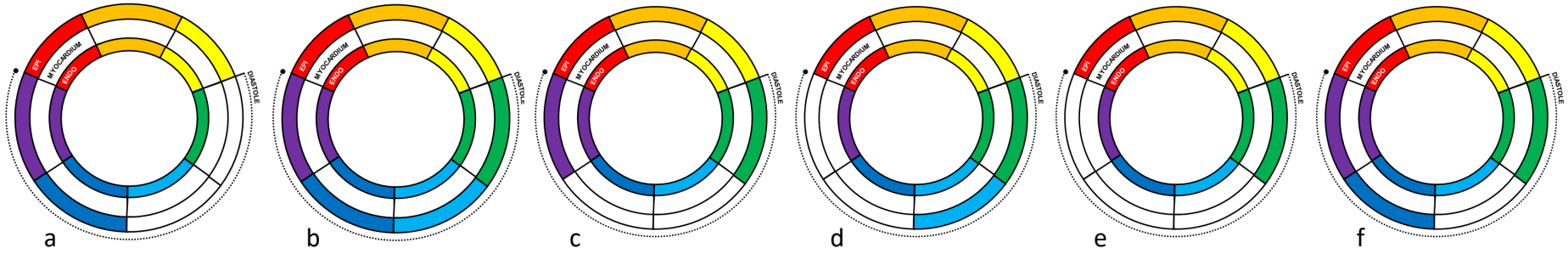
Diastolic intramural activation Diastolic endocardial activation Diastolic epicardial activation

Fig: 2

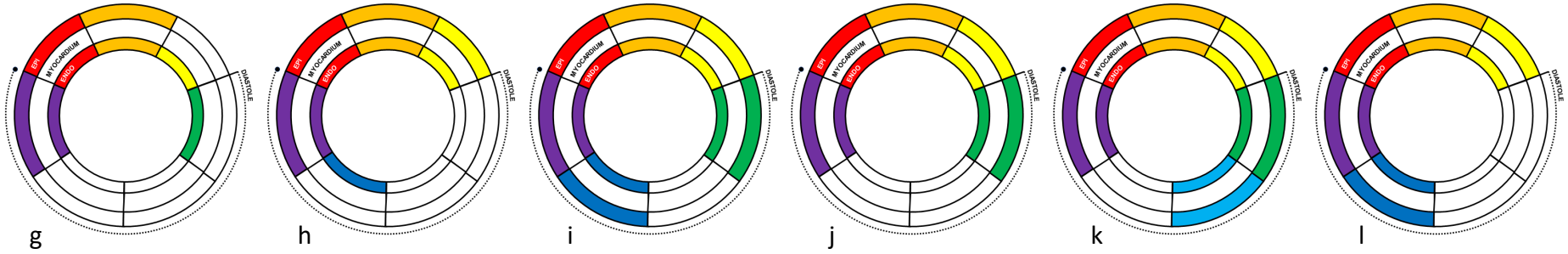
Intraoperative endo-epi mapping, myocardium unmapped

Explanted heart

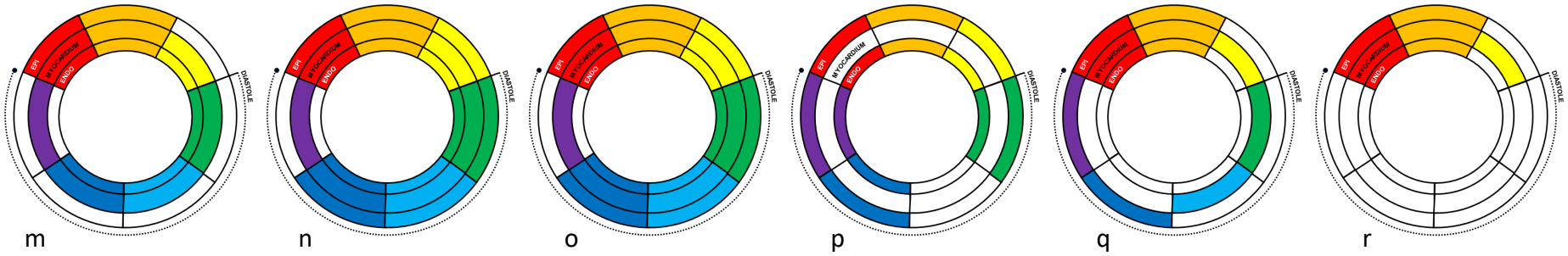
Preserved CL in endocardium (endocardial VT)

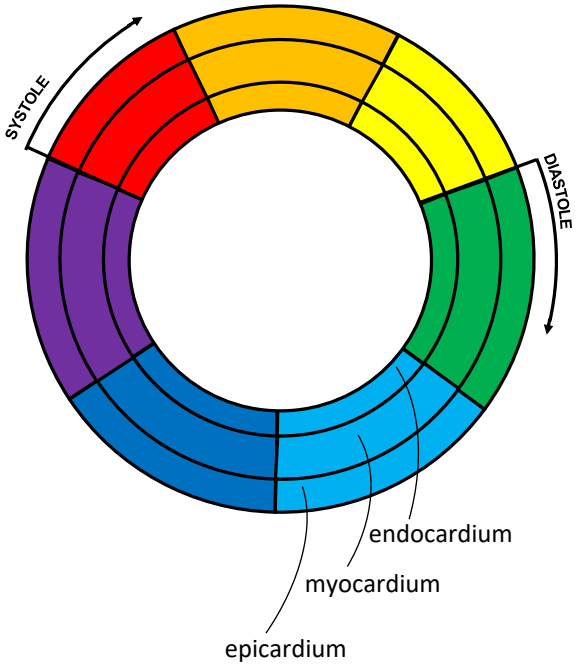


Missing CL in endocardium & epicardium (?intramural VT)



Endocardium, epicardium & intramural needle mapping





Intramural VT- preserved CL in myocardium

VT of unknown origin- missing CL in epi, endo and myocardium ?septal

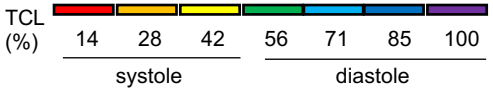


Fig: 3