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Printed Circuit Board Electrodes for Transmural Cardiac Mapping

Derek J. Dosdall, *Member, IEEE*, Jian Huang, William M. Smith, *Fellow, IEEE*, James D. Allred, J. Scott Allison, and Raymond E. Ideker, *Fellow, IEEE*

***Abstract*— Plunge needle recording techniques have provided valuable insights into transmural activation in cardiac tissue. Construction of plunge needles has been a costly and time intensive endeavor. Plunge needles constructed with standard printed circuit board (PCB) technology and methods are outlined. PCB plunge needles are less expensive in terms of raw materials and time required for construction than hypodermic stock or epoxy plunge needles. Tested PCB plunge needles recorded signals comparable to signals recorded by other plunge needles. PCB plunge needles provide an economical and rapid alternative to previously published techniques for plunge needle design.**

Keywords—**electrophysiology, transmural cardiac recording, plunge needle recording**

I. Introduction

Many techniques have been used to map cardiac activation. High speed cinematography, optical mapping, surface ECG, and direct electrical mapping with plaques, socks, and catheters have provided many insights into normal and pathological cardiac activation sequences. All of these techniques provide information about global activation sequences or activation patterns on the epicardial or endocardial surfaces.

Intramural recordings from electrodes in plunge needles have led to a greater understanding of the transmural activation patterns of sinus rhythm and cardiac arrhythmias. With plunge needle techniques, highly localized transmural activation patterns can be mapped.

Plunge needles have typically been manufactured in one of two ways: 1) stainless steel hypodermic needles are individually machined and threaded with fine wire [1-3], or 2) heat shrink tubing is threaded with fine silver wire and filled with fiberglass strands and epoxy [4, 5]. Both of these techniques are tedious and time consuming, and the needles are prone to failure with repeated use.

With progressing technology and increased competition among online printed circuit board (PCB) manufacturers, PCB manufacturing techniques have become economical and efficient. Therefore, we developed a PCB plunge needle that can substantially reduce the time and costs associated with the construction of plunge needles.

II. Needle Design and Fabrication

A. Plunge needle design

Printed circuit boards with 4 layers can be manufactured economically, and the board may be designed to be compact and space efficient. This allows the design to have up to 4 traces occupying the same area of the board. By using 4 layer boards, the 12 traces required for the 12 point plunge needles can be distributed evenly between the four layers. This allows the 12 traces occupy the space of 3 trace and space widths.

Printed circuit board designs were created with EAGLE (Easily Applicable Graphical Layout Editor) 4.1 Layout software (CadSoft Computer, Inc, Delray Beach, FL, USA). EAGLE standard version (non-profit license) was used to design 4 layer boards. The initial board design consisted of a variety of plunge needle configurations. The designed board was 2 x 4 inches (5.1 x 10.2 cm) and contained a total of 24 plunge needles, with either 6 or 12 electrodes on each needle. The board material specified was FR4 with a final thickness of 31 mils.

The plunge needles had either 1 or 2 mm spacing between electrodes. Drilled holes (12 mil drill size) plated through the board were used as the recording electrodes. Since the cost of using blind or buried vias (vias that do not go through the entire board) increases the cost of the board dramatically, plated holes that connected to each layer were used. A 5 mil annular ring was specified around the drilled holes. Trace widths and spacing of 5 mils were used to connect the electrodes to hookup wire pads. Hookup wire pads were placed on the portion of the plunge needle that was not to be inserted into cardiac tissue. These pads were 1x1 mm in size and were sufficiently large to be able to solder wire directly to the pads without the need for specialized bonding equipment. The pads were placed on either outer layer of the board so that 6 point plunge needles had 3 pads on each side of the board, and 12 point plunge needles had 6 pads on each side of the board. Figure 1 shows a PCB layout for one of the 24 plunge needles in the EAGLE Layout design.

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D. J. Dosdall is a postdoctoral fellow with the Department of Biomedical Engineering at the University of Alabama at Birmingham, 1670 University Ave, Volker Hall B140, Birmingham, AL 35294 (phone 205-975-2105, email: djd@crml.uab.edu).

J. Huang, J. S. Allison, and J. D. Allred, are with the Department of Cardiology at the University of Alabama at Birmingham, Birmingham, AL 35294.

W. M. Smith has appointments with the Departments of Biomedical Engineering and Medicine at the University of Alabama at Birmingham, 1670 University Ave, Volker Hall B140, Birmingham, AL 35294.

R. E. Ideker has appointments within the Departments of Medicine, Physiology, and Biomedical Engineering at the University of Alabama at Birmingham, 1670 University Ave, Volker Hall B140, Birmingham, AL 35294 (email: rei@crml.uab.edu).

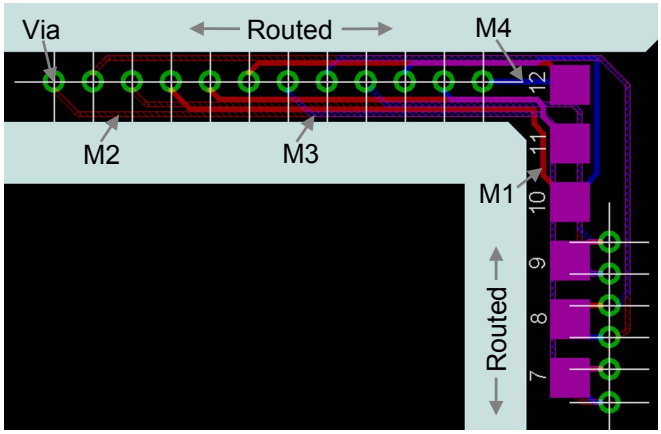

Figure 1 An example of a PCB layout of a 12 point, 1 mm spaced plunge needle. Green=vias; gray=routed edges of needle; 4 signal layers: red (M1), crosshatched red (M2), crosshatched blue (M3), blue (M4); purple=overlapping signal layers

A soldermask layer covered all of the surfaces except the electrodes and the hookup pads. This soldermask layer is an insulator, and ensures that only the proper surfaces will be exposed to the cardiac tissue.

A standard 1/16" bit was specified to make the internal cutouts and slots that defined the principal dimensions of the plunge needles. The routing was such that the needles were not separated from each other before they were shipped from the manufacturer. Each needle was routed out such that the distal end of the plunge needle was still connected to the distal end of another plunge needle. This process reduced the flexing that might be associated with routing out thin sections of PCB material. CNC (Computer Numerical Control) routing by the manufacturer provided the fine resolution required to accurately cut out the needles.

While the base metal layer for the traces, electrodes, and vias is copper, PCB manufacturers offer a variety of final finishing material options. These options include silver, gold, tin, OSP (organic Solderability Preservatives), copper, HASL (Hot Air Solder Leveling), and others. Immersion silver finishing was specified for this design.

B. Fabrication

Quotes from multiple manufactures were requested. The initial request was for 2 boards and a turn time of 2-3 weeks. Prices ranged from approximately $500-$3500 for the initial order. Larger quantities of boards could be ordered at the same time for a slightly higher price. An example of a quote received was $530 for the first board, $576 for 12 boards, or $684 for 36 boards. A PCB manufacturer (San Francisco Circuits, Inc.; San Fancisco, CA, USA) was selected. The boards were received within one week of submission of the design. Figure 2 shows the printed circuit boards as they were delivered from the manufacturer.

C. Needle Preparation

The individual needles were separated from each other with a band saw, and the distal tips were sharpened with a belt sander. After separation of the individual needles, the measured dimensions of the needles were approximately 32 mils by 70 mils (approximately 0.8 mm by 1.8 mm). An example of a PCB plunge needle is shown in Figure 3.

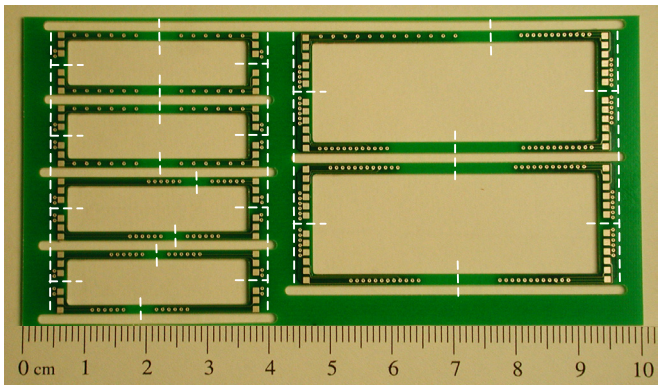

Figure 2 PCB of plunge needle boards as received from the manufacturer. Six point plunge needles are shown on the left, while 12 point plunge needles are shown on the right. The individual needles were separated by cutting along the white dashed lines.

Hookup wire was soldered to the pads, and appropriate headers were added. After the wires were soldered in place, the solder joints were painted with an insulating coating (GC Electronics).

Attempts to chloridize the electrodes were unsuccessful. The silver plating appeared to be insufficiently thick to allow for chloridization. When current was passed through the electrodes to develop a silver-silver chloride layer, the copper was exposed, and corrosion occurred.

III. Performance

The chest of an anesthetized 39 kg pig was opened by median sternotomy and the heart was exposed. The heart

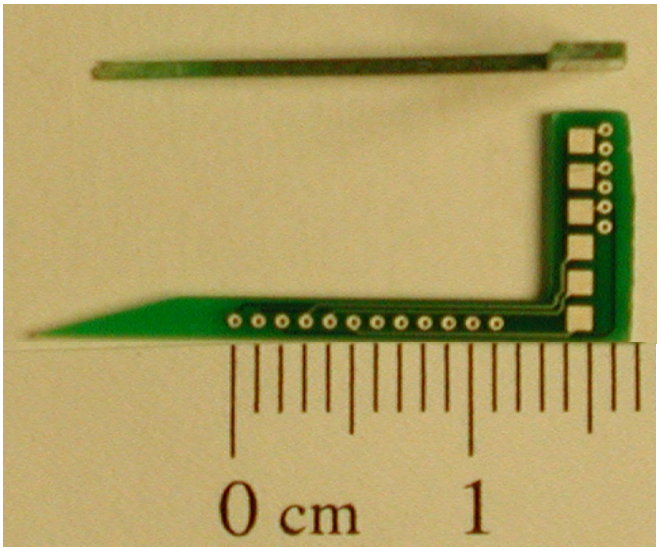

Figure 3 Cross sectional and top view of a 12 point PCB plunge needle showing the cross-sectional profile (top) and width of the needle.

was suspended in a pericardial cradle. Defibrillation coils were inserted into the right ventricular apex and into the superior vena cava. Four 12-point and three 6-point PCB plunge needles were inserted into the left ventricular free wall and anterior surface. The plunge needles were inserted into the heart without difficulty, and there were no incidences of broken or damaged plunge needles during insertion or during the course of the experiment. All of the plunge needles remained firmly in place throughout the experiment.

Injury potentials, typically seen in plunge needle studies, were allowed to subside for at least 30 minutes before proceeding with the experiment. Sinus rhythm was recorded from unipolar and bipolar pairs of electrodes on the PCB plunge needles.

After sinus rhythm was recorded, ventricular fibrillation was induced through a direct 9 Volt DC stimulus applied to the right ventricle. Ventricular fibrillation was allowed to persist for 20 seconds, and a defibrillation shock was administered.

Unipolar and bipolar transmural activations were recorded at 16 KHz with the PCB needles. Figure 4 shows unipolar and bipolar recordings from PCB plunge needles from this experiment, as well as epoxy plunge needles from a similar experiment conducted previously in our laboratory. Of the 66 unipolar recordings, 60 demonstrated reasonable signals with large amplitude, low noise recordings.

After a defibrillation shock of 600 Volts, the amplifiers in the 60 channels with acceptable signals recovered by 14±8 ms (average ± standard deviation) after the end of the shock.

VI. Discussion

The recordings from the PCB plunge needles are similar to recordings from epoxy plunge needles. Activation recordings were sharp and distinct, and activation times and sequences could be identified using previously published criteria [6, 7].

An important difference observed between the PCB and epoxy needle recordings was that the PCB plunge needle recordings exhibited enlarged t-waves as compared to the activation amplitude. This difference may be attributed to one of two reasons: 1) The PCB plunge needles were larger than the epoxy needles, and thus caused more localized tissue damage upon insertion. Measured diameters of 12 point epoxy and hypodermic stock needles were 35 mils (0.9 mm) and 45 mils (1.1 mm), respectively. The damage done by the PCB needles (which measured 32x70 mils) may have caused the injury potentials to last longer than those observed by other needle types. 2) The epoxy needles had an effective electrode size of 3 mils, while the PCB needles had a 25 mil circle on each side of the PCB as an effective electrode surface. The normal activation front is narrow, less than 1 mm thick [8], with positive potentials immediately in front of the wavefront and negative potentials immediaely behind it. Since the diameter of the electrodes in the PCB needles (>0.6 mm) is almost as wide as the wavefront, these positive and negative potentials are recorded simultaneously as the wavefront passes the electrode, so that the recorded electrogram is smaller in amplitude than with the smaller recording electrode (<0.1 mm) of the epoxy needle. Since the repolarization wavefront is much broader than the depolarization wavefront, this effect is not nearly so pronounced during the T wave. Therefore, the larger area of the recording site for the PCB than the epoxy needles (7 mils^2 vs. 981 mils^2) may account for the differences in the recorded traces.

When using plunge needles for Purkinje fiber recording, it is believed that contacts around the circumference of the plunge needle may provide better signals than small point electrodes [9-11]. The epoxy needles provide only a small recording site on one side of the needle, while hypodermic stock needles may be built with a wire wrapped around the circumference of the needle to increase the surface area of the recording site. The PCB plunge needles as demonstrated do not provide circumferential recording sites, but do provide large recording sites on both sides of the plunge needles, thus coming closer to the circumferential recording technique. Therefore, PCB needles may serve well for

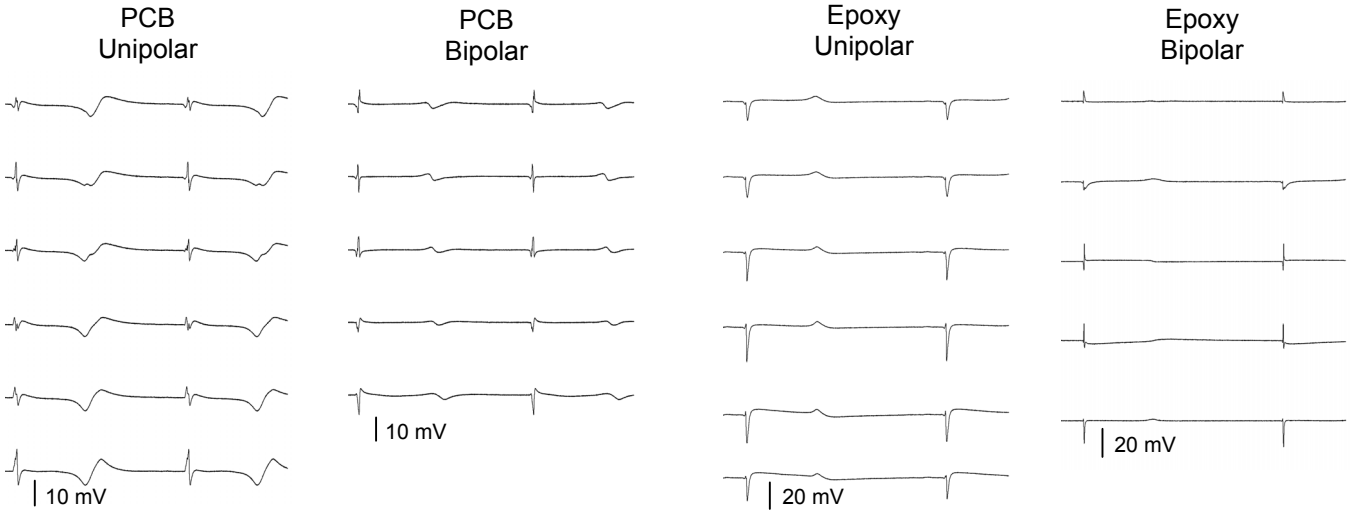

Figure 4 Myocardial activations as recorded by a 6 electrode PCB and fiberglass-epoxy plunge needles. Each recording above is 1 second in length.

Purkinje fiber recording needles.

PCB plunge needles reduce the time required to make plunge needles for a protocol and increase the uniformity of the plunge needles. With protocols requiring over 100 plunge needles, several months of labor to construct plunge needles must be performed. PCB needles substantially reduce the time required to prepare for these protocols.

Plunge needles made with PCBs must be connected with hookup wire to appropriate headers so that they may interface with the mapping system. This process is still labor intensive, but the time required for production of plunge needles for a protocol is reduced by approximately 50% by eliminating the production of epoxy or hypodermic stock needles. Techniques to reduce the time to connect the PCB needles are currently being investigated.

When using plunge needles in defibrillation studies, disruption of the polarization caused by the half cell potential can be an issue immediately after defibrillation shocks. Chloridizing the electrodes can help reduce voltage buildup due to shocks, which can saturate amplifiers and make it impossible for some time to record action potentials that follow large shocks. However, with the PCB plunge needles, the chloridization process has proven difficult. Techniques may be developed to thicken the silver layer on the electrodes so that a silver-chloride layer may be established, but the recovery times and recordings with the silver plated electrodes seem to be sufficient for most plunge needle recording techniques.

Epoxy and hypodermic stock plunge needles are typically built with 3-5 mil silver wire. This wire can cost as much as a US $1 per foot and approximately one foot of silver wire is used per electrode. Therefore, a 12 point plunge needle has a material cost of up to US$12. The PCB plunge needles as shown cost approximately US$2. The price per plunge needle diminishes rapidly when larger numbers of boards are produced.

V. Future Work

The size of the PCB plunge needles should be reduced to minimize the damage done upon insertion of the needles into cardiac tissue. A revised PCB board is currently being manufactured with needles that will be approximately 20x50 mils, which will reduce the displaced volume of tissue by more than 50%. The volume of these new needles will be comparable to the displaced volume of the epoxy plunge needles.

The final finished layer for the PCB electrodes may need future consideration. Since the layer of silver deposited by the immersion silver process is thin (2-5 micro inches), development of a silver-silver chloride interface is not feasible. Additional plating of silver on the electrodes may improve the recording capabilities by allowing for the development of the Ag/AgCl interface. Alternative finish layers of gold are also possible.

Durability studies have not been conducted with these plunge needles. While the needles themselves provide substantial mechanical rigidity, the longevity of the electrode interface and the materials in contact with tissue should be determined.

V. Conclusions

PCB plunge needles provide an option for plunge needle fabrication techniques that is economical in time and cost. Recordings from PCB plunge needles demonstrate clean signals that are comparable to signals recorded by other plunge needles. These needles may enable better plunge needle experiments that shed further light on transmural cardiac activation by reducing time and cost associated with the construction of plunge needles.

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