Cardiovascular Catheter With an Expandable Origami Structure

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Interventional catheter ablation treatment is a noninvasive approach for normalizing heart rhythm in patients with arrhythmia. Catheter ablation can be assisted with magnetic resonance imaging (MRI) to provide high-contrast images of the heart vasculature for diagnostic and intraprocedural purposes. Typical MRI images are captured using surface imaging coils that are external to the tissue being imaged. The image quality and the scanning time required for producing an image are directly correlated to the distance between the tissue being imaged and the imaging coil. The objective of this work is to minimize the spatial distance between the target tissue and the imaging coil by placing the imaging coil directly inside the heart using an expandable origami catheter structure. In this study, geometrical analysis is utilized to optimize the size and shape of the origami structure and MRI scans are taken to confirm the MRI compatibility of the structure.

Materials and Methods

Geometry/Mathematical Model. An optimal shape design for the origami structure was determined by evaluating the geometry and the available space for storing electronics. The symbols given in the following equations are shown in the Nomenclature section. The structure is a square grid comprised of \( n \times n \) smaller individual squares (8 \( \times \) 8 in the prototype displayed in Fig. 1). The height, \( h \), of the fully stowed configuration is limited by the Fig. 1(a) is given by

\[
h = \frac{d}{n}\n\tag{1}
\]

where \( d \) is the diameter of the fully expanded configuration (Fig. 1(d)) and \( n \) is the number of folds across the horizontal or vertical direction. The maximum allowable height of the stowed configuration is considered because the structure could get stuck in the aortic arch if the height is too large. Figure 2(a) shows an MR image of the aortic arch with an overlaid image of the stowed origami structure as it passes through the aortic arch. The area, \( A_s \), of the fully stowed configuration (perpendicular to the axis of the catheter) can be determined by

\[
A_s = (h + t \times 4n)^2\n\tag{2}
\]

where \( t \) is the material thickness. The diameter of the FA limits the maximum allowable stowed area. The surface area, \( A_{fa} \), of the fully expanded configuration is

\[
A_{fa} = \left( \frac{\pi}{4} \right) d^2\n\tag{3}
\]

The diameter of the left atrium (LA) limits the maximum allowable expanded surface area. Figure 2(b) highlights the areas in the FA and LA where the origami structure will be stowed and expanded. The expanded surface area to stowed area ratio, \( R_{as} \), is defined by
It is necessary for this ratio to be as large as possible in order to optimize the shape of the flasher and obtain the maximum achievable signal-to-noise ratio (SNR).

**Mechanical Fabrication.** The expandable origami structure was fabricated by folding a 40 mm × 40 mm sheet of biocompatible polycaprolactone into an iso-area flasher origami pattern [8]. The material properties of the expandable structure allow it to be flexible enough to fold down to fit inside the body vasculature, yet stiff enough to expand once inside the heart chamber. After the structure has been deployed inside the heart and has captured the images, it is pulled out of the heart while still in the expanded configuration. The structure collapses on itself in the process, rendering it unusable for future imaging.

Once the base of the structure was assembled, a coil of 5 mm width copper was applied near the edge of the apparatus in order to form a receiver coil (Fig. 3(a)). Figures 3(b)–3(d) show prototypes of expandable structures containing 2, 4, and 8 imaging coils, respectively, in order to illustrate the potential for parallel imaging using this structure. This simple fabrication method allows for ease of prototyping as well as a straightforward proof of concept.

**Electronics.** The imaging coil was connected to a tuning–matching circuit (Fig. 4(a)) sealed in a box at the proximal end of the stylet through a microcoaxial cable [9,10]. The circuit was tuned and matched based on a single-coil topology to prove the concept of the origami structure incorporated with imaging electronics. A network analyzer was then used to tune the embedded circuit to 128 MHz (3T Larmor frequency) and used to match the circuit to the universal standard of 50-Ω resistance (Fig. 4(b)).

The second-order RLC circuit consists of a resistor that consumes energy and induces a damping effect during the resonance. The energy is stored in the capacitor and inductor, both of which determine the resonance frequency of the circuit. Referring to Ref. [11], the resonance frequency of the system can be written as

\[
f = \frac{1}{2\pi\sqrt{LC}}
\]
where \( L \) and \( C \) are the inductance and capacitance of the circuit, respectively. From Eq. (5) alone, it can be seen that there are infinite combinations of \( L \) and \( C \) to generate a specific resonance value. However, it is worth noting the quality factor, acting as another important consideration of designing the RLC circuit, which can be written as

\[
Q = \frac{1}{R} \sqrt{\frac{L}{C}}
\]  

(6)

A larger \( Q \) value correlates to a larger amount of magnetic energy that can be stored by the micro coil. Therefore, a trade-off between \( L \) and \( C \) need to be made in the tuning–matching of the coil. The \( q \) factor of the imaging coil circuit was calculated to be 8.533.

### MRI Compatibility Test

An MR image that has been negatively affected by the presence of a noncompatible device or object has a lower SNR. Certain devices or objects may not cause artifact disturbances due to either being solely constructed of compatible materials or by virtue of a large physical separation. Active devices (which contain electrically powered components or are otherwise capable of producing electromagnetic (EM) field emissions) can cause SNR reduction if their emitted fields are picked up by the scanner receive coil. Every active component of the system with the intent of being used within the scanner room was tested independently to evaluate its effect on MR image SNR and shielding before the system was tested as a whole.

The implemented test method was adapted from the protocol put forward by Chinzei et al. [12] for electrical and electronic components. According to the standard defined by Chinzei et al., the acceptable level of SNR reduction is up to 10%. However, this value is intended as a guideline rather than a strict qualifier of compatibility. In practice, the acceptable level of SNR reduction is dependent on the intended method of application. A very low degree may be required for the determination of soft tissue boundaries from an image, but a much less stringent requirement may be necessary for image guided gross positioning of instruments.

The implemented test method was conducted as follows:

1. A container was filled with \( \text{CuSO}_4 \) solution (1.25 g/l concentration) and scanned with a spin echo and a gradient echo sequence; these images were used as the control image. The image sequence parameters must be maintained constant throughout the duration of the subsequent testing.
2. The origami structure was placed next to the phantom without power connected and the phantom was scanned with the same scan sequence combination.
3. In the same configuration, a further scan was taken with the origami structure closed and connected to the scanner.
4. In the same configuration, a further scan was taken with the origami structure expanded and connected to the scanner.
5. DICOM format images were produced. The SNR of an image is calculated using Eq. (7), where \( P_{\text{center}} \) is the mean signal of a 40 x 40-pixel region at the center of the phantom image and \( SD_{\text{corner}} \) is the standard deviation of the signal of a 40 x 40-pixel region at the corner of the image. The variation of SNR is calculated by subtracting the SNR value of the corresponding control image.

\[
\text{SNR} = \frac{P_{\text{center}}}{SD_{\text{center}}} 
\]  

(7)

The method requires the origami structure in the bore to be connected to the scanner with the flasher actuated at different stages (e.g., stowed and expanded). As such, the full system including the auxiliary tuning and matching electronic hardware must be included in the scanner room during the test.

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**Fig. 4** (a) Circuit diagram of the tuning–matching circuit. The circuit was tuned based on a single-coil topology to prove the concept of the origami structure incorporated with imaging electronics. (b) Network analysis displaying the reflection efficiency of the coil resonance frequency tuned to 128 MHz for 3T Larmor frequency.

**Fig. 5** Plots displaying (a) stowed height, (b) stowed area, and (c) expanded surface area against expanded diameter and the number of folds contained across the width of the structure.
**Results**

**Geometry/Mathematical Model.** The geometric evaluation of the expandable origami structure was used to create a mathematical model for determining the optimal dimensions of the structure. Figure 5 shows plots displaying the relationship of height \( h \), stowed area \( A_s \), and expanded surface area \( A_e \) to the expanded diameter and the number of folds. Using these plots, we can define the ideal shape of the expandable structure based on the curvature of the aortic arch, the inner diameter of the guide catheter, and the diameter of the LA. The average diameter of the FA at the hip is approximately \( 8.2 \pm 0.14 \text{ mm} \) [13]. The average diameter of the LA is approximately 27–38 mm in women and 30–40 mm in men [14]. Using these data, we can find appropriate values for the height \( h \), the stowed area \( A_s \), and the expanded area \( A_e \) using Eqs. (1)–(3). \( h \) is calculated from Eq. (1) to be 4.25 mm using an estimated diameter \( d \) matching that of the 34 mm average diameter of the LA in humans [14] and using \( n = 8 \) as in the prototype shown in this report. \( A_s \) is calculated via Eq. (2) to be an estimated 196 mm\(^2\) using a material thickness \( t \) of 0.25 mm. \( A_e \) is calculated via Eq. (3) to be approximately 1120 mm\(^2\) (Fig. 6). The expanded

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**Fig. 6 Instructions for folding expandable origami structure:** Step 1: Cut out a circular sheet of paper. Step 2: Fold the four horizontal valley (HV) folds and the three horizontal mountain (HM) folds. Step 3: With the same sheet of paper and in the same orientation, fold the four vertical mountain (VM) folds and the three vertical valley (VV) folds. Step 4: Fold VM3 to VM2. Step 5: Fold HM2 down to HM3. Step 6: Turn over to bottom side. Step 7: Fold top half of back vertical mountain 2 (BVM2) to back vertical mountain 3 (BVM3). Step 8: Turn over to top side and pull left and right halves of HM2 apart until top layers separate from underlying layer. Step 9: Fold right half of HM2 to HM1. This should form a central square under the first layer of folds (illustrated in yellow box). Step 10: Fold HM2 to VM3 and fold HM3 and VM4 together between them, forming the diagonal bottom right (DBR) fold. Step 11: Fold HM2 to VM2 and fold HM1 and VM1 together between them, forming the diagonal top left (DTL) fold. Step 12: Turn over. Step 13: Fold back horizontal mountain 2 (BHM2) to BVM2 and fold BHM1 and BVM1 together between them, forming BDTL. Step 14: Fold BHM3 to BVM2 and fold BHM4 and BVM3 together between them, forming BDBR. Step 15: Push the outside corners together and keep orientation of previous folds. Step 16: Continue pushing corners together until top and bottom edges come together.
surface area to stowed area ratio \( R_p \) is therefore estimated to be 5.71 using Eq. (4) (Table 1).

MRI Compatibility Test. The SNR reduction of the expandable origami structure was examined. The experiment was conducted in a 3T Siemens MRI scanner. The results are shown in Fig. 7. The maximum SNR reduction in the origami catheter was 0.54% with the turbo spin echo (TSE) sequence, and 0.46% with the True fast imaging with steady-state free precession (True FISP) sequence. Even though the SNR reduction varies in different scan conditions, they are all within the acceptable level of 10% proposed by Chinzei et al. [12], showing good compatibility of the individual components. This experiment demonstrates the usability of the expandable origami structure with its individual electronic components in the MR environment.

Discussion

Treatment of cardiac arrhythmia through catheter ablation can permanently resolve the condition and significantly improve patients’ quality of life. The expandable origami structure for storing MRI imaging coils on the tip of a catheter offers an improved method for treatment of cardiac arrhythmia, but further studies are required to validate the safety and the capabilities of the structure. The expandable structure must be able to integrate with the catheter through either some effective means of attachment or through direct fabrication of the two parts as one. In vivo animal trials and human pilot studies must be conducted to confirm the devices ability to safely deploy inside the LA and safely retract from the body. The shape of the structure will be compared to other potential shapes to determine the safest structure. For example, a voluminous structure could potentially offer more safety as opposed to a flat structure, because it would not contain sharp edges. Further

Table 1: Origami structure versus mechanical constraint case study

<table>
<thead>
<tr>
<th>Structure dimension</th>
<th>Mechanical constraint</th>
<th>Calculated value</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H ) (height)</td>
<td>Aortic arch curvature</td>
<td>4.25 mm ( ^1 )</td>
<td>(1)</td>
</tr>
<tr>
<td>( A_s ) (stowed area)</td>
<td>FA inner diameter</td>
<td>196 mm(^2 )</td>
<td>(2)</td>
</tr>
<tr>
<td>( A_e ) (expanded area)</td>
<td>LA inner diameter</td>
<td>1120 mm(^2 )</td>
<td>(3)</td>
</tr>
<tr>
<td>( R_p ) (area ratio)</td>
<td>FA and LA inner diameters</td>
<td>5.71</td>
<td>(4)</td>
</tr>
</tbody>
</table>

MRI scans must be performed to validate the devices ability to perform real-time cardiac imaging.

Conclusion

This work presents the design of a novel expandable origami mechanism that aims to assist in diagnostic and therapeutic stages of EP treatments. The expandable structure was developed by folding a thin sheet of biocompatible polycaprolactone into an iso-area flasher and the embedded electrical circuit was constructed by applying imaging coils around the structure. The circuit was tuned and matched via network analysis to the Larmor frequency of a 3T MRI at 128 MHz. Equations relating expanded surface area and stowed area are derived from basic geometry in order to optimize the shape of the flasher based on patient anatomy. SNR reduction results demonstrate that the imaging coil is MRI compatible. Future experiments performing actual cardiac imaging is required to validate the efficacy of the device.

Acknowledgment

This material is based upon work supported by the National Science Foundation (NSF) REU site program 1359095 and the University of Georgia–Augusta University seed grants.

Nomenclature

\( A_s \) = surface area of the fully expanded configuration

\( A_e \) = area of the fully stowed configuration (perpendicular to catheter axis)

\( C \) = capacitance

\( d \) = diameter of the fully expanded configuration

\( f \) = frequency

\( h \) = height of the fully stowed configuration

\( L \) = inductance

\( n \) = number of folds across the horizontal or vertical direction

\( P_{center} \) = mean signal of a 40 \( \times \) 40 pixel region at the center of the phantom image

\( Q \) = quality factor

\( R \) = resistance

\( R_p \) = expanded surface area to stowed area ratio

\( SNR \) = signal-to-noise ratio

\( SD_{center} \) = standard deviation of the signal of a 40 \( \times \) 40 pixel region at the corner of the image

\( t \) = thickness of material

References


