Comparison of Optimization Algorithms for a Tubular Aspiration Robot for Maximum Coverage in Intracerebral Hemorrhage Evacuation

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INTRODUCTION

Non-aneurysmal intracerebral hemorrhage (ICH) is a significant burden to quality of life, society, and life itself. It comprises approximately 20% of all strokes with 40% and 55% median mortality rates at 30 days and 1 year, respectively [1]. The current standard of care consists of conservative medical management and treatment of any risk factors for repeat hemorrhage or progression (e.g. hypertension, coagulopathy). Many studies have addressed the role of surgery in intracerebral hemorrhage [1]. There appears to be a significant benefit in highly selected patients, especially those in which the hematoma comes close to the surface and is in the supratentorial compartment. Additional injury to the brain might occur in reaching the hemorrhage surgically as they are frequently in eloquent regions.

The ability to reach these hematomas through a trajectory that minimizes disruption of healthy brain and also allows for a dexterous aspiration within the hemorrhage is desirable. This may allow for decompression or removal of the hematoma and possibly salvaging the penumbra of at risk brain surrounding the lesion. A promising enabling technology are smaller, yet dexterous surgical manipulators and robots [2]. Tubular manipulators, also known as active cannulas [3], are particularly well suited for ICH surgery [4]. In this system, the needle-sized manipulator reaches the hemorrhage on a straight path. The curved inner tube allows debulking of the accumulated blood from within by coordinated motion during aspiration. By using differently curved aspiration tubes subsequently, the majority of the hemorrhage can be evacuated in a minimally invasive manner. Based on our initial results presented in [4], we introduce two new and less computationally intensive optimization methods to select aspiration tubes maximizing the volume coverage.

MATERIALS AND METHODS

The tubular aspiration robot is composed of a stiff guide tube, which is straight in order to reach the hemorrhage. An aspiration tube, which is superelastic (NiTi) with diameter 1mm, is inserted through the guide tube. It is composed of a straight section followed by a precurved section with constant curvature (see Fig. 1). The robot has 3 degrees of freedom (DOF): translation of the guide tube, translation and axial rotation of the aspiration tube. The kinematics of this robot has been described in [4] and allows computation of the shape of the robot for a given set of actuator values q=(α,β_1,β_2).

In this paper, we consider preoperative coverage planning. This planning problem is performed on 3D surface data representing the hemorrhage of the patient, obtained from computed tomography images and a straight entry path from the skull to the hemorrhage defined by the surgeon. We have shown that subsequent use of aspiration tubes with different curvatures leads to good coverage of the hemorrhage volume [4]. Thus, the optimal selection is performed from a set of potential tubes parameterized by the radius of the curved section $S = \{r_1, \dots, r_n\}$ and $L_c = r\pi$ (Fig 1). The goal of optimal coverage planning is to find a subset $S^* \in S$ with k aspiration tubes, which maximize the volume coverage of the hemorrhage. k can be predefined or incremented during planning until the clinically desired coverage is achieved. We quantify the covered volume as the ratio between the number of voxels (unit volume 1mm^3) reachable with the aspiration tube's tip and the overall number of voxels representing the hemorrhage (see [4]).

We previously presented a brute force algorithm [4], which determines the coverage for all possible combinations of k tubes in S and chooses S^* as the combination with maximum coverage. For large k and n this combinatorial optimization problem increases in complexity by $O(n) = n!\,(k!\,(n-k)!)^{-1}$. Thus, we propose two alternative algorithms in this paper.

The first is a greedy algorithm, which initially selects r_1 with the best coverage from S. In the second step, S is reduced to $n-1$ elements and r_2 with best coverage is selected out of S and so on. Thus, the number of combinations is reduced compared to the brute force

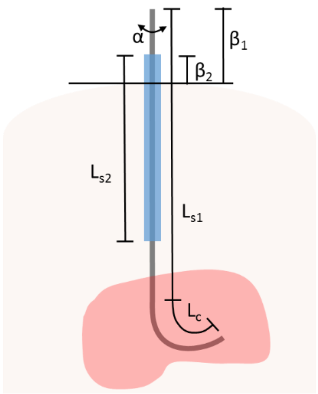

Fig. 1 Tubular aspiration robot with 3 DOF (α, β_1, β_2). Design parameters are tube lengths (L_{s1}, L_{s2}, L_c, and r).

algorithm with complexity $O(n) = \sum_{i=n-(k-1)}^{n} i$. For $k = 1$ the greedy algorithm achieves the same result as the brute force method.

Our second algorithm approximates the optimal tube radii based on our empirical results obtained with the brute force algorithm. This approximation algorithm does not involve computation of coverage during the selection as it uses a heuristic to determine the aspiration tubes radii. Here, we select the first tube with radius closest to half of the hemorrhage's extent in direction of the entry path. The second and third tube will be selected with smaller radii than the first aspiration tube (decremented in 1mm steps). The computational complexity is reduced to $O(n) = 1$.

We evaluated the performance of all 3 tube optimization algorithms on 8 representative patient ICH cases. Fig. 2 illustrates the 3D surface models of the hemorrhages. For each case we randomly generated 5 straight entry paths from a random position on the skull surface to the centroid of the hemorrhage volume. Thus, we obtained a total of 40 trials. For each trial, we determined the coverage achievable for an initial set of tubes $S = \{6,7,8,9,10,11,12,13,14,15,16\}$, L_{s1}=300, L_{s2}=140 (in mm), and for $k = \{1,2,3\}$ using each optimization algorithm.

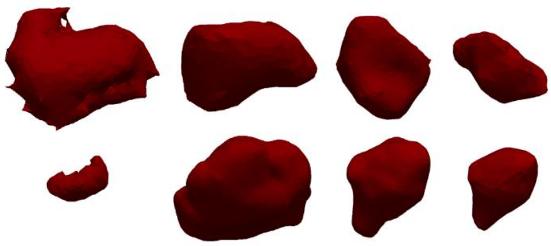

Fig. 2 Intracerebral hemorrhage geometries for 8 patient cases.

RESULTS

The coverage distribution over all 40 trials for the brute force, greedy, and approximation algorithms are summarized in histograms in Fig. 3-5 for 1, 2, and 3 tubes respectively. For all 40 trials, a volume coverage over 50% can be reached, which is considered clinically beneficial. It can be observed, that the concentration shifts significantly from 70-80% coverage with 1 tube to 80-90% with 2 tubes. The usage of 3 aspiration tubes allows for coverage mostly over 80%. The greedy algorithm leads to comparable results to the brute force method.

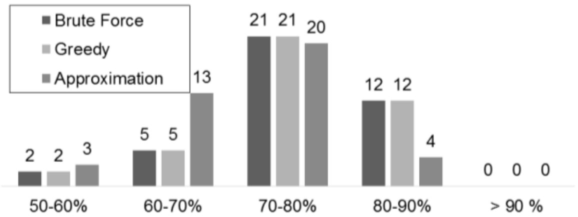

Fig. 3 Coverage distribution for $k = 1$ aspiration tube.

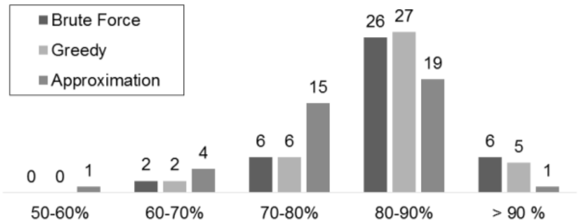

Fig. 4 Coverage distribution for $k = 2$ aspiration tubes.

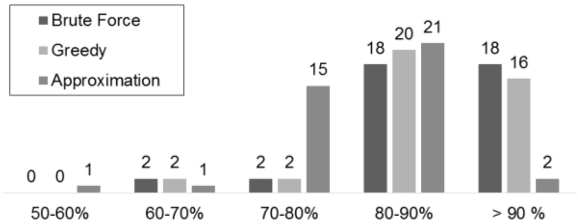

Fig. 5 Coverage distribution for $k = 3$ aspiration tubes.

In terms of computation time, brute force takes about 10 min, greedy about 22 s, and approximation algorithm about 6 s for one case on a regular PC (Matlab).

DISCUSSION

In this paper, we introduced two alternative optimization algorithms to determine a set of aspiration tubes, which maximizes coverage for evacuation of intracerebral hemorrhages. Our results indicate that 1 to 3 tubes selected from an overall set of 11 precurved aspiration tubes result in clinically significant coverage. The approximation algorithm may be favorable in those clinical cases with no time for preoperative planning.

Our current work focuses on computing an optimal motion plan (i.e. sequence of actuator values) for the selected aspiration tubes which allows for quick and safe evacuation of the hemorrhage in vivo. Extensive animal trials will be needed in the future to show clinical feasibility. Ultimately, we expect improved surgical outcome for patients suffering from intracerebral hemorrhages.

ACKNOWLEDGEMENT

This research was supported under NIH award R21 NS087796. The authors thank T.-D. Nguyen from the Center of Mechatronics for data processing.

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