Auditory Support for Resection Guidance in Navigated Liver Surgery

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Background An alternative mode of interaction with navigation systems for open liver surgery was requested. Surgeons who use such systems are impeded by having to constantly switch between viewing the navigation system screen and the patient during an operation.

Methods To this end, an auditory display system for open liver surgery is introduced with support for guiding the tracked instrument towards and remaining on a predefined resection line. In order to evaluate the method, a clinically orientated user study with 12 surgeons was conducted.

Results Qualitative results from the user study show that the proposed auditory display is recognized as a useful addition to the current visual mode of interaction. A statistical analysis revealed that participants spent less time looking on the screen (10 % versus 96 %). Accuracy for resection guidance was significantly improved when using auditory display as an additional information channel (0.6 mm versus 1.4 mm), however, the overall time for the resection task was shorter without auditory display (47 sec versus 24 sec).

Conclusions By reducing dependence on the visual modality during resection guidance, the auditory display is well suited to become integrated in navigation systems for liver surgery.

Keywords: computer-assisted surgery; surgical navigation; liver surgery;

Introduction

Surgical navigation systems provide intraoperative assistance by displaying surgical instruments in relation to preoperative planning data of the liver [1–4]. Similar technology has already exhibited good results in orthopedic surgery and neurosurgery. The navigated resection of tumors in the liver enables a higher degree of precision and could lead to smaller resection volumes, more frequent tumor-free margins, and thus, improved outcomes [5]. However, surgeons frequently need to consult the navigation system, which leads to increased mental load and time pressure during surgery [6]. Viewing the navigation system’s screen interrupts the surgeon’s attention to the working area.

The purpose of this work is to integrate concepts from the field of auditory display to enhance intraoperative visualizations for navigated liver surgery. Auditory display is applied as an additional information channel. It might reduce the dependence on the visual display. Thereby, it frees the eyes for other tasks, and provides high temporal resolution and fast processing [7].

Although auditory alarms and monitoring devices are commonplace in operating rooms, audio has been a neglected modality in navigated surgery. During liver resection, the auditory channel is
relatively unused by the surgeon, and thus is more open to provide information that supplements or complements the visual display.

This work presents a solution for a primary problem in navigated liver surgery: the overburdened dependence on the visual display during resection guidance. This work focuses on marking the resection path on the liver surface. The resection marks help determine the subsequent cut path through the liver parenchyma. Until now, resection guidance has been supported solely by visual displays.

Related Work

Despite research in the field of alarms and auditory status monitoring [8, 9], only a few papers describe auditory display which support navigated surgical tasks. To the knowledge of the authors, only two groups have developed auditory displays for this field.

Wegner et al. [10, 11] introduced a navigation system for the blind placement of a biopsy needle. Based on an electromagnetic tracked needle, surgeons attempted to follow a planned trajectory within a custom gelatin phantom with an embedded target. Three relevant methods are described in their papers: a beat interference method for which two sinus waves (one with fixed, the other with varying frequency) are mapped to the positional error in one spatial dimension, an auditory distance measurements where at each millimeter an audible click is triggered, and a 2D wave table to explore surface characteristics of anatomical 3D model. Although the proposed methods by Wegner et al. showed great potential, formal evaluations were not reported in literature.

A group from the University Medical Center in Utrecht, Netherlands presented auditory display for resecting a floral foam phantom meant to simulate brain tissue [12] and later for operation on six actual patients [13]. When the tracked instrument approached the tumor, the system produced a pure tone with a duration of 0.1 seconds emitted approximately 3 times per second. Frequency and amplitude of the tone increased when approaching the target. The resection using auditory display was compared to resection with visual-based navigation (using a computer monitor for display) and with a heads-up display [12]. Resection quality and resection time did not significantly differ in results between interaction with auditory display and visual display. In clinical tests, the auditory display was employed on 6 patients and evaluated on instrument handling during the course of surgery. The study results showed that the speed of the instrument tip was not significantly faster when using auditory support. However, in both studies, participants felt that they performed better when auditory feedback was added because they could focus more on the working area.

Materials and Methods

This section describes an auditory display for image-guided liver surgery. First, the existing navigation system, the underlying planning data, and the auditory feedback engine are described. Second, a novel method for auditory resection guidance is introduced. Third, the performed evaluation of the developed auditory display is described.

Navigation System: CAS-One

The CAS-One surgical navigation system (CAScination AG, Switzerland) is used within this project to visualize planning models relative to tracked surgical instruments. CAS-One provides visual support during liver resection and has been evaluated in the context of clinical trials [4]. The system consists of an infrared-based optical tracking system (Vicra, Northern Digital Inc., Canada), an ultrasound device, a touchscreen, and a computer unit. A rigid body with passive markers is intraoperatively mounted on surgical instruments (ultrasound and dissector), or on a pointer for laboratory experiments. Landmark-based registration is applied during the first phase of the procedure, so that the modalities of the physical patient and 3D planning model align.

The planning models are generated from CT or MRI scans acquired from the patient’s liver using planning software for liver surgery [14]. Besides anatomical 3D models of the liver, the planning
model includes relevant functional information such as a virtual resection surface [15]. One element of the virtual resection surface is the resection line (on the organ surface), which is used within the evaluation of this work.

**The Auditory Feedback Engine**

Two development platforms were chosen, MeVisLab [16] for medical image processing framework and SuperCollider [17] for audio synthesis. The developed prototype application was independently implemented from the certified navigation software. All necessary visualizations for navigation support including the representation of tracked instruments and 3D planning models were provided by a customized MeVisLab application installed on the navigation system. In addition, the application continuously sends distances and information about associated object entities to the SuperCollider engine using the OSC (Open Sound Control) protocol. In the following subsection, a novel method for auditory resection guidance is presented.

**Auditory Resection Guidance**

For complex liver operations, resection surfaces are preoperatively defined using surgical planning software. Intraoperatively, surgeons aim to resect according to these plans with the help of surgical navigation systems. Before cutting the liver, the resection path is marked on the organ surface. An accurate marking of the resection path is a decisive factor for the quality of the resection as a whole. The marks provide orientation aid during the relatively long cutting phase (≈ 1-2 hours) and thus impact the subsequent cut path through the liver parenchyma.

The proposed auditory feedback for resection guidance is a function of \( \delta \), where \( \delta \) describes the distance between surgical instrument tip and the nearest point on the planned resection line. A precomputed Euclidean distance transformation provides \( \delta \) for each position in the patient dataset. Thus, \( \delta \) can be accessed by the auditory feedback engine in constant computation time.

The distance from the instrument tip on either side of the resection line is divided into three margins:

- **safe**,  
- **warning**,  
- **and outside**.

The first margin, called safe, is located on both sides of the resection line. When the instrument tip is in this margin, it is permissible for the surgeon to resect or mark. The second margin, the warning range, is located outside of the safe margin and reaches from the outer border of the safe range to the warning-range width. When the instrument tip is located in this margin, the surgeon is roughly near the planned resection line but not close enough for a safe resection marking. Finally, the outside margin includes all distances that are further from the resection line than the outside width of the warning margin. The distances for the safe and warning margins can be set by the surgeon or planning staff depending on the surgical situation.

To communicate the presence of these different margins and to direct the surgeon towards the resection line, two tones for auditory resection guidance are proposed which correspond to both the safe and warning margins. When the instrument tip is in the safe margin (0 ≤ \( \delta \) ≤ safe width), signifying that it is permissible to mark the resection line, the safe tone is produced. When the tip is in the warning range (safe width < \( \delta \) ≤ warning width), the warning tone aids the surgeon in directing the instrument tip to enter the in-range margin. When the instrument tip is in the outside margin (warning width < \( \delta \)), no tone is produced. The combination of both warning and confirmation tones provides the user with a way of both locating and remaining on the planned resection line.
Prior Work

Based on our prior work in the field of auditory display [18, 19] a refined resection guidance model is introduced. Within this prior work, different auditory display models for resection guidance have been developed. These first models ranged from very simple ones using only a single modulated sine wave, to more complex models that features banks of digital resonating bodies, to ones that modeled real-life sounds such as ringing bells. A preliminary user study was carried out, first to provide a general consensus on whether or not auditory display would be beneficial for navigated liver surgery, and then to gather clinicians’ opinions regarding the functions and aesthetics of a range of exploratory auditory display models. The study revealed that auditory display was recognized by a majority of surgeons to be a useful addition to the visual interaction with the navigation system. A systematic analysis of user comments confirmed that the auditory feedback also combated main limitations of the current navigation system, i.e., the dependence on the visual display and the lack of notification when approaching risk structures. In addition, the meaning of the sound and the interaction with the system were easily learned within less than two minutes of training. The second aim of these preliminary studies was to gather comments about a selection of different auditory display models for resection guidance. Comments regarding these first models were used in the development of the refined resection guidance model.

A Refined Resection Guidance Model

As part of the process of continual evaluation and refinement, the most popular elements of the exploratory resection guidance sound models were used to create a single model that could be used for the quantitative evaluation described in this paper. The concept of this model is broadly similar to a Geiger counter in that the inter-onset interval of a series of very short auditory events is one parameter that is mapped to the urgency of a situation. In the case of resection guidance, an increase in distance from the planned resection line causes an increase in urgency.

Safe Margin Tone  When the instrument tip is in the safe margin, a “safe margin tone” is produced to guide the surgeon to $\delta = 0$ and to inform that it permissible to mark the resection at that point. The safe margin tone consists of two elements. First, a two-pole resonant filter with a frequency of 698.5 Hz $^1$ and a 60 dB decay time of 1.0 second is triggered repeatedly at a variable inter-onset interval. At a distance of $\delta = 0$, this inter-onset interval is 0.66 seconds, and at the edge of the safe margin, the interval is 0.18 seconds. By moving the instrument tip so that the inter-onset interval is longer, the surgeon is guided towards the planned resection line. Second, a bank of sine oscillators with frequencies of 220.0, 261.6, 349.2, 440.0, and 523.3 Hz $^2$ is produced when $\delta = 0$ and muted at all other distances. Thus, this confirmation element informs the surgeon when it is optimal to mark the line.

Warning Margin Tone  When the instrument tip is outside the safe margin, a warning margin tone helps guide the surgeon towards the safe margin. Similar to the safe margin tone, a series of repeating two-pole resonant filters are employed. In this model, three primary auditory characteristics are used to relay distance information and thus convey a sense of urgency (see [20]) when approaching the outside of the warning margin and a sense of calm when approaching the safe margin. Each of these variables varies linearly over $\delta$.

Inter-Onset Interval  The inter-onset interval times of the triggered resonators varies with distance. At the inside edge of the warning margin, the interval is 0.33 seconds , and at the outside edge, the interval is 0.09 seconds.

$^1$corresponding to MIDI note 77

$^2$corresponding to MIDI notes 57, 60, 65, 69, and 72
Tone Length  The 60 dB decay time of the resonating tones varies with distance. At the inside edge of the warning margin, the decay time is 1.0 second, and at the outside edge, the decay time is 0.5 seconds.

Pitch  The pitches of the resonators relay both distance and the side of the resection line in which the instrument tip is located. Moving the tracked instrument to the left of the resection line causes the tones to rise in pitch. Directly at the left inside edge of the warning margin, the pitch of the resonator is 784.0 Hz and over the width of the warning margin increases to 880.0, 1046.5, 1174.7, 1396.9, 1567.9, and 1760 Hz. Moving to the right of the resection line causes a fall in pitch. Directly at the right inside edge of the warning margin, the pitch of the resonator is 587.3 Hz and over the width of the warning margin decreases to 523.3, 440.0, 392.0, 349.2, 293.7, and 291.6 Hz.

The combination of onset frequency, tone length, and rising and falling pitch relay to the surgeon both the distance to the resection line and which side of the resection line the tracked instrument occupies. By moving the instrument back and forth across the safe and warning margins, the surgeon should be able to use these auditory cues to place the instrument tip directly on the planned resection line and be aware when the instrument deviates from the optimal planned line.

Evaluation

The objective of this work is to evaluate the suitability of auditory display as an enhancement to visual display in navigated liver surgery. Therefore, a clinically oriented study was conducted in which participants were asked to accomplish surgical tasks on a special manufactured 3D liver phantom. User performance was evaluated quantitatively by analyzing instrument movement and aspects of human-computer interaction.

Liver Phantom

Because an evaluation of the new interaction techniques would not be fruitful unless physical representations of a human liver were present, a CT liver dataset with segmented anatomical structures was used to create a stereolithographical model of the liver. This liver phantom only includes an outer shell with a cuboid cavity in the front to enable access to the interior with the tracked instrument. A piece of floral foam (mosy colorfoam) was trimmed to fit inside this cavity to provide tactile resistance to the tracked instrument during testing (Fig. 1a). The phantom was mounted on a wooden board together with a trackable marker shield, which allowed for easy calibration with the navigation system’s camera.

Reference Criteria

Appropriate reference criteria for the evaluation were found by an analysis of which characteristics of the auditory display could potentially improve the surgical workflow of open liver interventions. The dependence on the visual display, which is a primary problem, was observed during the study. In addition, the movement of the instrument tip was compared. The following reference criteria were defined:

- Total time participants looked at the screen relative to looking at the phantom
- Time needed to draw the resection line
- Mean distance between planned resection line and subject-drawn resection line

3corresponding to MIDI notes 79, 81, 84, 86, 89, 91, and 93
4corresponding to MIDI notes 74, 72, 69, 67, 65, 62, and 60
Figure 1: (a) Liver phantom with floral foam (green) inside and (b) virtual 3D model of the liver and planned resection line (red) visualized on the navigation system’s display.

Experiment Design

The tests were performed in a clinical environment with 12 surgeons from the Robert-Bosch Hospital in Stuttgart, Germany. The liver phantom was affixed to an examination table. Participants were asked to stand next to the liver phantom. The navigation systems display was placed on the opposite side of the table, as common during clinical interventions which employ video displays (see Fig. 2).

First, two training tasks had to be performed by the participants. Therefore, a red resection line and a 3D model of the liver phantom were displayed on the navigation system’s display (see Fig. 1b). Participants were asked to transfer the resection line visualized on the video monitor to the liver phantom by lightly marking the path on the floral foam using a pointer whose position was tracked by the navigation system. Participants were instructed to look at the video monitor only if necessary, and to concentrate on the surgical instrument and the liver phantom. One training task was to be
performed without auditory support (visual only) and the other training task with auditory support (combined condition).

Second, eight test tasks had to be performed by the participants. Thereby, four resection lines (with the 3D model of the liver phantom) were separately presented two times on the screen of the navigation system. The test tasks were divided into two groups: While four tasks \( V_1 - V_4 \) did not make use of auditory display (visual only), the other four tasks \( A_1 - A_4 \) presented both visual and auditory displays (combined condition). The presentation of these test tasks occurred in random order. In order to reduce the memory effect, a randomization algorithm was chosen which prohibited two test tasks with the same resection line to be performed in succession.

Before starting each test, participants were informed of the group to which the upcoming test belonged. Participants were further asked to look at the video monitor only when necessary. After marking the resection line on the foam, participants were asked to draw the final resection line a second time. The position and orientation of the pointer were recorded during the whole experiment. In addition, all tests were recorded with a video camera.

Third, each participant completed a questionnaire consisting of personal questions (age, gender, handedness, surgical experience . . . ) and statements for which the participants chose the degree to which they agreed or disagreed.

Analysis

A post-experiment video analysis provided the timing data for subjects’ looks at the screen or the phantom, respectively. These data were used to construct the time budget data and the mean times between changes of looks between phantom and screen.

Data for marking accuracy was sampled using the tracking mechanisms of the navigation system. The distance \( \delta \) between the pointer tip position and the nearest point on the resection line was calculated for each sample. Because these samples were taken in equal temporal distance, arithmetic means of \( \delta \) would be skewed by different drawing speeds. When, for example, a subject would not move the tracked pointer at all, remaining in a position with low \( \delta \), the data with low \( \delta \) would accumulate over time and thus overrepresent a low \( \delta \) in the mean. Therefore, the mean distance between planned resection line \( I_p \) and subject-drawn resection line \( I_d \) was introduced as a benchmark for marking quality. Given the arclength \( s \) on \( I_d \), the mean distance is defined in the continuum as:

\[
\frac{1}{L} \cdot \int_{I_d} \delta(s) ds, \text{ where } L = \int_{I_d} ds \text{ is the total length of } I_d.
\]

Statistical analysis was performed with the software environment R (www.r-project.org) and consisted of comparisons of the arithmetic means between data for the auditory and visual conditions. We tested differences using the Wilcoxon test and defined a \( p < 0.05 \) as statistically significant (n=12).

Results

For all reference criteria, we found differences between the visual and combined conditions. For the visual only condition, subjects looked approximately 96% of the time at the screen. This time was reduced to around 10% for the condition where the auditory signal was additionally available (Fig. 3a).

When the additional auditory information was available to the subjects, deviation from the planned resection line was smaller than with the visual information alone (Fig. 4b). However, subjects could not mark the resection line as fast, when relying on the auditory information as opposed to the visual display only (Fig. 5).

Qualitative data for this evaluation was gathered from both voluntary comments from the participants as well as a questionnaire filled out by each participant. From this data, the direction of future development may be guided. Table 1 lists each statement and the average response and standard deviation.
Figure 3: Proportion of time looking at screen for combined condition (min = 0.00, 1st qu. = 0.03, median = 0.10, 3rd qu. = 0.23, max = 0.30) and visual condition (min = 0.90, 1st qu. = 0.93, median = 0.96, 3rd qu. = 0.96, max = 0.99), n = 12, p < 0.00043.

Figure 4: Mean distance [mm] between planned resection line and subject-drawn resection line for combined condition (min = 0.31, 1st qu. = 0.53, median = 0.68, 3rd qu. = 1.00, max = 1.62) and visual condition (min = 0.36, 1st qu. = 0.85, median = 1.48, 3rd qu. = 2.19, max = 4.00), n = 12, p < 0.00245.
Figure 5: Mean time per task for combined condition (min = 29.49, 1st qu. = 38.95, median = 46.76, 3rd qu. = 63.97, max = 73.17) and visual condition (min = 13.88, 1st qu. = 18.58, median = 24.56, 3rd qu. = 28.09, max = 31.49), n = 12, \( p < 0.000004 \).

**Discussion**

The clinically oriented tests that were performed in the context of this work revealed that auditory feedback could be a beneficial extension to surgical navigation systems. However, tests during surgical interventions have to still be performed in order to further adapt the proposed sound model for clinical routine. Specifically, the effects of environmental sounds such as speech, cutting, or warning signals from anesthesia devices on the surgeons’ interaction and recognition of the auditory display must be evaluated.

Overall, the qualitative questionnaire showed that the subjects found the approach of using auditory display for resection marking as promising and well suited for the task. Surgeons requested aesthetically pleasing sounds that could be tolerated to hear over a time range long enough for surgical tasks. However, it is difficult to discover sound models that meet these requirements as well as providing the required resection guidance support in a clear way. An adequate variety of sound models might be provided to give surgeons a choice of equally functional sound models. In addition, these sound models might be made easily configurable for surgeons or assistants to improve acceptance and reduce possible annoyance. Moreover, industrial standards such as IEC 60601-1-8 for alarms in medical equipment [21] have to be taken into account in order to meet legal requirements for audio in operating environments.

In our evaluation, the auditory display significantly reduced the time that surgeons looked on the navigation system screen. Simultaneously, the auditory display reduced the mean distance to the planned resection line. However, the mean time needed for each task was almost doubled. Thus, our auditory display reduces the dependency on the visual display and increases accuracy, albeit at the cost of task completion time.

One contributing factor for this increase in task completion time could be that the auditory display alerted the surgeon when leaving the safe margin. This auditory notification may have caused a more cautious (but also more accurate) marking of the resection line than without having this information. A second contributing factor could be the new introduction of the auditory display to the subjects, many of whom had experience working with visual navigation systems but none with auditory displays. When using the visual display alone, the interaction with the system was similar to using a computer mouse, because the position and movements of the on-screen instrument directly corresponded to those of the physically tracked instrument. Due to the novelty of our method, a
The sounds could be heard well 3.92 (±0.29).
The sounds were appropriate for the operating situation 3.25 (±0.75).
The meaning of the sounds was clear 3.67 (±0.65).
The system was intuitive 3.58 (±0.67).
The audio feedback matched the visual feedback 3.42 (±0.67).
The interaction was fun to use 3.58 (±0.90).
The sounds helped me concentrate on the resection task 3.58 (±0.90).
The sounds reduced my dependence on the visual display 3.17 (±0.83).
I would use the sound feedback in my surgical task 3.33 (±0.65).
I would recommend this to a colleague 3.33 (±0.65).

Table 1: Results of the questionnaire with chart showing average responses and standard deviation (SD), with a response of 1 corresponding to “strongly disagree” and a response of 4 corresponding to “strongly agree”.

longer and more intense training period would likely reduce the task completion time. Conversations with test surgeons revealed that longer task times are not necessarily a negative effect if these longer times accompany an increase in concentration. In the qualitative questionnaire, most subjects agreed that the auditory display helped to concentrate on the resection task.

A third contributing factor to increased task completion time could be the study conditions, which did not exactly match the situation of an actual liver resection. Although the task to mark a resection line on a liver phantom is similar to resection marking on a real human liver, one important difference is that during real liver surgery it would be irresponsible to mark a resection line on the liver by looking nearly 100% of the time at the screen, as several subjects did during our tests. Therefore, it could be assumed that during actual liver surgery the time looking at the screen decreases, while the time to mark a resection line increases. For further laboratory studies, the study design should consider conditions that stimulate participants to look more often at the liver phantom, e.g., by showing essential information on the phantom that needs to be perceived by the participant to pass the test.

Our method builds upon work by Wegner et al. [11] and Woerdeman et al. [13], who provided a groundwork for applying auditory display to navigated surgery tasks. However, our work aims to go beyond basic approaches, such as those of Woerdeman et al., and more deeply explore the ability of alternative modalities like auditory display can have to reduce stress and increase concentration and accuracy in navigated surgery.

Because the auditory display system has shown promise in helping to improve the accuracy of resection marking and reducing the amount of time looking on the screen, it may also improve other aspects of navigated liver surgery, and by extension, other types of navigated surgery as well. In the domain of liver surgery, auditory display has also been explored [19] for notifying the surgeon of potential risk structures in the vicinity of the tracked instrument, such as veins and tumors that should not be damaged. By emitting warning signals when the instrument tip enters predefined distances to the risk structures, the surgeon could be notified of presence of such a risk without having to look at the visual display and taking concentration away from the patient. However, when considering clinical applicability of available navigation systems for liver surgery, it is important to mention that (to the knowledge of the authors) nowadays only the marking step is supported with adequate registration accuracy. An accurate, continuous tracking of liver movement during the cutting phase is still under research [2, 3, 22]. The method proposed in this paper intends to support the marking step, but could also be applied for the cutting phase in the future.

In addition to navigated liver surgery, auditory display methods could be useful additions to other types of surgery for which visual contact to the situs is important or for which there is a strong dependence on a visual display, including neurosurgery, laparoscopic surgery, and radio-frequency
ablation. Further work must discover for which cases auditory display is beneficial and the optimal means of implementing such displays.

References


