ORIGINAL ARTICLE

The Impact of 3-Dimensional Reconstructions on Operation Planning in Liver Surgery

ARCHIVES EXPRESS

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Background: Operation planning in liver surgery depends on the precise understanding of the 3-dimensional (D) relation of the tumor to the intrahepatic vascular trees. To our knowledge, the impact of anatomical 3-D reconstructions on precision in operation planning has not yet been studied.

Hypothesis: Three-dimensional reconstruction leads to an improvement of the ability to localize the tumor and an increased precision in operation planning in liver surgery.

Design: We developed a new interactive computer-based quantitative 3-D operation planning system for liver surgery, which is being introduced to the clinical routine. To evaluate whether 3-D reconstruction leads to improved operation planning, we conducted a clinical trial. The data sets of 7 virtual patients were presented to a total of 81 surgeons in different levels of training. The tumors had to be assigned to a liver segment and subsequently drawn together with the operation proposal into a given liver model. The precision of the assignment to a liver segment according to Couinaud classification and the operation proposal were measured quantitatively for each surgeon and stratified concerning 2-D and different types of 3-D presentations.

Results: The ability of correct tumor assignment to a liver segment was significantly correlated to the level of training ($P<.05$). Compared with 2-D computed tomography scans, 3-D reconstruction leads to a significant increase of precision in tumor localization by 37%. The target area of the resection proposal was improved by up to 31%.

Conclusion: Three-dimensional reconstruction leads to a significant improvement of tumor localization ability and to an increased precision of operation planning in liver surgery.

Arch Surg. 2000;135:1256-1261

MAJOR ADVANCES have been achieved in virtual operation planning and navigation in surgery, especially in neurosurgery[1,2] and orthopedic surgery.[3-5] The advantage of a firm bony reference frame is not available in visceral surgery. Virtual operation planning on the basis of 3-dimensional (D) reconstruction of soft tissue organs has to circumvent the obstacles of the inherent mobility and flexibility of the target organs.[6-13] To our knowledge, it has not yet been analyzed whether 3-D reconstructions and simulations would improve the perception of a given liver tumor or the precision of operation planning in liver surgery. Liver resection planning has been based on Couinaud classification with 8 autonomous segments.[14] However, liver segment anatomy is altered by tumor growth, preceding operations, regenerative growth, and anatomical variants.[15] Because of the limited reliability of the standard liver model, we developed a computer-based quantitative volumetric 3-D operation planning system for liver surgery.[6,7]

The aim of this study was to determine whether the localization of liver tumors and the resection proposals can be improved by using different modes of 3-D simulations compared with 2-D computed tomography (CT) scans. We also aimed to examine the correlation between the training level of the individual surgeons and the benefits derived from different types of 3-D reconstructions.

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RESULTS

TUMOR ASSIGNMENT TO THE LIVER SEGMENTS

The surgeons were asked to identify the segment(s) in which the tumor is located. The answers stratified according to

MATERIALS AND METHODS

OPERATION PLANNING SOFTWARE

The basis for the clinical study was the 3-D operation planning system that we have developed and which is being introduced into clinical routine.[6,7] The structure of the software used for operation planning has been previously described.[16,17] The integration of computer-aided operation planning requires all steps of the analytic process realized on a computer-based teleradiologic platform. The particular task consists of the following steps:

- Semiautomatic segmentation of liver parenchyma and hepatic tumor.
- Automatic segmentation of the vascular trees.
- Editing of the vascular trees to separate the portal system from the hepatic venous system.
- Calculation of dependent vascular branches and dependent liver tissue.
- Conventional segment classification for data sets with insufficient vessel contrast.
- Calculation of a resection proposal and visualization of the results.

The software has been implemented as a plug-in in the radiological viewing system CHILI (Steinbeis-Transferzentrum Medizinsche Informatik, Heidelberg, Germany).[18]

TWO-DIMENSIONAL SEGMENTATION

The first step is the segmentation of the image data to tag the liver and the diseased areas within the liver tissue. This was accomplished with a 2-D interactive tool (UltraPad A5; Wacom Computer Systems GmbH, Neuss, Germany).

SEGMENTATION OF THE VASCULAR SYSTEMS

The segmentation of the vessels is based on an algorithm that generates a symbolic description of the vessel tree in addition to segmenting the vessels.[16,19] By starting at the stem of the portal vein, the automatic algorithm passes through the data set to find connected vessel structures. The hepatic vein system also typically is enhanced and incidentally may be included in the segmentation result. This is due to a variable peak time of the contrast medium within the hepatic vascular structures. For resection planning the vascular trees have to be analyzed separately. Therefore, an editing step is necessary to separate portal veins from hepatic veins.

EDITING OF THE VASCULAR SYSTEM

The segmentation process and the limited resolution of the CT scans may have generated invalid pseudoconnections between the 2 venous systems that can be separated interactively. Hence, at the end of this process, 2 independent vascular trees will result for further computerized analysis (**Figure 1**).

CONVENTIONAL SEGMENT CLASSIFICATION

The traditional classification of the liver segments by Couinaud classification uses straight planes to define the segments. These planes are determined by the main stem of the 3 hepatic veins and the first branches of the hepatic portal tree. This strategy can only result in an estimation of the true liver segments, which indeed are far more complex in structure. Only in data sets with rudimentary vascular trees may an individualized Couinaud classification strategy be used as a compromise to approximate reality. This is performed by an additional module that allows an interactive positioning of the segmental interfaces.[19] It consists of 3 vertical planes and 4 horizontal planes that divide the liver into 8 segments. Each of these planes may be distorted. Different views of this set of intersections are shown in **Figure 2**.

RESECTION PLANNING AND VISUALIZATION

After defining the 3-D position of the tumor and the vascular trees, the safety margin (typically 1 cm) is defined around the tumor in all 3 dimensions. Finally, the vessels traversing the safety margin are determined and followed into the periphery. Their dependent liver tissue can be calculated. The resection proposal of the computer comprises the tumor, the tissue within the safety margin, and the dependent liver tissue. This represents the anatomically correct minimal resection proposal. Finally, different types of visualizations with increasing information content can be chosen and viewed as interactive movies (**Figure 3**).

As the system uses volume rendering (all 3-D information is present during the calculation process), volume information of the segments and the resection proposals are instantly available. This is necessary to define the partial hepatic resection rate to estimate postoperative liver function.

CLINICAL STUDY

A total of 81 surgeons at various training levels were exposed to CT scans and computer-generated 3-D images of 7 virtual patients with liver tumors. In a preliminary test, only those tumor localizations were selected that were situated at difficult locations in respect to the 3-D mental imaging ability of specialists; the tumors were positioned at the borders where the traditional simplified Couinaud classification comes into conflict with the individual vascular tree–based segment borders. The surgeons were divided into 4 groups according to their level of training (**Table 1**).

The images of the 7 patients were presented in 4 different modes in random order. According to the amount of information supplied by the images, the presentation modes are defined as “2-D,” “3-D,” “4-D,” and “5-D” according to their increasing inherent amount of information (**Table 2**). The 3-D images were presented in animations that could be rotated freely by the surgeon.

STUDY DESIGN

The 7 patients with 4 presentation modes were presented in random order to the 81 surgeons. They had to perform the following tasks:

- State the liver segment in which the tumor resides.
- Mark the location of the tumor onto 3 given projections of the liver model.
- Make a minimal resection proposal by drawing resection planes into the same liver model.

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ANALYSIS

The results were stratified according to the groups of surgeons and according to the presentation modes. For the tumor allocation to the liver segment, 10 points were awarded if all segments were correctly identified in which the tumor resides. If the tumor was located in more than one segment, the 10 maximal achievable points were divided between these segments. Erroneously identified segments were awarded minus points according to the formula mentioned earlier. The marking of the tumor and the resection proposals on the liver model were captured with a digitizing board and compared with the computer-generated tumor localization and resection proposals that have been evaluated by surgeons and radiologists.

STATISTICS

A variance analysis followed by a *t* test with Bonferroni correction were applied to normal distributed values. The Kruskal-Wallis test followed by Wilcoxon test were applied to nonnormal distributed values. Discrete parameters were tested with the χ^2 test with continuity correction.

the groups of surgeons demonstrated a good representation of the training level if the surgeons were confronted with traditional 2-D CT scans. As most of the tumors are situated at the borders of the vascular tree–based segments, the classification by Couinaud was expected to interfere with the exact anatomy. As expected, results for tumor allocation did not reach 100%. The specialized group achieved the best results with 6.2 points, while group B reached 4.2 points; group C, 3.6 points; and group D, 3.2 points (**Figure 4**).

Surprisingly, the transition from 2-D CT scans to simple 3-D presentations did not lead to an improvement in tumor allocation to the liver segment classification scheme of Couinaud. On the contrary, the surgeons performed worse. These results were confirmed in all 4 groups. The unusual 3-D reconstruction even leads to an equilibrium of performances of the different groups in tumor allocation. This part did not test whether the surgeon has a realistic 3-D imagination (the ability of transferring a single tumor position from the 2-D CT slices into the 3-D world) of the true tumor position in the liver. The tumor assignment to the liver segments on the basis of 2-D CT slices could have been trained without any realistic transfer imagination to the 3-D world. In other words, a surgeon may have recognized a tumor situated within segment 7 but would fail to demonstrate exactly where the tumor is localized in a liver model. This ability of transferring 3-D imagination was tested in the next step.

TUMOR LOCALIZATION IN THE LIVER MODEL

The surgeons had to transfer the tumor site from the 2-D CT scans into a liver model. The performance of the 4 groups were surprisingly very similar and thus not dependent on

Figure 1. *The 2 venous vessel systems can be separated in a 3-dimensional reconstruction. The portal system has to be segmented to calculate the segment classification of the liver.*

surgeons' training level. However, there was a significant improvement when 3-D reconstructions were presented (**Figure 5**). In this step we tested the 3-D imagination, ie, the ability of transferring a single tumor position from the 2-D CT slices into the 3-D world. This step did not test the ability to imagine the 3-D vascular tree with its dependent branches. This was the task of the next step.

RESECTION PROPOSALS

The surgeons were asked to draw their resection proposals for each patient in 3 given projections of a liver model. These projected resection proposals were called *target areas*. During this test the surgeons were asked to give the minimal resection proposal, including the tumor, the safety margin, and the dependent liver tissue. Alternatively, the surgeons could also proceed in a classic way by resecting the whole liver segment. We calculated the average percentage of the correct target area

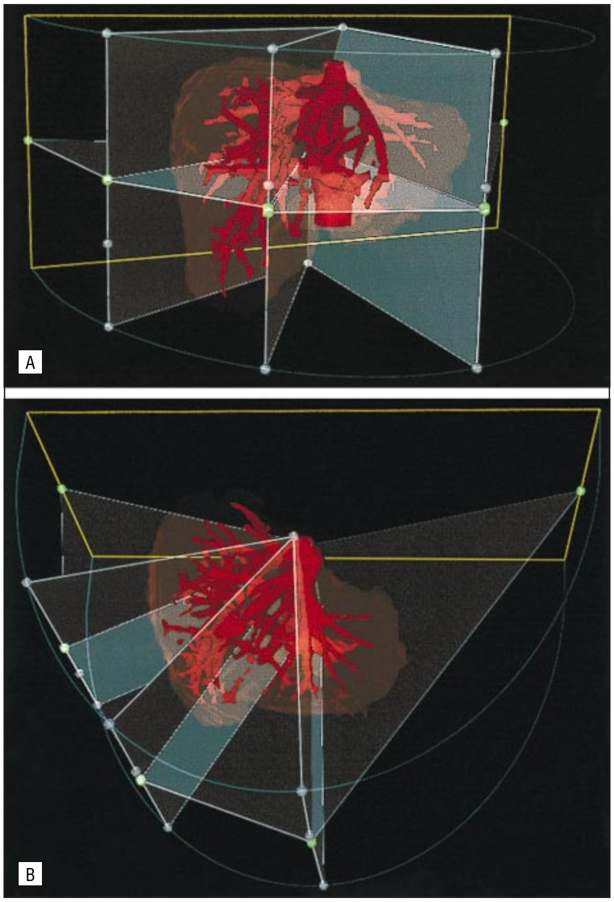

Figure 2. *The conventional segment classification proposed by Couinaud is additionally implemented in the planning system.*

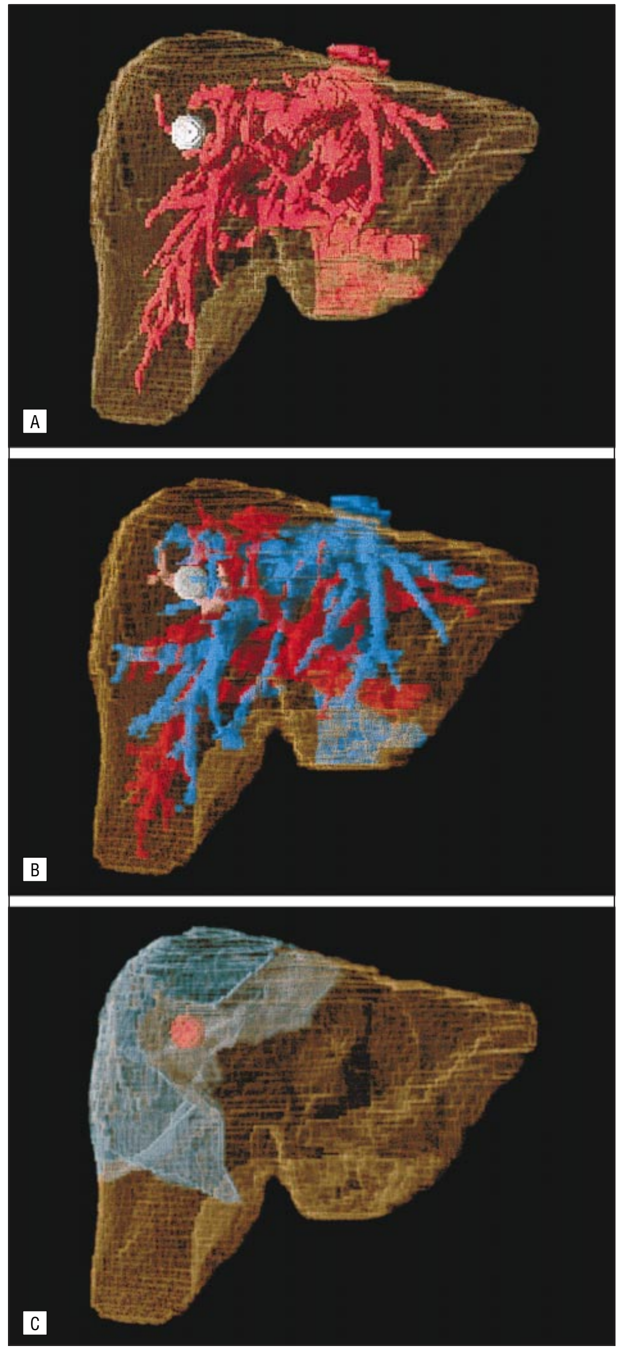

Figure 3. *Different types of presentation modes: Simple 3-dimensional reconstruction (A), reconstruction with separated vascular trees, including the highlighted security margins (B), and resection proposal of the computer (C).*

found and the amount of answers that achieved more than 80% of the actual target area composed of the tumor, safety margin, and dependent liver tissue. The results are stratified according to the 4 groups. A significant and measurable improvement could be demonstrated for the 3-D, 4-D, and 5-D presentations (**Figure 6** and **Figure 7**).

COMMENT

Since 1954, Couinaud's liver segment classification has become the standard basis for liver surgery,[14] but segment anatomy is variable and depends on tumor growth, preceding operations, regenerative growth, and anatomical variations.[15] Therefore, we developed a computer-based 3-D operation planning system that allows the analysis of the 3-D segmental anatomy of the liver, the calculation of safety margins, and the definition of the dependent liver tissue, which results in minimal resection proposals.[6,7]

Prior to our clinical trial, the impact of the 3-D presentation modes in terms of better tumor assignment, tumor localization, and liver resection proposals were not clearly determined. Despite the complexity and variability of the intrahepatic vascular trees, it was assumed that a trained liver surgeon would determine the exact 3-D position of a liver tumor from traditional 2-D images, although this has not been measured yet. The determination of the exact 3-D extension of a liver segment by pure mental imaging on the basis of 2-D CT scans seemed more difficult. The identification of dependent liver tissue seemed even more complex. The surgeon would have to determine the safety margin around the tumor and would have to follow the vessels that pass through this area by mental imaging to find the minimal resection volume. Independent from the procedure, the final goal must be the extraction of the tumor together with its safety margin and the dependent liver tissue, leaving as much sound liver tissue as

Table 1. Classification of Surgeons and Surgeons-in-Training

Group	Level of Training	Qualification
A (n = 4)	Specialized	>50 Livers operated
B (n = 18)	Experienced	>10 Livers operated
C (n = 24)	No experience	No livers operated, >5 liver operations assisted
D (n = 35)	Beginner	No liver operation attended

Table 2. Classification of Presentation Modes*

Presentation Modes	Description
2-D	Conventional 2-D CT scans
3-D	Simple 3-D reconstruction of the liver
4-D	Color-coded 3-D liver reconstruction with separated vascular trees of portal and hepatic veins, including safety margins around the tumor
5-D	Combination of the 4-D presentation mode with conventional 2-D CT scans

**D indicates dimensional; CT, computed tomographic.*

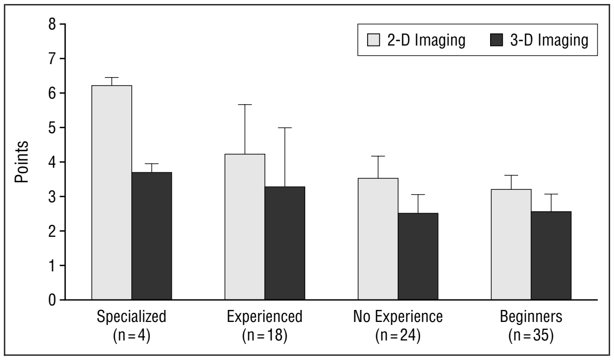

Figure 4. *Tumor assignment to liver segments. The 4 groups of surgeons are well represented according to their levels of training. The surgeons performed worse when they were presented with 3-dimensional (D) imaging compared with 2-D computed tomograpic scans (2-D vs 3-D was significant in the specialized group;* P<.05).

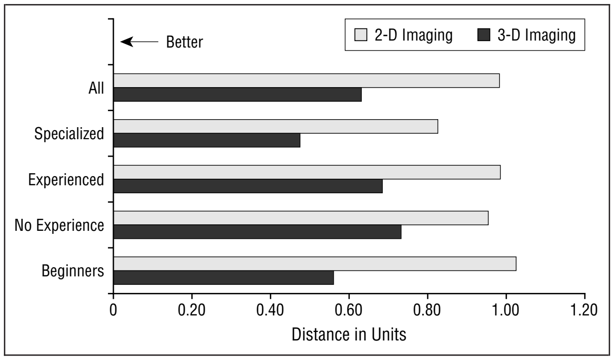

Figure 5. *A significant improvement of tumor localization is evident with 3-dimensional (D) imaging. The enhanced precision of the tumor localization is shown with shorter bars. The specialized group gains the most from the new system.* P<.05 *in all groups.*

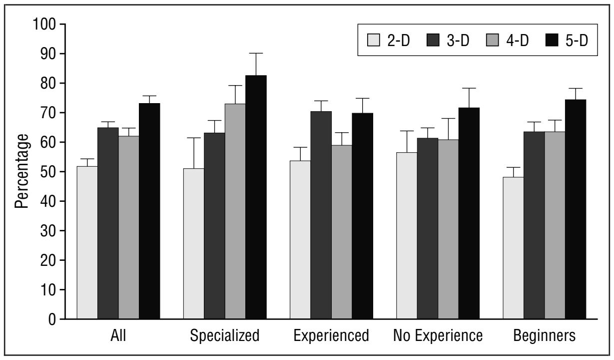

Figure 6. *The significant and measurable improvement of the surgeons' resection proposals with higher-dimensional (D) imaging is evident. Improvements from 2-D to 5-D are significant in all groups (All,* P<.01; *specialized,* P<.01; *experienced,* P<.01; *no experience,* P<.05; *and beginners,* P<.01).

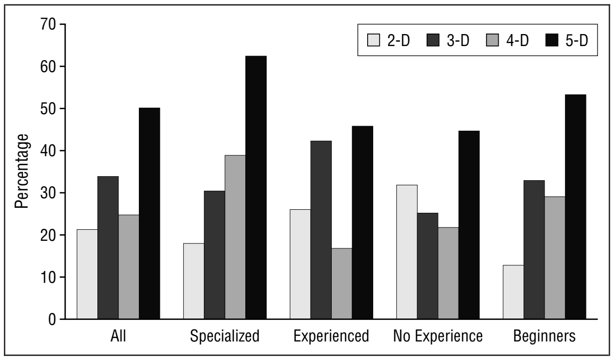

Figure 7. *Number of answers that achieved 80% to 100% of the actual target area composed of the tumor, security margin, and dependent liver tissue. There is a significant improvement with the 5-dimensional (D) presentation mode, leading to an improvement by 45% in the specialized group (*P<.01).

possible. To circumvent these imagination problems, more simple and only approximate resection planes were chosen in the past. This could lead to extended resections or to devascularized liver areas.

The results of the tumor localization based on conventional 2-D CT scans correlated with the surgeons' training level, as it was easy for the surgeons to adjust the tumor localization according to the vessels. With the introduction of the 3-D images, the results of the tumor localization dropped surprisingly, and there was no correlation with the surgeons' level of training anymore. This may be due to the nontraditional presentation method in which the main stems of the portal and hepatic veins are partially obscured by the smaller and more distant vascular branches. This led to difficulties in identifying the liver segments. On the other hand, it may be speculated that the simplified classification by Couinaud interferes with the real vascular tree seen in the transparent liver model, which subsequently led to disorientation of the surgeons. This hypothesis was supported by the finding that the tumor localization transfer into the liver model was significantly better when 3-D reconstructions were presented.

Additionally, the resection proposals improved dramatically with the added amount of information provided by higher-D imaging. Best results were achieved with the combination of conventional 2-D CT scans and 3-D images in which the vascular trees and safety margins were highlighted with different colors. The experienced surgeons benefit the most from this additional information calculated into the images. None of the resection proposals achieved 100%, which points out the demand of a complete virtual operation planning proposal generated by the computer. On the basis of our investigation, even experienced liver surgeons had some difficulties with tumors located at segmental borders. They may profit especially in these cases from higher-D reconstructions.

We were able to show quantitatively the significant improvement of operation planning in liver surgery by using 3- and higher-D presentations.

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