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Review Article
Application of three-dimensional visualization technology in hepatectomy: a systematic review

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Abstract: Objective: This study systematically reviewed the global application of 3D visualization technology in liver surgery. Methods: PubMed database was searched for English language reports regarding the application of 3D visualization technology in hepatectomy published from 2000 to 2016. The included articles were classified and deeply analyzed. Results: 34 articles were included and reported 1,553 cases. Thirteen studies assessed the accuracy of 3D techniques to estimate for resection volume and margin. The 3D estimated values revealed a good correlation with actually measured values. The coefficient range was 0.874-0.995 ($P < 0.001$) for the resected liver volume and 0.702-0.967 ($P < 0.01$) for the resection margin. Five studies compared differences in liver volume estimation between 3D and conventional two-dimensional (2D) imaging technologies. These 3D-estimated values had significantly smaller errors than 2D-estimated values, as compared with the actual measured volumes ($P < 0.05$). Five studies evaluated the effects of 3D and 2D technologies on surgical procedure and efficacy. 3D technology was associated with shorter surgical duration and less intraoperative blood loss ($P < 0.05$), and was also superior based on other indicators including incidence for postoperative complications and laboratory test results. Conclusion: 3D visualization technology can clearly display the anatomical structures of the liver and features of the lesions. 3D visualization can accurately estimate liver volume and the resection margin, and is more accurate than traditional 2D imaging. This technology plays an important role in preoperative evaluation and surgical planning, and is also helpful during surgery and postoperative recovery. The application of 3D technology improves the efficacy and safety of hepatectomy.

Keywords: Three dimensional visualizations, hepatectomy, liver resection, liver disease

Introduction

Three-dimensional (3D) visualization technology has been used in medical field for many years and has been extensively used for the treatment of liver diseases [1-4], especially with hepatectomy. During the preoperative planning of hepatectomy, surgeons should clearly understand the liver anatomy and lesion characteristics. However, conventional two-dimensional (2D) images provide limited information of the resection range and path for detailed surgical planning. With the rapid development of digital medical technology, 3D visualization technology is now more applied in liver resection surgery. 3D technology can intuitively and clearly display the liver anatomy, as well as the routes and variations of the intrahepatic vascular system with multiple angles. This technology can accurately localize lesions, estimate the liver volume and surgical margins, and simulate surgery. Furthermore, it also plays important roles in preoperative evaluation and surgical planning and implementation. Many researchers have reported the application of 3D technology in the surgical treatment of a variety of liver diseases. However, these surgical approaches for various diseases differ, and study methods and results also have unique characteristics. Therefore, the aim of the present study was to systematically and comprehensively review the latest applications of 3D techniques in the field of liver surgery.

Materials and methods

A literature search of the PubMed database was conducted limited to full-text articles and

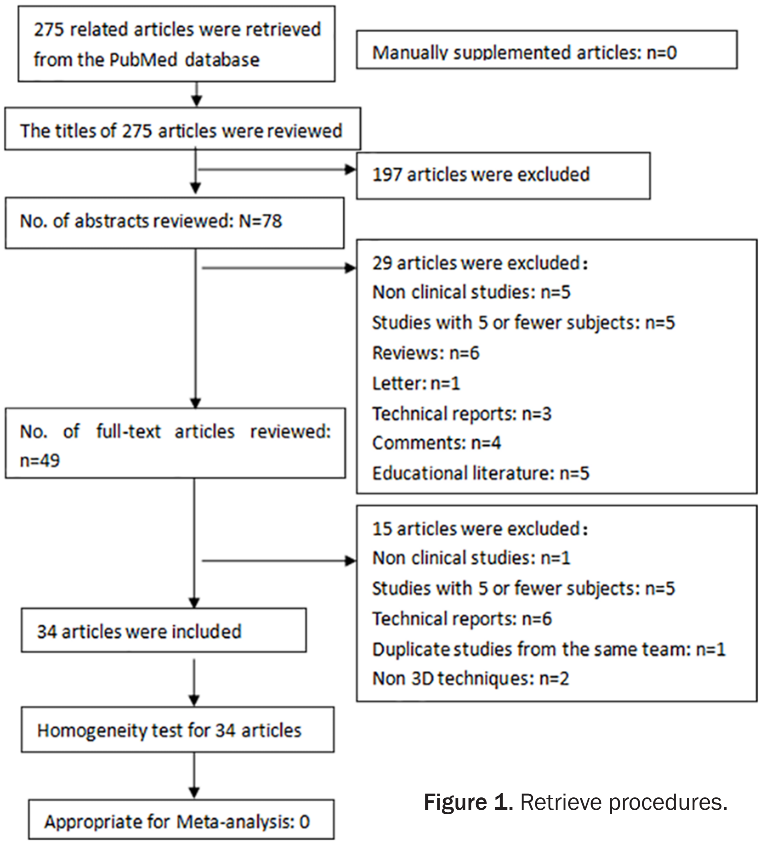

Figure 1. Retrieve procedures.

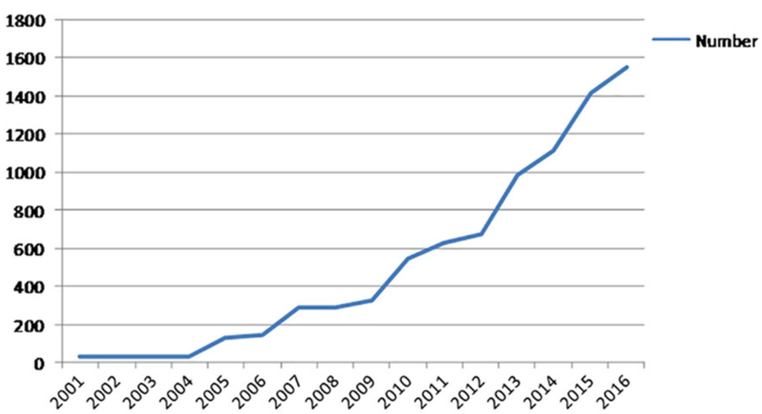

Figure 2. Increasing trend of the application of 3D techniques in the treatment of liver diseases by hepatectomy.

clinical studies published in English between October 2000 and October 2016. The search terms used alone or combined included: (1) hepatectomy and liver resection; (2) three dimensional, visualization, reconstruction, computer simulation, computer-assisted and virtual; and (3) hepatic, liver and liver disease. All references of the retrieved articles and related publications, as well as related supplemented studies, were also reviewed manually. The study designs of these included articles included clinical trials and observational studies. Case reports, studies with < 5 subjects, review articles, comments, articles used for educational purpose, technical articles, and duplicated studies were excluded. Each article was carefully reviewed to exclude the study data from the same team and potential duplications. After screening, a total of 34 articles were included; and the data was extracted and classified. These studies were described, analyzed and reviewed. Then, associated figures and tables were plotted.

Results

Systematic search and description of included studies

A total of 275 articles were retrieved from the search of the PubMed database. Through reviewing the titles, 197 articles were excluded. Furthermore, a review of the abstracts excluded an additional 29 articles and full-text reviews further excluded 15 articles. Finally, 34 articles were included for analysis. A flowchart of the review process is shown in **Figure 1**. Homogeneity testing revealed that none of the articles were appropriate for meta-analysis, which was because of the following reasons: (1) the diversity of included liver diseases; (2) different study designs; (3) use of a variety of surgical approaches; and (4) various observational indicators. Therefore, only a systematic review was conducted in the present study. From 2001 to 2016, the number of the reports that applied 3D technology in hepatectomy steadily increased (**Figure 2**). These included articles reported 1,553 cases of 3D visualization-guid-

Table 1. Application of 3D technology in the treatment of liver disease by hepatectomy (ordered by publications year)

Author	Country	Published year	Published Journal	Study period	Disease	Number of cases	Male	Female	Age (years)
Wigmore et al. [5]	Scotland	2001	Annals of Surgery	NR	Liver tumor	27	13	14	68
Lang et al. [6]	Germany	2005	Arch Surg	NR	Liver tumor	25	14	11	52
Saito et al. [7]	Japan	2005	Hepatology	2001-2004	Liver tumor	72	51	21	62
Kamiyama et al. [8]	Japan	2006	World J Surg	2002-2003	Liver disease	17	11	6	57.82
Yamanaka et al. [9]	Japan	2007	World J Surg y	2001-2005	Hepatocellular carcinoma	113	81	32	65+9
Endo et al. [10]	Japan	2007	Surgery	2003-2006	Hilar cholangiocarcinoma	15	NR	NR	65
Dong et al. [11]	China	2007	Pediatr Surg Int	1999-2005	Children liver tumor	18	8	10	4.2
Yamanaka et al. [12]	Japan	2009	J Hepatobiliary Pancreat Surg	1993-2008	Liver tumor	35	25	10	63+9
Radtke et al. [13]	Germany	2010	Ann Surg	1999-2007	Liver disease	157	117	85	56+12
Chen et al. [14]	China	2010	International Journal of Surgery	2006-2008	Liver tumor	38	NR	NR	39
Fang et al. [15]	China	2010	Chinese Medical Journal	NR	Liver tumor	17	8	9	NR
Lamata et al. [16]	England	2010	Surg Endosc	2008	Liver tumor	7	NR	NR	NR
Sasaki et al. [17]	Japan	2011	The American Journal of Surgery	2004-2008	Hilar cholangiocarcinoma	19	13	6	67
Pianka et al. [18]	Germany	2011	Arch Surg	NR	Liver tumor	13	10	3	60
Mise et al. [19]	Japan	2011	British Journal of Surgery	2004-2009	Liver tumor	55	43	12	64
Wang et al. [20]	China	2012	Dig Surg	2007-2009	Hepatocellular carcinoma	13	12	1	55
Stavrou et al. [21]	Germany	2012	Advances in Medical Sciences	2002-2009	Liver tumor	29	NR	NR	NR
Ariizumi et al. [22]	Japan	2013	J Hepatobiliary Pancreat Sci	2010-2011	Liver tumor	92	65	27	69
Fang et al. [23]	China	2013	J Am Coll Surg	2005-2012	Intrahepatic bile duct stone	56	28	28	50.6+11.5
Takamoto et al. [24]	Japan	2013	The American Journal of Surgery	2009-2012	Liver tumor	83	61	22	65
Tang et al. [25]	China	2013	Asian Pacific J Cancer Prev	2009-2010	Hepatocellular carcinoma	22	NR	NR	NR
Kingham et al. [26]	America	2013	J Gastrointest Surg	2008-2011	Liver tumor	64	44	20	58.5
Be'gin et al. [27]	Canada	2014	Surg Endosc	2006-2009	Liver tumor	36	NR	NR	56
Xie et al. [28]	China	2014	Journal of Gastroenterology and Hepatology	2010-2011	Relapsed intrahepatic bile duct stone	20	7	13	NR
Simpson et al. [29]	America	2014	J Am Coll Surg	2008-2010	Liver tumor	66	33	33	54
Okuda et al. [30]	Japan	2015	Surgery	2009-2014	Cholangiocarcinoma	49	34	15	64+11
He et al. [31]	China	2015	World J Gastroenterol	2011-2015	Hepatic alveolar hydatid disease	59	32	27	41.4+13.1
Fang et al. [32]	China	2015	J Am Coll Surg	2008-2014	Central hepatocellular *carcinoma*	60	52	8	47.5+13.8
Tian et al. [33]	China	2015	World J Gastroenterol	2013-2014	Central hepatocellular *carcinoma*	39	34	5	54.3+12.1
Oshiro et al. [34]	Japan	2015	World J Gastroenterol	2010-2013	Liver tumor	99	78	21	65
Su et al. [35]	China	2016	Pediatr Surg Int	2012-2015	Children liver tumor	16	10	6	15.12+13.16
Warmann et al. [36]	Germany	2016	Journal of Pediatric Surgery	2004-2016	Liver tumor	18	12	12	33
Guan et al. [37]	China	2016	Biomed Res Int	2006-2010	Hepatocellular carcinoma	92	75	17	52.48+8.36
Zygomalas et al. [38]	Greece	2016	Med Biol Eng Comput	2013-2014	Liver tumor	12	6	6	54.2

NR: not reported.

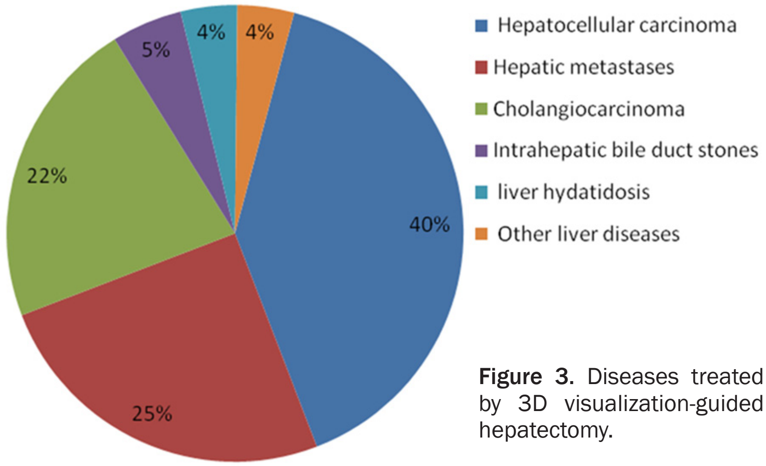

Figure 3. Diseases treated by 3D visualization-guided hepatectomy.

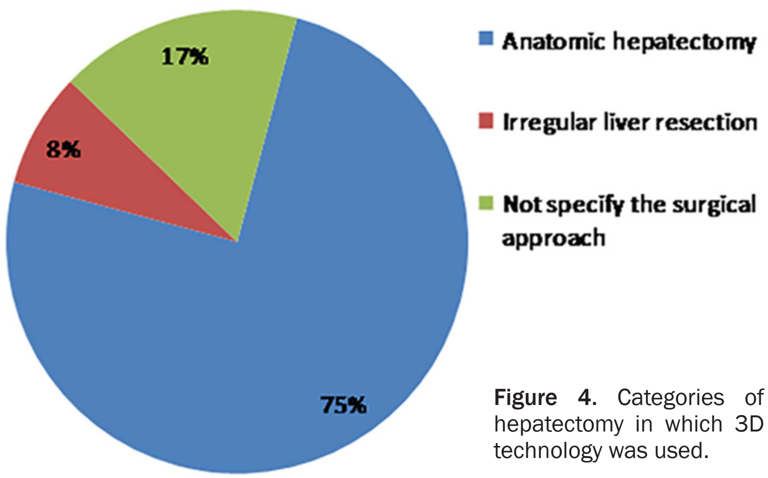

Figure 4. Categories of hepatectomy in which 3D technology was used.

ed hepatectomy for a variety of liver diseases. Among these cases, liver malignancies were predominant. The date of publication ranged from 1993 to 2016. The study subjects included adults and children (**Table 1**) [5-38]. 3D printing and intraoperative real-time navigation are an extended utility of 3D visualization in the investigation stage in liver surgery. However, there were few related articles and most were case reports with < 5 subjects. Moreover, the contents were often the introduction of new technologies and sharing of experience. Therefore, these related articles were not included in the present study. The two types of technologies are described in the "Discussion" section.

Diseases treated by 3D visualization-guided hepatectomy

Liver malignancies were predominant in cases treated by 3D visualization-guided hepatectomy. Among these reports, hepatocellular carcinoma accounted for 40% of cases, cholangiocarcinoma accounted for 22% of cases, hepatic metastases (from colon and rectal cancer, duodenal cancer, adrenal tumor, etc.) accounted for 25% of cases, intrahepatic bile duct stones accounted for 5% of cases, liver hydatidosis accounted for 4% of cases, and other diseases, including liver hemangioma, gallbladder cancer, liver focal hyperplasia nodules, liver adenoma, hepatoblastoma, liver mesenchymal tumor, hepatic hemangioendothelioma, liver sarcoma, teratoma, and liver malignant fibrous histiocytoma combined with hepatic cystadenoma, accounted for 4% of cases (**Figure 3**).

Categories of hepatectomy where 3D technology was used

Hepatectomy, in which 3D technology was used, were dominated by anatomic hepatectomy; which accounted for 75% of cases., Irregular liver resection accounted for 8% of cases; and the remaining 17% did not specify the surgical approach (**Figure 4**). Anatomic hepatectomy included major hepatectomy (*n* = 213), bisegmentectomy (*n* = 61), segmentectomy (*n* = 183), limited resection (*n* = 166), sectionectomy (*n* = 71), mesohepatectomy (*n* = 23), left trisectionectomy (*n* = 33), right trisectionectomy (*n* = 28), left hemihepatectomy (n = 97), right hemihepatectomy (*n* = 150), *extended* left hemihepatectomy (*n* = 47), and *extended* right hemihepatectomy (*n* = 65) (**Figure 5**).

A total of 13 articles evaluated the accuracy of 3D technology to estimate the liver volume and resection margin

The evaluation method was chosen to calculate the correlation or difference between 3D-estimated values and the actual measured values. Results revealed a high correlation and small

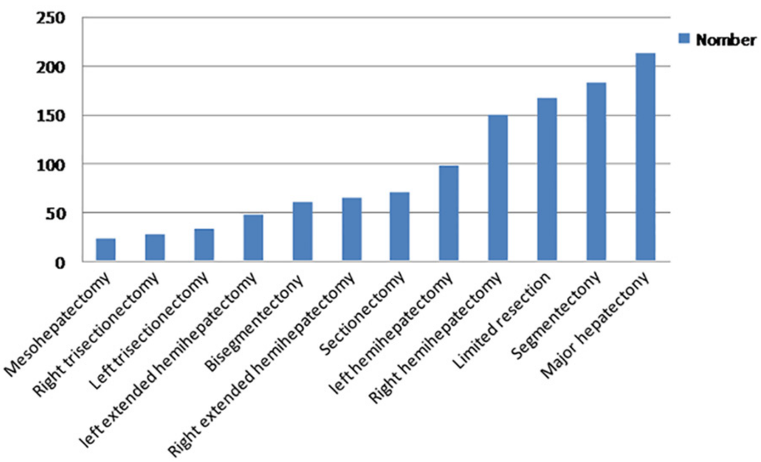

Figure 5. Surgical approaches for anatomical hepatectomy.

discrepancy between the 3D-estimated resected liver volume, residual liver volume and resection margin; and these actual values were measured intra- or post-operatively (**Table 2**). In addition, these results revealed that 3D technology could accurately estimate the liver volume and resection margin. Ariizumi *et al.* [22] calculated the accuracy of 3D estimated values in different surgical approaches: for sectionectomy, the correlation between the estimated liver volume and actual value was relatively high (R = 0.985, P < 0.0001), and the median error was 26 mL; for hemihepatectomy, the R was 0.967 (P < 0.0001) and the median error was 38 mL. In addition, the estimated and actual values in non-cancerous liver lesions also revealed a good correlation. For example, in cirrhosis, chronic hepatitis and normal liver tissue, the coefficients (R) for resected liver volume were 0.984 (P < 0.0001), 0.988 (P < 0.0001) and 0.9777 (P < 0.0001), respectively. Zygomalas *et al.* [38] compared the estimated residual liver volumes with the actual intraoperatively measured values and found a significant correlation. For residual liver volume, R = 0.99 (P < 0.0001). Simpson *et al.* [29] compared 3D-estimated values with postoperative CT results, and for residual liver volume, R = 0.941 (P < 0.001).

A total of five articles evaluated the correlations and differences between 3D and traditional 2D technologies to estimate liver volume

By calculating the correlations and differences between 3D and 2D technologies to estimate the liver volume of patients in the same group, results revealed that 3D and 2D technologies were generally well correlated in the estimation of total liver volume, resected liver volume, residual liver volume, and tumor volume. However, there were differences among these different surgical approaches. For example, Radtke *et al.* [13] and Lang *et al.* [6] both found significant differences in *extended* left hemihepatectomy; but there was no significant difference in right hemihepatectomy and extended right hemihepatectomy between the 3D and 2D groups. Comparisons with actually measured values suggest that 3D estimation was more accurate. For example, Yamanaka *et al.* [9] and Pianka *et al.* [18] compared resected liver volume estimated by 2D and 3D technologies and found that the estimation errors by 3D technology were significantly smaller from the estimation errors by 2D technology (P < 0.01) (**Table 3**).

Five clinical studies evaluated the impact of 3D technology on surgical procedure and efficacy

The associated indicators of surgical procedure and efficacy were compared among patients who underwent liver resection with and without preoperative planning, and the assessment of 3D technology. These results revealed that these disease conditions were similar, but the surgical duration was shorter and blood loss was less with 3D-guided hepatectomy. Furthermore, there was no significant difference in the length of hospitalization (**Table 4**). In terms of postoperative complications, including biliary fistula, ascites, incision infection, pleural effusion and liver failure, there was no significant difference in most results between the 3D and 2D groups. However, two teams reported that the incidences of biliary fistula, ascites and liver failure were lower in the 3D group than in the 2D group (P = 0.04) [30, 32]. Fang *et al.* [23, 32] reported that postoperative serum bilirubin level in the 2D group was significantly higher than in the 3D group (P = 0.032), while the hemoglobin level was significantly lower in the

Table 2. Studies investigating the accuracy of 3D-estimated liver volume or resection margin

Author	Disease	Number of cases (N)	Male	Female	Age (years)	Volume measurement (Correlation or difference between 3D-estimated value and actual value)	Margin (Correlation or difference between 3D-estimated value and actual value)
Yamanaka et al. [9]	Hepatocellular carcinoma	113	81	32	65+9	Resected liver volume: R = 0.96, P < 0.0001	R = 0.84, P < 0.01, error: 1.6 ± 2.6 mm.
Be'gin et al. [27]	Liver tumor	36	NR	NR	56	Resected liver volume: R = 0.874, P < 0.001. Tumor volume: R = 0.758	NR
Tian et al. [33]	Central liver cancer	39	34	5	54.3+12.1	No significant difference in tumor volume: P = 0.910	No significant difference: P = 0.488
Chen et al. [14]	Liver tumor	38	NR	NR	NR	No significant difference in resected liver volume: P > 0.05	NR
Takamoto et al. [24]	Liver tumor	83	61	22	65	Resected liver volume: R = 0.9942, P < 0.01	NR
Yamanaka et al. [12]	Liver tumor	35	25	10	63+9	Resected liver volume: R = 0.995, P < 0.0001	R = 0.702, P < 0.01, error: 1.3 ± 4.8 mm
Saito et al. [7]	Liver tumor	72	51	21	62	Resected liver volume: R = 0.96, P < 0.0001	R = 0.84, P < 0.01, error: 1.6 ± 2.6 mm
Ariizumi et al. [22]	Liver tumor	92	65	27	69	Resected liver volume: R > 0.9, P < 0.0001	NR
Wigmore et al. [5]	Liver tumor	27	13	14	68	Resected liver volume: R = 0.94, P < 0.0001,	NR
Kingham et al. [26]	Liver tumor	64	42	22	58.5	NR	Error: 6.5 ± 3.7 mm
Simpson et al. [29]	Liver tumor	66	33	33	54	Residual liver volume: R = 0.941, P < 0.001	NR
Zygomalas et al. [38]	Liver tumor	12	6	6	54.2	Residual liver volume: R = 0.99, P < 0.0001	NR
Wang et al. [20]	Hepatocellular carcinoma	13	12	1	55	Resected liver volume: R = 0.995, P < 0.0001	R = 0.967, P < 0.0001

NR: not reported.

Table 3. Correlation or difference in the estimation of liver volume by 3D and 2D technologies

Author	Study period	Disease	Number of cases	Male	Female	Age	Correlation or difference of 3D and 2D in the estimation of liver volume
Yamanaka et al. [9]	2001-2005	Hepatocellular carcinoma	113	81	32	65+9	3D-estimated resected volume and actually resected volume: R = 0.96, P < 0.0001; 2D-estimated resected volume and actually resected volume: R = 0.74, P < 0.05; 3D error: 9.3 ± 6.0 ml; 2D error: 174 ± 37 ml; the difference of the errors was statistically significant
Be'gin et al. [27]	2006-2009	Liver tumors	36	NR	NR	56	Correlation between 3D-estimated and 2D-estimated liver volume: total liver volume: R = 0.989, P < 0.001; resected liver volume: R = 0.966; residual liver volume: R = 0.917; tumor volume: R = 0.989.
Radtke et al. [13]	1999-2007	Liver diseases	157	NR	NR	56+12	Difference of the 3D and 2D-estimated resected liver volume: significant in *extended* left hemihepatectomy (P < 0.001), significant in left trisectionectomies (P = 0.008); not significant in right hemihepatectomy and extended right hemihepatectomy.
Lang et al. [6]	NR	Liver tumors	25	14	11	52	Difference of the 3D and 2D-estimated resected liver volume: significant in *extended* left hemihepatectomy and left hemihepatectomy combining wedge hepatectomy of right lobe.
Pianka et al. [18]	NR	Liver tumors	13	10	3	60	Comparison of 3D or 2D-estimated resected volume and actually resected volume: 3D error: 110.0 ml; 2D error: 203.8 ml; the difference was significant (P < 0.001).

NR: not reported.

Table 4. Difference in surgical duration, blood loss, and length of hospitalization between the 3D and 2D groups

Author	Disease	Number of cases		Male		Female		Age (years)		Surgical duration (minute)			Blood loss (ml)			Hospitalization days		
		3D	2D	3D	2D	3D	2D	3D	2D	3D	2D	*P* value	3D	2D	*P* value	3D	2D	*P* value
Fang et al. [32]	Hepatocellular carcinoma	60	56	52	50	8	6	47.5 ± 13.8	46.5 ± 13.3	294.5 ± 61.9	324.3 ± 83.1	P = 0.028	695.0 ± 338.7	651.8 ± 343.0	P = 0.968	12.5 ± 4.2	14.5 ± 4.5	P = 0.227
Okuda et al. [30]	Cholangiocarci-noma	49	69	34	32	15	37	64 ± 11	66 ± 9	782 ± 277	635 ± 123	NR	2687 ± 3685	1750 ± 1609	NR	NR	NR	NR
He et al. [31]	Hepatic alveolar hydatid disease	59	47	32	24	27	23	41.4 ± 13.1	42.5 ± 13.2	227.1 ± 51.4	304.6 ± 88.1	P < 0.05	308.1 ± 135.4	458.1 ± 175.4	P < 0.05	12.2 ± 2.8	12.0 ± 2.8	P > 0.05
Su et al. [35]	Pediatric live tumor	16	10	10	6	6	4	16.13 ± 12.16	14.34 ± 11.27	137.8 ± 17.51	192 ± 34.66	P < 0.01	21.81 ± 14.05	53.5 ± 21.35	P < 0.01	NR	NR	NR
Fang et al. [23]	Intrahepatic bile duct stones	56	42	28	24	28	18	50.6 ± 11.5	53.5 ± 12.6	218.8 ± 55.5	254.7 ± 65.6	P < 0.005	258.0 ± 167.5	321.2 ± 162.7	NR	12.1 ± 4.5	10.9 ± 4.4	P > 0.05

NR: not reported.

2D group than in the 3D group ($P = 0.033$). In a study conducted by Okuda *et al.* [30], there was a significant difference in tumor stage between the 2D and 3D groups, since there were more T4-stage cases in the 3D group ($P = 0.025$). The incidence of portal vein reconstruction was also higher in the 3D group than in the 2D group ($P = 0.002$). Since the conditions of patients were rather different between these two groups, surgical duration and blood loss were both higher in the 3D group than in the 2D group. However, when limited to the initial resection, the proportion of negative resection margins and invasive cancer-free ratio were both higher in the 3D group than in the 2D group ($P = 0.03$ and $P = 0.02$, respectively). Moreover, for intrahepatic bile duct stones, the stone recurrence rate was also significantly lower in the 3D group than in the 2D group ($P < 0.004$). These results suggest that 3D technology may be helpful to improve the efficiency and safety of liver resection surgery. However, without adequate follow-up data, the effect of 3D technology on the efficacy of hepatectomy could not be evaluated.

Impact of 3D technology on surgical strategy

Few studies have reported that the use of 3D technology led to the change in surgical strategy based on 2D results [6, 10, 13, 14]. A total of 70 cases were involved, including 43 cases for which the resection range was expanded, 17 cases of vascular reconstruction, and four cases that were unfit for surgical treatment due to inadequate estimated residual liver volume. In these three cases, 2D assessment revealed no surgical opportunity. However, after 3D reassessment, it was decided that surgery was viable.

Other special reports regarding the application of 3D visualization

The application of 3D technology in the treatment of pediatric liver tumors has been reported. [11, 35] 3D technology has significant value in preoperative planning of various pediatric-specific liver tumors. 3D-assisted surgery was associated with shorter surgical duration and less intraoperative blood loss. Guan *et al.* [37] compared the efficacy of 3D-assisted hepatectomy to radiofrequency ablation for the treatment of small liver cancer. They found that when radiofrequency ablation can also be used as an alternative, and that 3D-assisted hepatectomy should be the first choice. The application of 3D technology in relapsed intrahepatic bile duct stones and the resection of liver metastasis of colon cancer have also been reported to achieve satisfactory efficacy. Stavrou *et al.* [21] reported that 3D technology was adequate for planning Associated Liver Partition and Portal vein ligation for Staged hepatectomy (ALPPS).

Discussion

With the development of digital medical technology, 3D visualization technology has increasingly been used in liver surgery. 3D visualization technology can reconstruct 3D liver models from computed tomography images. Furthermore, 3D visualization not only displays the blood vessels and bile ducts in the liver more clearly, but also has the ability to estimate liver volume and simulate the surgery. 3D visualization plays an important role in preoperative planning, and is ever more commonly used in liver surgery. In 2000, Lamade *et al.* [39] reported that 3D technology was superior to traditional 2D imaging for *preoperative tumor localization and preoperative planning. In 2001,* Wigmore *et al.* [5] reported the clinical application of 3D technology in liver resection, and evaluated the accuracy of 3D visualization to estimate the volume of the resected liver. Since then, the number of reports regarding the application of 3D visualization in liver surgery has gradually increased. In this study, we systematically reviewed the literature for English language articles published worldwide from 2000 to 2016, and analyzed the current status and progression of 3D visualization in liver surgery.

3D technology is widely used for the surgical treatment of various liver diseases. Our results revealed that 3D technology has increasingly been used for the treatment of liver malignancies, including hepatocellular carcinoma, cholangiocarcinoma and hepatic metastases; which account for 87% of all cases. Liver cancer is one of the most lethal malignant tumors [40], and hepatocellular carcinoma is the most common primary liver cancer, accounting for 70%-90% of all cases [41]. Our results revealed that 3D technology was used in approximately 40% of hepatocellular carcinoma cases. The anatomical structure of the liver is complex, and has many important vessels distributed in the parenchyma and vascular variation, which is common [42]. The biological characteristics of liver cancer determine the close relationship between tumors and liver tissues. Ultrasonography, computed tomography (CT), and magnetic resonance imaging are the most commonly used imaging technologies for the preoperative evaluation of liver cancer [43]. However, in many cases, 2D imaging is insufficient to clearly display the tumor and important vessels or their relationships, which creates a certain difficulty and risk of surgery. 3D imaging can clearly display the anatomical structures of the liver, accurately localize tumors, and show the relationship between the tumor and blood vessels. This technology can also be used for simulating the liver resection and designing a rational surgical plan to improve the safety and effectiveness of surgery. Therefore, 3D technology has been widely used in surgical treatment of liver malignancies. Lang *et al.* [44] performed a feasibility assessment of 3D technology for the resectability of relapsed liver metastases of colon cancer. The residual liver volume could be accurately predicted, which resulted in an improvement in the success rate of reoperations. The 3D reconstruction of intrahepatic and extrahepatic bile ducts can fully display the *anatomical* relationship between the bile ducts, blood vessels, and tumors, and has certain advantages over traditional 2D imaging. Therefore, 3D technology is very helpful in the surgical treatment of cholangiocarcinoma. Okuda *et al.* [26] reported that for the first resection, the ratio of the negative resection margin and invasive cancer-free ratio were significantly greater in the 3D group than in the 2D group. Accurate localization of intrahepatic bile duct stones has consistently posed a problem to liver surgeons. 3D reconstruction images of the bile duct system clearly display the bile duct branches at all levels, as well as the size and location of stones, which provides key information for planning the surgical approach. Various surgical paths can be simulated using a 3D model to develop a surgical plan with minimum trauma, while the problems of excessive resection and stone residue can be largely avoided. Fang *et al.* [19] reported that the application of 3D technology in the treatment of intrahepatic bile duct stones was associated with a relatively low recurrence rate. He *et al.* [27] investigated the application of 3D technology in hepatic resection of hepatic alveolar echinococcosis, and found that liver morphology and structure often change in response to disease-induced damage. Furthermore, intrahepatic multiple lesions are also common. Assisted by 3D technology, personalized surgical approaches can be planned to successfully implement the surgical plan and achieve satisfactory efficacy. 3D technology also plays an important role in the treatment of pediatric liver tumors, which are characterized by the diversity and complexity of pathological changes. In addition, the relatively small liver volume and large tumor volume of pediatric patients complicate surgical intervention. Surgeons can use 3D images to elucidate these lesions more clearly and design a safe and rational operation plan to reduce the surgical duration and intraoperative blood loss. Fuchs *et al.* [45] applied 3D technology in the surgical treatment of pediatric hepatic vascular malformations, and their results support the important role of 3D technology in the diagnosis and preoperative planning of liver diseases.

Precise liver resection, which is anatomical resection based on the structure of the liver, is the most effective and safest surgical approach. The application of 3D visualization technology has helped more and more surgeons to perform precise liver resections. Prior to 3D technology, liver surgeons were required to translate 2D images into 3D images to understand disease conditions and establish a surgical plan, which largely relies on long-term accumulated experience. Furthermore, the accuracy of this method varies among surgeons; and without intuitive 3D images, important information of the liver structure may be missed, thereby decreasing the rationality of preoperative planning and operational safety. 3D technology can display the anatomical structures of the liver and lesion characteristics dimensionally, and in great detail. Moreover, this technology can also be used to estimate the liver volume and resection plane, as well as simulate the operation, in order to facilitate the implementation of precise anatomical hepatectomy. Our study revealed that 3D technology was applied in approximately 75% of anatomical liver resections, while irregular liver resection only accounted for 8%. Segmental liver resection accounts for the biggest proportion, which can benefit from many 3D techniques that display the internal structures of individual liver segments, thereby helping surgeons understand the blood supply and vein reflux of liver segments. Ueno *et al.* [46] used 3D techniques to display the anatomical structures of liver segments and perform precise laparoscopic anatomic hepatectomy, which significantly reduced surgical trauma. Associating liver partition and portal vein ligation for staged hepatectomy (ALPPS) is one of the most important technical innovations in the field of hepatobiliary surgery in recent years. ALPPS can be applied to liver cancer patients with a relatively small residual liver volume, and who cannot tolerate extensive liver resection [47]. ALPPS is increasingly used in clinic as a new surgical strategy [48, 49]. 3D visualization is well suited for ALPPS, as this technique can simulate the ligation of the portal vein, adjust the resection plane, estimate the residual liver volume, predict liver regeneration, and provide a feasibility analysis for second-stage liver resection. Together, these features can facilitate the successful implementation of ALPPS.

Accurate preoperative assessment and surgical strategies are of great significance for hepatectomy. However, traditional 2D images sometimes fail to provide adequate anatomical information and pathological features, which may lead to an irrational surgical strategy, resulting in severe liver damage. For instance, *inadequate resection* increases the risk of recurrence, while excessive resection results in inadequate residual liver volume and postoperative liver failure. 3D technology can improve preoperative planning. A study conducted by Hansen *et al.* [50] revealed that preoperative risk analysis based on 3D-modelling could increase risk awareness and assist surgeons to design surgical strategies with a safer resection margin, minimizing the loss of liver volume. These reported strategy modifications based on 3D visualization include changes to the extent of resection, vascular reconstruction, and resectability evaluation. 3D visualization displays the relationship between lesions and liver structures more clearly, thereby helping the surgeons define the extent of resection more accurately. This favors the curative resection of tumors and prevents liver failure due to the inadequate remnant liver volume. In addition, by clearly displaying the important vessels and their branches in the liver, 3D visualization can also be used to assess the impact of vessel ligation or the resection of the remaining liver tissues, as well as the necessity of vascular reconstruction. Mise *et al.* [15] applied 3D technology to observe the route and supply region of the hepatic vein, and to assess the impact of reconstruction of the hepatic vein on the blood supply of the involved liver tissues. A study conducted by Lamade *et al.* [39] highlighted the value of 3D technology in preoperative planning by comparing differences between 3D and 2D technologies in preoperative assessment. 3D technology revealed more accurate tumor localization and selection of the extent of resection. These accuracies increased by 37% and 31%, as compared with 2D technology. Tang *et al.* [25] conducted surgical planning through the 3D-assisted estimation of resected liver volume, and determined whether hepatectomy was feasible according to the proportion of the resected liver. The surgical plan and actual operation showed good consistency.

The estimation of liver volume and resection margin is critical to surgical planning, and 3D technology can improve the accuracy of liver volume estimation [5, 14, 51]. Our study revealed a strong correlation between 3D-estimated value and the actual measured liver volume, suggesting that 3D technology can accurately estimate the liver volume and resection margin. A comparison with 2D technology revealed a good consistency between 3D and 2D technologies for the estimation of liver and tumor volumes, suggesting that 3D technology has a similar reliability as traditional 2D technology; while a comparison of actual measured values revealed greater accuracy with 3D technology, especially for the estimation of the resection margin. The features of 3D technology facilitate the precision of preoperative assessment and planning, and improve intraoperative efficacy and safety.

3D technology also influences surgical procedures and postoperative efficacy. It has been recognized that 3D-assisted hepatectomy is associated with a shorter surgical duration. This is because, depending on the 3D technology, surgeons have a better understanding of the liver anatomy and lesion features before the surgery. Therefore, the surgical plan is more rational, which facilitates the smooth implementation of the operation. The application of 3D technology is helpful in reducing intraoperative blood loss, improving safety, and promoting postoperative recovery. Although there was no significant difference in the length of hospitalization between these 3D and 2D groups, the 3D group had certain advantages in terms of postoperative complications, as demonstrated by the lower incidence of biliary fistula, ascites and liver failure in the 3D group. Studies have also shown that 3D-assisted hepatectomy resulted in a higher proportion of negative resection margins, which is critical for prognosis [26]. In addition, the application of 3D technology reduces intraoperative blood loss in pediatric hepatectomy, which is of great clinical significance in pediatric liver resection [31]. Laboratory examinations revealed that postoperative serum bilirubin and hemoglobin levels were superior in the 3D group. All of these findings indicate that 3D technology is helpful for the implementation of an operation and postoperative recovery, which may have potential impacts on prognosis. However, more clinical trials and long-term follow-up data are required to more fully evaluate the effect of 3D technology on the efficacy of hepatectomy.

3D printing technology and intraoperative real-time navigation technology are extensions of 3D visualization. However, the application of these advanced digital medical technologies in hepatectomy remains in the exploratory stage. Igami *et al.* [52] used a 3D-printed transparent liver model to find small liver tumors, which were undetectable with intraoperative ultrasound, and found that the application of 3D printing in the surgical treatment of small liver cancer achieved satisfactory effects. Xiang *et al.* [53] applied 3D printing technology-assisted hepatectomy to treat a complex massive hepatocarcinoma with variations of the portal vein. The printed liver model was used for preoperative planning, as well as intraoperative navigation. At present, the high cost of 3D technology remains an obstacle to its clinical application. Oshiro *et al.* [54] invented a new 3D-printed liver model for hepatectomy, which reduced cost, shortened production time and improved visualization. 3D technology translates abstract 3D images in the surgeon's brain to intuitive 3D images on the computer, while 3D printing technology transforms virtual 3D images to an actual solid model [55]. 3D-printed models offer greater advantages in the display of anatomical structures and lesions, the estimation of liver volume and resection margin, as well as operational simulation. Hence, this technology plays an important role in preoperative planning and intraoperative navigation.

Real-time intraoperative navigation is one of the most challenging techniques in the field of surgical research. With the development of digital medical technology, a variety of navigation techniques have been applied in hepatectomy. One of these applications is the use of intraoperative ultrasound for real-time navigation [56, 57]. Some researchers have reported the transformation of 3D information into a liver "risk map", which was applied for intraoperative navigation to reduce surgical risk [12, 58]. Ntourakis *et al.* [59] introduced augmented reality guidance technology for the treatment of minimal residual liver metastases of colon cancer after chemotherapy. This technique can display the liver structure in real time, and detect small lesions by combining preoperative 3D reconstruction images and intraoperative real-time patient images. Hannes *et al.* [60] reported the use of a real-time navigation system based on intraoperative CT imaging. Intraoperative CT images can be simultaneously transformed into 3D images to realize real-time navigation. Aoki *et al.* [61] reported the application of 3D virtual endoscopy in the navigation of laparoscopic hepatectomy, which increased surgical precision. Liu *et al.* [62] applied an indocyanine green-mediated infrared fluorescence detection technique for intraoperative navigation, which helped to determine the resection margin and guide hepatectomy. Buchs *et al.* [63] applied real-time navigation technology to robotic liver surgery to improve the surgeon's orientation and increase the precision of tumor resection. Although real-time navigation technology remains in the stage of innovation and exploration, this technology has shown a broad application potential in hepatectomy.

3D visualization technology is widely used in the surgical treatment of many liver diseases, as it facilitates the realization of precision hepatectomy. 3D visualization can clearly show the anatomical structures of the liver and lesion features, and accurately estimate the liver volume and resection margin. This technology plays an important role in preoperative assessment and planning, and benefits surgical implementation and postoperative recovery. Furthermore, the application of 3D technology increases the safety and efficacy of hepatectomy, and may have a potential impact on disease prognosis.

Disclosure of conflict of interest

None.

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