Review Article

Current Technology in Navigation and Robotics for Liver Tumours Ablation

Stephen KY Chang,[1] *MBBS, FRCS Ed (Gen Surg),FAMS*, Wah Wah Hlaing,[1] *MBBS*, Liangjing Yang,[2] *BEng (Hons)*, Chee Kong Chui,[2] *PhD*

Abstract

Radiofrequecy ablation is the most widely used local ablative therapy for both primary and metastatic liver tumours. However, it has limited application in the treatment of large tumours (tumours >3cm) and multicentric tumours. In recent years, many strategies have been developed to extend the application of radiofrequency ablation to large tumours. A promising approach is to take advantage of the rapid advancement in imaging and robotic technologies to construct an integrated surgical navigation and medical robotic system. This paper presents a review of existing surgical navigation methods and medical robots. We also introduce our current developed model — Transcutaneous Robot-assisted Ablation-device Insertion Navigation System (TRAINS). The clinical viability of this prototyped integrated navigation and robotic system for large and multicentric tumors is demonstrated using animal experiments.

Ann Acad Med Singapore 2011;40:231-6

Keywords: Computer aided surgery, Liver, Radiofrequency ablation

Introduction

Hepatocellular carcinoma (HCC) is the sixth most common cancer[1] and the liver is the most common site of metastatic disease for intra-abdominal malignancies. Surgical resection of primary and metastatic hepatic tumours remains the gold standard of therapy. However, patients with advanced disease, unfavourable tumour anatomic location, large size or number of lesions, inadequate liver reserve, or severe comorbid conditions will preclude surgery and are not suitable for surgical resection.

For this group of patients, a wide range of local ablative therapies have been developed. Radiofrequency ablation (RFA) is one of the most widely used techniques and has been shown to have efficacy in term of overall-survival and disease-free survival.[2] However, treatment efficacy is dependent on the completeness of the ablation, and radiofrequency ablation has limited application in treatment of large tumours (tumours >3cm) and multicentric tumours.[3]

Current strategies to improve ablation efficacy have evolved to include accurate preoperative imaging, 3-dimensional image reconstruction with preoperative planning and robot-assisted placement of the ablation needle. This paper provides a review of the current available technology and development in this field.

Current Limitations to Radiofrequency Ablation

Radiofrequency ablation (RFA) has proved to be an effective and safe alternative for patients who are not suitable for surgery.[2-4] RFA is a well tolerated procedure with a mortality rate of 0% to 1.2% and a complication rate of 3% to 7%.[3] A major limitation of RFA is that it can only treat a small volume of tumour. The maximum diameter of the ablation sphere produced by most RF devices is 3 cm. The rate of complete ablative necrosis decreases with the size of the tumour, particularly those larger than 3 cm. Therefore, multiple overlapping ablation is applied to cover large volume tumour (>3cm). This will require multiple needle insertions. Due to the lack of 3D image guidance, complete ablation of tumour is not guaranteed.

Current practice for transcutaneous radiofrequency ablation involves a series of imaging and manual insertion based on the judgment of radiologists or surgeons. This method is tedious and is often subjected to uncertainties.

[1] Department of Surgery, National University Hospital, Singapore
[2] Department of Mechanical Engineering, National University of Singapore, Singapore
Address for Correspondence: Dr Chang Kin Yong, Stephen, Division of Hepatobiliary and Pancreatic Surgery, Department of Surgery, University Surgical Cluster, Level 8, NUHS Tower Block, 1E Kent Ridge Road, Singapore 119228.
Email: cfscky@nus.edu.sg

Though real time ultrasound image guidance is available, this method has several limitations such as the inadequacy in depth perception and the creation of transient hyperechoic zone due to the microbubbles in ablated tissue,[5,6] thus precluding accurate subsequent placement of ablation needles for overlapping ablations.

During execution of RFA needle insertion, surgeons are required to avoid major blood vessels, biliary structure and gastro-intestinal tract. Without sophisticated image guidance, the success of RFA depends largely on individual surgeon's experience. The treatment outcomes are therefore subjected to uncertainties.

Current Models of 3D Reconstruction and Pre-procedure Planning

Various 3 dimensional (3D) reconstruction algorithms have been used successfully for many years.[7,8] Today reconstruction software like MIPAV™ (Medical Image Processing, Analysis and Visualization) has matured and many technical details have already been refined. In addition to the commercial 3D reconstruction software, several developer communities have been making available open source software libraries and platforms dedicated to medical applications. Examples would be the Image-Guided Surgery Toolkit (IGSTK) (http://www.igstk.org), Medical Imaging Interaction Toolkit (http://mbi.dkfz-heidelberg.de) and Medical Imaging Toolkit (http://www.mitk.net). The Medical Imaging Toolkit features a functional application called 3D Med for image segmentation and display.

However, the reconstruction is predominately used for pre-procedure assessment and post-procedure follow-up.[9] This is because there are several major problems with real-time image reconstruction. Error in registration and reconstruction can be caused by breathing, patient movement, organ shift due to change in patient's position and the RFA procedure itself. Various tracking and correction systems have been developed[10] but application in real-time is still limited and further research and development are needed.

There are many research projects aiming at developing advanced visualisation and pre-procedure planning specifically for liver surgery. They include the "RF-SIM"[11] which is a comprehensive surgery simulation tool for pre-procedure simulation and planning of RFA liver surgery, an immersive virtual reality environment with advanced image segmentation features and man-machine interface,[12] and an augmented reality guidance system for RFA.[13] We have been collaborating with the Biomedical Precision Engineering Lab in The University of Tokyo, Japan to characterise and visualise the normal, pathological and ablated liver tissue using magnetic resonance (MR) elastography during RFA.

Although the size and shape of RFA have been measured and represented using theoretical models,[14-16] and clinical evaluation of needle placement strategies for multiple RFA application has also been reported,[17] computer planning of optimal RFA treatment is highly complex. The fundamental biophysics of tissue ablation is not completely understood.

Current Models of Robot-assisted Surgical Navigation Systems

The first interactive surgical navigation systems were developed almost simultaneously in Japan and Europe[18-20] which combined frame based stereotaxy with modern medical imaging. The navigation system developed in The University of Tokyo, Japan[18] comprised multi-axis mechanical measuring arms equipped with angular sensors, and video equipment for digitalising computer tomography (CT) scans from conventional films. Due to the almost simultaneous appearance of similar CT and then the MR-based navigation systems in the mid-1980s, these similar applications have been given different names. The term "computer aided surgery" is now widely used to refer to the navigation system that combines preoperative CT/MR imaging with a passive digitiser. The term "computer assisted surgery" is more often used to describe a surgical system with active robotic devices. Computer aided (or assisted) surgery (CAS) is probably the most suitable term for all the different clinical and engineering methods where computer is directly applied to surgery. The different methods include diagnostics, navigation, telesurgery, medical robotics, virtual and augmented reality. The relatively recent term — CIS for computer integrated surgery is used almost identically to CAS.

The development in CAS was started in neurosurgical and orthopedic applications. The constraints due to the rigid structure of bones and the encapsulation of brain in the skull facilitate the early computer assisted surgical procedures. There is a rapid progress in CAS over the last few decades. Navigation systems have been used for various surgical treatments[21-23] including removal of deep-seated brain tumours, paranasal sinuses treatment, and total knee replacement. Prototype robot-assisted navigation systems for cancer treatment of soft tissue such as breast, lung and liver have also been reported.[24-26] A needle insertion device for RFA of liver tumours was described in Sakuma et al.[27] It was a passive navigation system. The navigation arm, patient and preoperative model of the passive navigation system were registered by an optical position sensor system. The needle holder was mounted on a base that can rotate and move vertically. The lateral position can be fixed using a mechanical lock. Actual positioning of the needle was done using 2 longitudinal and 1 rotational motion. In Kobayashi et al,[28] liver deformation simulation was integrated into the image guided needle insertion system.

Commercially available navigation systems (Fig. 1) such as the StealthStation® TREON™(Medtronic Inc), SteathStation® ION™ (Medtronic Inc), Stryker® Navigation System II™ (Stryker Inc), Stryker® ENlite™ (Stryker Inc), VectorVision® BrainLab™ (BrainLab Inc), EasyTaxis™ (Philips Medical Systems Inc) and Atlas™ (Medical Intelligence Inc) have been used in various principal of surgery with some successes. Nevertheless, the existing surgical navigation systems, registration and tracking apparatus[29,30] still comprise mainly passive operations and involve manual control. They provide a form of spatial guidance but do not guarantee effective and consistent translation of preoperative plans to intraoperative executions.

Effective integration of medical robotics and image-guided navigation remains a challenge to the CAS community. By extending human surgeon's ability to plan and carry out surgical interventions more accurately and less invasively, robot-assisted surgical navigation system, can greatly reduce costs, improve clinical outcomes, and improve the efficiency of healthcare delivery. The field of medical robotic is relatively new,[31] and robot-assisted surgical navigation system for liver tumour RFA is far from being fully exploited. A solution to remedy this discrepancy is through a more efficient preparation of the intervention via computer simulation. However, computer simulation of medical robotic is still very much in its infancy.[32,33]

Our Current Developed Model: Transcutaneous Robot-assisted Ablation-device Insertion Navigation System (TRAINS)

The model features 3D imaged guided pre-procedure planning of needle trajectories and robot-assisted execution of planned needle trajectories. The model is designed to achieve complete ablation of large tumours that require multiple overlapping ablations.

(a) Operating process

First a diagnostic imaging, either Magnetic Resonance Imaging (MRI) or Computed Tomography (CT), is carried out to identify and locate the tumour. Using the imaging information, a 3D reconstructed image displaying the liver with its vascular structures and the relations to the tumour as well as surface skin markers is obtained. The 3D reconstructed image is created using advanced importance-driven visualisation software that we have developed. Three-dimensional images, together with a needle insertion and ablation simulation user interface, enable surgeon to plan the needle trajectories in order to achieve safe and complete ablation of the tumour. The planned trajectories are then fed to the robot-assisted system which executes the needle insertion as planned.

(b) Feasibility

The feasibility and applicability of our prototype model (Fig. 2) was validated through a live porcine experiment. A phantom tumour was created in the porcine liver and ablation was carried out using the proposed model. After the tumour ablation, the liver was resected and taken out for inspection (Fig. 3). It was noted that the tumour was accurately ablated with 1.65 mm of safety margin. The average deviation in concentricity between the ablated

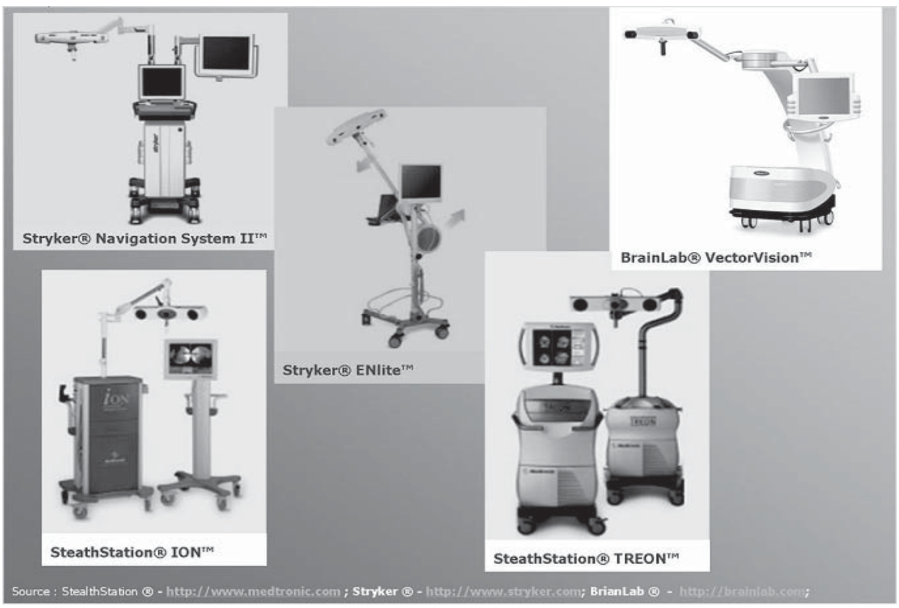

Fig. 1. Various model of commercially available navigation systems.

zone and the phantom tumour is 1.5 mm. This is done by the measurement of the difference in ablation centre and tumour centre.

(c) Features

The features in the proposed model include

(i) *3 D image guided pre-procedure planning of needle trajectories*: In order to achieve complete necrosis of large tumour, the model utilises multiple needle insertion with overlapping ablations. Application of multiple RF needles enhances control over the size and shape of ablation cavity. Coupled with pre-procedure planning of needle trajectories in three dimensional interface, it enables surgeon to achieve complete ablation of tumour while avoiding critical structures such as major vessels and biliary structures. A screenshot of the user interface is featured in Figure 4.

(ii) *Robot assisted surgical navigation system*: However multiple needles insertion for overlapping ablation is difficult to perform manually. Following the first ablation cycle, real time image of the tumour becomes distorted. Therefore surgeons are often deprived of visual information of the residual tumour and have to rely highly on non-intuitive image guidance in executing the preplanned ablation model. Performing such operation manually will also be subjected to uncertainties and inconsistent outcomes.

To achieve consistent and precise result with multiple overlapping ablations, the model applies a robotic system to execute multiple needles insertion with pre-determined insertion trajectories. The robotic system (Fig. 5) is equipped with customized adaptors to allow various needle trajectories. The technical details of the design and mobility are described in Yang et al.[34-36]

Moreover, the system allows surgeon to monitor the execution process. In the event of unexpected movements by the robotic system, the needle can be detached from robotic control via a quick release mechanism and the needle

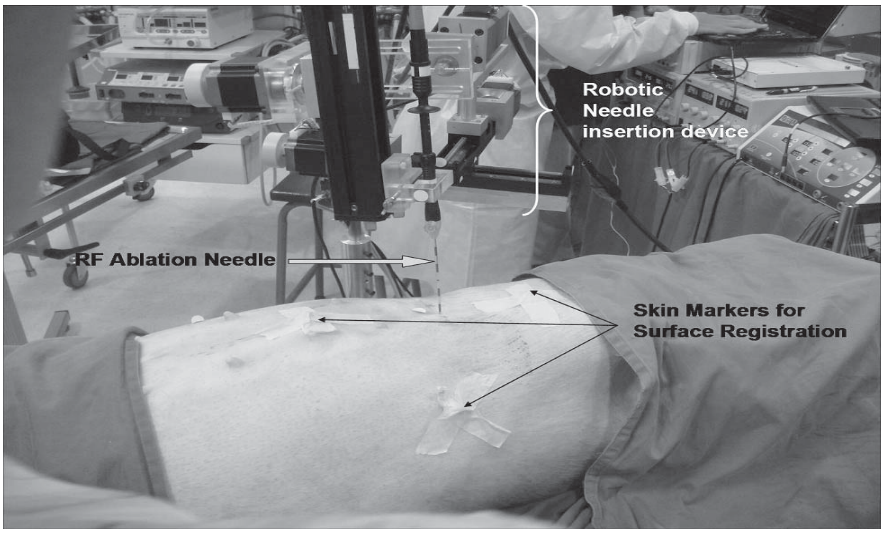

Fig. 2. TRAINS being used in the animal experiment.

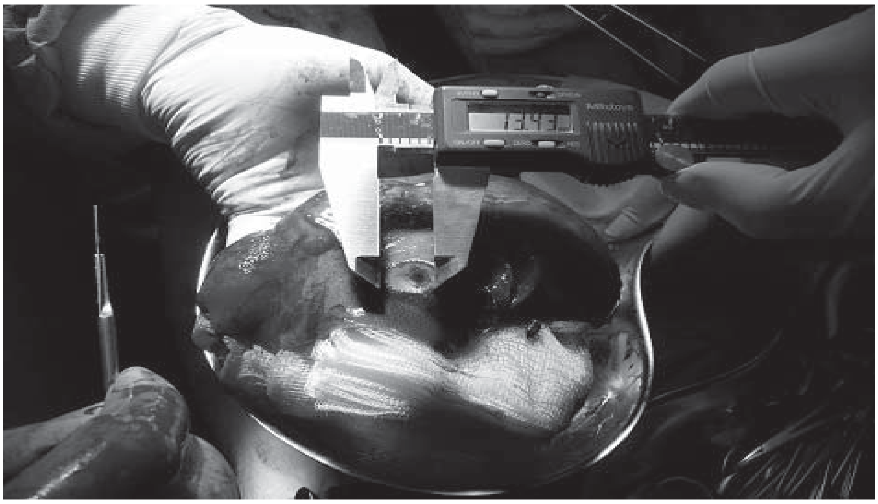

Fig. 3. Measurement of ablated region.

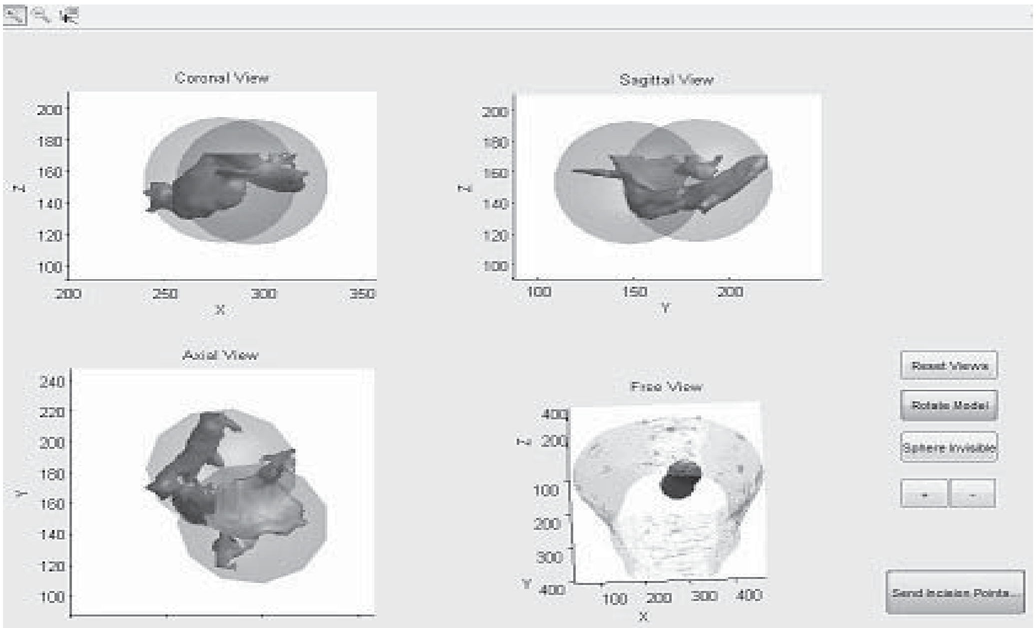

Fig. 4. User interface for ablation plan visualisation software.

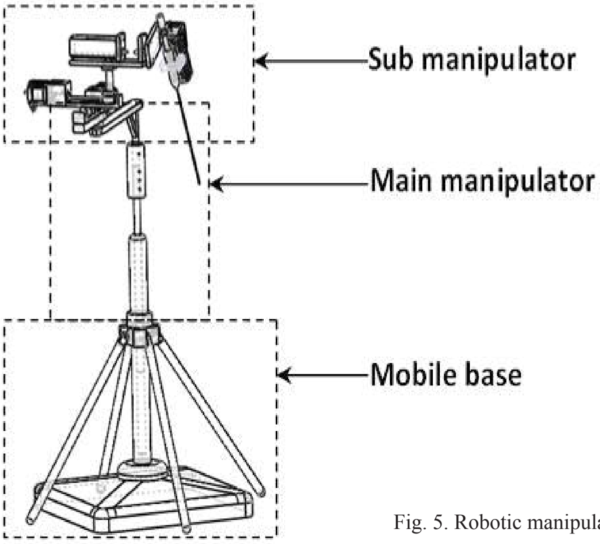

Fig. 5. Robotic manipulator for needle insertion.

insertion can be done manually. This manual overwrite mechanism allows the human operator to have a complete control over the operation.

(iii) *Sterilisation and safety*: The model takes into account sterilisation and safety issue. The components that come into contact with the patients can be sterilised in autoclave and all the electromechanical components can be covered with sterile sheaths. The system components are easily detached from the patient in case of emergency. A reliable power cut-off mechanism has also been integrated into the model as a risk control measure.

Conclusion

Current curative application of RFA is limited to small tumours (≤3cm) when the number of tumour is fewer than 3. Existing commercially available system are not linked with any robotic automatic interface. The existing navigation and medical robots could not be easily extended or modified for effective treatment of large liver tumors. In this paper, we also introduced TRAINS which is for transcutaneous robot-assisted ablation with 3D navigation. Our developed model is a promising one which allows ablation of large tumours and widens curative modalities for patients who cannot undergo conventional liver surgery. The clinical viability of this system is demonstrated via animal experiments.

REFERENCES

1. Parkin DM, Bray F, Ferlay J, Pisani P. Global cancer statistics, 2002. CA Cancer J Clin 2005;55:74-108.
2. Lau WY, Lai EC. The current role of radiofrequency ablation in the management of hepatocellular carcinoma: a systematic review. Ann Surg 2009;249:20-5.
3. Bruix J, Sherman M. Management of hepatocellular carcinoma. Hepatology 2005; 42:1208-36.
4. Rossi S, Di Stasi M, Buscarini E, Cavanna L, Quaretti P, Squassante E, et al. Percutaneous radiofrequency interstitial thermal ablation in the treatment of small hepatocellular carcinoma. Cancer J Sci Am. 1995;1:73-81.
5. Choi, D, Lim HK, Kim SH, Lee WJ, Jang HJ, Lee JY, et al. Hepatocellular carcinoma treated with percutaneous radio-frequency ablation: usefulness of power Doppler US with a microbubble contrast agent in evaluating therapeutic response-preliminary results. Radiology 2000; 217:558-63.
6. Goldberg SN, Gazelle GS, Solbiati L, Livraghi T, Tanabe KK, Hahn PF, et al. Ablation of liver tumors using percutaneous RF therapy. AJR Am J Roentgenol 1998;170:1023-8.
7. Calhoun PS, Kuszyk BS, Heath DG, Carley JC, Fishman EK. Three-dimensional volume rendering of spiral CT data: theory and method. Radiographics 1999;19:745-64.
8. Racadio JM, Babic D, Homan R, Rampton JW, Patel MN, Racadio JM, et al. Live 3D guidance in the interventional radiology suite. AJR Am J Roentgenol 2007;189:W357-64.
9. Israel O, Keidar Z, Iosilevsky G, Bettman L, Sachs J, Frenkel A. The fusion of anatomic and physiologic imaging in the management of patients with cancer. Semin Nucl Med 2001;31:191–205.
10. Giesel FL, Mehndiratta A, Locklin J, McAuliffe MJ, White S, Choyke PL, et al. Image fusion using CT, MRI and PET for treatment planning, navigation and follow up in percutaneous RFA. Exp Oncol 2009;31:106-14.
11. Villard C, Soler L, Gangi A. Radiofrequency ablation of hepatic tumors: simulation, planning, and contribution of virtual reality and haptics. J Comput Methods Biomech Biomed Eng 2005;8:215-27.
12. Reitinger B, Bornik A, Beichel R, Schmalstieg D. Liver surgery planning using virtual reality. IEEE Comput Graph Appl 2006;26:36-47.
13. Nicolau S, Pennec X, Soler L, Ayache N. A complete augmented reality guidance system for liver punctures: first clinical evaluation. Med Image Comput Comput Assist Interv 2005;8:539-47.
14. Ni Y, Mulier S, Miao Y, Michel L, Marchal G. A review of the general aspects of radiofrequency ablation. Abdom Imaging 2005;30:381-400.
15. Mulier S, Ni Y, Miao Y, Rosiere A, Khoury A, Marchal G, et al. Size and geometry of hepatic radiofrequency lesions. Eur J Surg Oncol 2003;29:867-78.
16. Berjano EJ. Theoretical modeling for radiofrequency ablation: state-of-the-art and challenges for the future. Biomed Eng Online 2006;5:24.
17. Chen MH, Wei Y, Yan K, Gao W, Dai Y, Huo L, et al. Treatment strategy to optimize radiofrequency ablation for liver malignancies. J Vasc Interv Radiol 2006;17:671-83.
18. Watanabe E, Watanabe T, Manaka S, Mayanagi Y, Takakura K. Three dimensional digitalizer (neuro-navigator): a new equipment for CT guided stereotaxic surgery. Surg Neurol 1987;27:543-7.
19. Roberts DW, Strohbehn JW, Hatch JF, Murray W, Kettenberger H. A frameless stereotaxic integration of computerized tomographic imaging and the operating microscope. J Neurosurg 1986;65:545-9.
20. Reinhardt H, Meyer H, Amrein E. Computer aided surgery: Robotik fur Hirnoperationen? Polyscope plus 1986;6:1-6.
21. Reinhardt H, Trippel M, Westermann B, Gratzl O. Computer aided surgery with special focus on neuronavigation. Comput Med Imaging Graphs 1999;23:237-44.
22. Chu ST. Endoscopic sinus surgery under navigation system – analysis report of 79 cases. J Chin Med Assoc 2006;69:529-33.
23. Stulberg SD, Loan P, Sarin V. Computer-assisted navigation in total knee replacement: results of an initial experience in thirty-five patients. J Bone Joint Surg Am 2002; 84:90-8.
24. Alderliesten T, Loo C, Schlief A, Paape A, Van Der Meer M, Gilhuijs K. Application of an image-guided navigation system in breast cancer localization. Proc SPIE 2009;7261:726111
25. Akeboshi M, Yamakado K, Nakatsuka A, Hataji O, Taguchi O, Takao M, et al. Percutaneous radiofrequency ablation of lung neoplasms: initial therapeutic response. J Vasc Interven Radiol 2004;15:463-70.
26. Mundeleer L, Wikler D, Leloup T, Warzee N. Development of a computer assisted system aimed at RFA liver surgery. Comput Med Imaging Graph 2008;32:611-21.
27. Sakuma I, Awao T, Masamune K, Nakagori T, Asano T, Inada H, Dohi T. International Conference on Computer Assisted Radiology and Surgery (CARS) 2000:978.
28. Kobayashi Y, Onishi A, Watanabe H, Hoshi T, Kawamura K, Hashizume M, et al. Development of an integrated needle insertion system with image guidance and deformation simulation. Comput Med Imaging Graph 2010;34:9-18.
29. De La Barrera JLM, Sarvestani A, Boehringer MJ, Schoepp H, Buehner U.. Surgical Navigation Tracker, System and Method. Patent Application Publication. United States: 2005.
30. Clayton JB, Melkent A, Foley KT, Sherman MC. Percutaneous Registration Apparatus and Method for Use in Computer-Assisted Surgical Navigation. Patent Application Publication.United States: 2006.
31. Taylor RH, Stoianovici D. Medical robotics in computer-integrated surgery. IEEE Trans Robotics and Automation 2003;19:765-81.
32. Chui CK, Sakuma I, Topology independent model for medical robotic simulation. 17th Conference of Japan Society of Computer Aided Surgery (JSCAS) 2007:177-178.
33. Freund E, Heinze F, Rossmann J. Robotic simulation system for precise positioning in medical applications. Scientific Workshop on Medical Robotics. Navigation and Visualization 2004:270-77.
34. Yang L, Chui CK, Chang S. Design and development of an augmented reality robotic system for large tumor ablation. International Journal of Virtual Reality 2009;8:27-35.
35. Yang L, Chng CB, Chui CK, Lau DPC. Model-based design analysis for programmable remote center of motion in minimally invasive surgery. Robotics, Automation and Mechatronics (RAM), 2010.
36. Yang L, Wen R, Qin J, Chui CK, Lim KB, Chang SK Y. A robotic system for overlapping radiofrequency ablation in large tumor treatment. IEEE/ASME Transactions on Mechatronics (TMECH), 2010.