The development and evaluation of a virtual radiotherapy treatment machine using an immersive visualisation environment

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Abstract

Due to the lengthy learning process associated with complicated clinical techniques, undergraduate radiotherapy students can struggle to access sufficient time or patients to gain the level of expertise they require. By developing a hybrid virtual environment with real controls, it was hoped that group learning of these techniques could take place away from the clinical departments.

This paper presents initial evaluation of the use of a three-dimensional immersive visualisation environment (IVE) to simulate a working radiotherapy treatment machine. A virtual patient complete with a range of different treatment sites was used to enhance learning and teaching of beam alignment in 3D. Pre- and post-questionnaires were used to evaluate the perceptions of 42-year 1 pre-registration students with regards to the learning that had taken place.

93% of students perceived an improvement in their understanding and confidence in their technical skills as a result of using the IVE. The mean overall improvement was 21.2% ($p<0.00001$), and this was positively correlated to perceived realism of the application. The application was reported to be both realistic and enjoyable. Feedback suggested it has a role to play in development of technical skills and also pre-clinical induction. More work with the application is ongoing to clarify that role and the potential benefits of this technology.

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1. Introduction

1.1. Clinical training

Radiotherapy students are expected to acquire a multitude of skills during their clinical placements in oncology departments. Prominent among these are the ability to communicate with patients in a caring and empathic manner and considerable psychomotor skills. Although it is obvious that the most effective place to learn these skills is in the clinical environment with real patients, this can be associated with difficulties. The need to provide reassurance and a high level of patient communication can frustrate efforts to learn psychomotor skills concurrently. Additionally, pressure on time due to lengthening patient waiting lists (Ash, Barrett, Hinks, & Squire, 2004) and more complex techniques such as intensity modulated radiotherapy (Intensity Modulated Radiation Therapy Collaborative Working Group, 2001) is increasingly encroaching on clinical resources. This pressure means that students may feel rushed and unable to maximise their learning of less common and potentially more demanding techniques. One such technique is “skin apposition”, where the patient couch and radiotherapy equipment has to be rotated and translated along up to 6 axes in order for the resulting radiotherapy beam to strike the surface of the skin perpendicularly. This demands good spatial awareness, psychomotor skills and ultimately a large amount of experience.

The preferred method of gaining this experience is to allow students to practice on dummy patients in a real treatment room. The time-consuming nature of this technique, however, coupled with the constant demand on resources for real patient treatments means that this is rarely feasible. It was hoped that an accurate interactive simulation of the technique would enable students to gain valuable practice without burdening the clinical departments. A realistic virtual reality environment would also allow students to make (and learn from) errors that would not be tolerated in the real world where patient safety and care of costly equipment are paramount considerations. To this end, it was decided to develop a virtual treatment room with genuine control systems and a range of practice treatment sites.

1.2. Virtual reality in medical training

Medical training, characterised by highly complex procedures with no room for trial and error is ideally suited to the use of virtual reality (VR) simulators. Opportunities for practice are severely restricted and traditionally have been limited to “in at the deep end” experiences on patients who desperately need the procedure doing correctly. VR applications have been successfully used to enhance training in procedures such as endotracheal tube placement (Mayrose, Kesavadas, Chugh, Joshi, & Ellis, 2003), arthroscopy (Ziegler, Fischer, Muller, & Gobel, 1995), bronchoscopy (Ost et al., 2001) and IV catheter placement (Engum, Jeffries, & Fisher, 2003). These medical simulators are usually small screen-based/equipment-based programs, which is ideally
suited to practice using specific small equipment such as a bronchoscope. The proposed simulation of something as large as a linear accelerator treatment room obviously demands the appreciation of the large-scale view and the ability to see and manipulate the environment in 3D. To maintain an acceptable level of presence in this situation, it was decided to utilise an immersive visualisation environment (IVE).

1.3. Immersive visual environments

There are different levels of sophistication of IVE’s and they can be neatly categorised into “closed” devices that present a virtual environment to individuals and “open” devices that replicate the environment around a group of people. Closed devices such as headsets allow the user to be fully immersed visually and aurally in a personal experience. Coupling this with haptic devices potentially allows the ultimate immersive experience possible. Modern retinal scanning technology such as that outlined by Tidwell, Johnston, Melville, and Furness (1995) offers the potential for unrivalled visual clarity and presence. Avatars have been used successfully to represent other participants in group work by authors such as Ødegård and Øygard (1997), but this brings significant demands on the technology as confirmed by Lee, Chai, Reitsma, Hodgins, and Pollard (2002).

For teaching purposes, group work has been shown to enhance learning since Vygotsky’s seminal work in the 1970s (Vygotsky, 1978), and for training in situations where teamwork is the norm in real life, closed immersions can be potentially restrictive. Although aural input has been successfully used by Jackson and Fagan (2000) to allow communication between users, visual cues from others are missing and the benefits of group interactions are diminished. A study by Newman, Johnson, Webb, and Cochrane (1997) confirmed that face-to-face interactions provided improved learning compared to computer interactions alone when in a problem-solving environment. When designing the current application, it became clear that open immersive technology would be most appropriate, allowing users to communicate directly and visualise each other within the environment. For these situations, a powerful solution is the use of large stereoscopic projection screens. Studies such as those by Patrick et al. (2000) and Tyndiuk et al. (2004) have confirmed the benefit of largewall displays for “manipulation” tasks involving spatial awareness and 3D movements. These can range from multiple walled environments to a simple single screen such as the Powerwall (University of Minnesota, 1998). A similar system was used for the development of this application.

2. Virtual treatment machine – requirements and development

2.1. Aim

The aim of the application was to provide students with a virtual environment containing a linear accelerator that they were able to control in real time using a genuine control pendant. This hybrid environment combining real and virtual objects was then to be used to train students to achieve good skin apposition. The skin apposition simulator application was not developed to replace clinical training. Instead, it aimed to provide a useful alternative in a safe environment that
is conducive to group learning and experimentation. It was seen as an enhancement rather than a replacement.

2.2. Requirements

For the application to be of use as a training tool, the level of realism needed to be considerable. Zeltzer (1992) neatly identified the three features of a virtual environment that contribute to realism as being autonomy, presence and interaction. The autonomy of this application is minimal since the real environment does not act autonomously and the control pendant determines all movement in the room. The only area of autonomy that could exist in this situation is that of the virtual patient. This was not felt to be a requirement, although potentially feedback or motion from the virtual patient could be used to increase realism. The presence and interaction in this application are intrinsically linked to the control system. The presence is the degree to which the user feels that they are really in the environment. To some extent, the uniqueness of the linear accelerator environment and the use of a real control system may contribute to students’ ability to interact intuitively with the application. Since the students have all had experience in the real environment and used a similar control system, the transfer of skills to the virtual environment should be intuitive.

3. Application development

3.1. Virtual linear accelerator

The VR environment utilises the three-dimensional Hull immersive visualisation environment (HIVE) to replicate a working linear accelerator, as previously described by Phillips, Ward, and Beavis (2005). The HIVE features a 16 × 8 foot stereo work-wall. The model was generated from measurements of a Varian CLINAC treatment machine (Varian Medical Systems, 2005). Laser scanning techniques using a Leica Geosystems HDS3000 were used to improve the accuracy of the model (see Fig. 1). For this application, an electron applicator and visible light field were added to the model.

3.2. Control system

A genuine Varian linear accelerator control pendant was employed as the user interface as shown in Fig. 2. Although in reality, some of the controls would be situated on the couch itself, achieving this would require the use of advanced haptic glove controls. The use of a genuine control system was deemed essential for engendering realism and presence in this application.

3.3. Virtual patients

A virtual patient was rendered using the Visible Human female dataset (National Library of Medicine, USA). Simple rectangles representing treatment sites were highlighted on the patient surface using conventional drawing software. This is equivalent to the clinical setting, where pen marks are drawn on the patient to delineate the treatment area. The sites were wrapped around
the 3D body, in order to provide a variety of challenges for treatment set-up using skin apposition as seen in Fig. 3.

4. Methodology

4.1. Aims

The primary aim of the study was to assess if the virtual treatment machine had enhanced students’ understanding of a complicated 3D task. It also aimed to provide information concerning
the ease of use and realism of the application, to guide further improvements. A direct comparison with equivalent training in the real environment was not attempted due to the disparity between the experiences. The whole patient interaction element was missing in the virtual environment and the IVE application did not attempt to better the experience. Rather the assessment was aimed at evaluating the usefulness of the application as a tool to supplement students’ clinical education and enhance their technical skills. The evaluation measured student understanding of the technique rather than skill acquisition. As with any practical skills training, it was deemed important that students first acquire the understanding of the technique, allowing the skills themselves to be acquired more easily in the clinical environment.

4.2. Assessment tool

A pre- and post-questionnaire design was used to collect quantitative data, using a 5-point Likert response adapted from Engum et al. (2003). A short self-assessment questionnaire was completed before using the virtual treatment machine. This provided baseline demographics regarding age, gender, previous clinical experience and control system use, as well as assessing student confidence as regards the 3 learning outcomes as seen in Table 1. The students rated how well

Table 1
Questionnaire statements regarding learning outcomes

<table>
<thead>
<tr>
<th>Learning outcome</th>
<th>Questionnaire statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Understand the technique principles</td>
<td>I understand what is required for good skin apposition</td>
</tr>
<tr>
<td>Understand how to apply technique</td>
<td>I know what movements to make to improve skin apposition</td>
</tr>
<tr>
<td>Have confidence to assist clinically</td>
<td>I could assist in the set-up of a skin apposition patient</td>
</tr>
</tbody>
</table>
they felt they understood the requirements of the technique, their understanding of how to apply this knowledge, and finally their confidence with the technique clinically. Thus underpinning knowledge, as well as understanding and full application of the knowledge was gauged.

The post-questionnaire included the same questions to determine if learning had taken place. Although fundamentally this was the most important finding, data were also collated concerning factors that could have affected this learning. Further Likert-style questions were included to collect data regarding ease of use, realism, level of interaction with the environment (control system) and enjoyment engendered by interacting with the application. Open questions at the end collected qualitative data regarding suggestions, problems and perceived benefits of the application, as described by Bergin and Fors (2003).

4.3. Analysis

Comparison of student responses before and after use of the application was performed using the paired t test to quantify the learning that had taken place. Correlation analysis was used to elucidate any factors contributing to performance or attitude.

4.4. Cohort

Forty-two first year pre-registration radiotherapy students at Sheffield Hallam University evaluated the application. Information was collected concerning students’ age, gender, and previous experience with the technique. There were 14 males and 28 females and the age range was from 19 to 51 with a mean of 29 and a mode of 34. All students had worked in the clinical environment for 5 weeks using a linear accelerator. A range of manufacturers’ equipment is in use across the students’ different clinical placement sites, and information was gathered concerning student experience with individual control systems.

5. Results

5.1. Internal reliability

Questions with opposing expected responses were correlated to determine the reliability of the cohort. There was a negative correlation of $-0.745$ between the answers to these questions, suggesting good reliability within the cohort.

5.2. Impact on learning

The pre- and post-test scores were compared using a paired t test to determine the effect of the application on learning. Table 2 shows the results of this analysis. Students felt that they had improved their understanding and confidence in their technical skills after using the VR application. The mean student confidence with the skin apposition technique was 51.8% before using the application. This rose to 73% confidence after using it ($p<0.00001$). Randomised controlled
studies are currently being developed to determine how much of this perceived improvement was solely due to the application and, crucially, how well this student confidence transfers to the clinical environment.

5.3. Ease of use and realism

Table 3 illustrates the student responses to a range of statements concerning the application. In this study, 88% of students reported that they found the application to be realistic and none of them reported it to be unrealistic. 69% of the students found the control system to be “easy to master”, whereas only 17% struggled with them. This was better than expected, since only 55% of the students had used identical controls (from the same manufacturer) clinically. As expected with any new multi-media teaching tool, 93% of students reported that they enjoyed using the virtual treatment machine. There were two exceptions with subjects reporting feelings of mild nausea and disorientation.

5.4. Correlation analysis

A range of factors was examined to determine those that contributed to student performance or attitudes, as summarised in Table 4. It is clear from the analysis that the level of perceived realism is correlated with both student performance and enjoyment, although the link between enjoyment and performance was weaker than expected. Much of the enjoyment factor could be attributed to the novelty of the technology and the high levels of enjoyment reported by students do hinder correlation analysis.

5.5. Student suggestions

Students were asked what benefits they thought the application offered over the clinical environment. 33% Specifically highlighted patient safety as an advantage, although others alluded to the absence of a patient as being advantageous to their learning of the technique. 38% of students...
reported that they felt less pressured, especially with respect to time. Other comments related to the ability to make and learn from mistakes. They appreciated the opportunity to experiment and generally felt less self-conscious while learning.

When asked an open question concerning any suggested improvements, 69% of the students stated that they would have preferred to spend more time practicing with the application. Other answers suggested that the application would be of use as an orientation tool before students attended their first clinical placement. Students also requested that they manipulate the viewpoint themselves. This was undertaken by an independent operator to maintain ease of control for the students. Future developments will replace this with altered viewpoints based on motion tracking of the user. Another common idea was for the simulation of patient movement to enhance the realism of the application.

62% of students felt that the VR technology had a role to play in the learning of practical clinical skills, such as those in the evaluated application. Other answers suggested that an IVE might help with teaching of 3D anatomy, physiology or complex physical concepts. Another theme that came out of the evaluation was the use of the virtual linear accelerator for pre-clinical orientation, enabling the students to learn some of the technical skills before attending clinical placements: At least one student reported that practice with this application “should be done before any clinical experience”.

Table 4
Correlation analysis of factors affecting performance

<table>
<thead>
<tr>
<th>Factor</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Factors affecting improvement</strong></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>0.215</td>
</tr>
<tr>
<td>Base line understanding (PreTest)</td>
<td>-0.290</td>
</tr>
<tr>
<td>Previous clinical experience</td>
<td>0.317</td>
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<tr>
<td>Female</td>
<td>0.222</td>
</tr>
<tr>
<td>Perceived realism</td>
<td>0.571</td>
</tr>
<tr>
<td>Enjoyment</td>
<td>0.371</td>
</tr>
<tr>
<td>Previous control system use</td>
<td>0.125</td>
</tr>
<tr>
<td>Ease of use</td>
<td>0.419</td>
</tr>
<tr>
<td><strong>Factors affecting enjoyment</strong></td>
<td></td>
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<tr>
<td>Age</td>
<td>-0.227</td>
</tr>
<tr>
<td>Base line understanding (PreTest)</td>
<td>0.110</td>
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<tr>
<td>Previous clinical experience</td>
<td>-0.067</td>
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<tr>
<td>Female</td>
<td>0.076</td>
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<tr>
<td>Perceived realism</td>
<td>0.525</td>
</tr>
<tr>
<td>Previous control system use</td>
<td>-0.041</td>
</tr>
<tr>
<td>Ease of use</td>
<td>0.131</td>
</tr>
<tr>
<td><strong>Factors affecting ease of use of controls</strong></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>-0.250</td>
</tr>
<tr>
<td>Female</td>
<td>-0.113</td>
</tr>
<tr>
<td>Perceived realism</td>
<td>0.412</td>
</tr>
<tr>
<td>Previous control system use</td>
<td>0.279</td>
</tr>
</tbody>
</table>
6. Discussion

6.1. Impact on learning

The results have shown that, as far as student perceptions and self-evaluation can demonstrate, the VR application has produced a 20% improvement in both understanding and confidence in technical skills. Further study is required, however, to demonstrate the extent to which this confidence can transfer to the clinical environment and whether skills have been acquired. Parallel studies are currently evaluating this and may reveal factors affecting this transfer process. The virtual treatment machine offers students the opportunity to develop their psychomotor skills as well as apply the principles behind the skin apposition technique in an IVE. Although the absence of a patient that affords ‘feedback’ could be said to reduce the effectiveness of this application as a clinical teaching tool, this study has shown that students felt that they were under less pressure. They were able to take their time without fear of worrying/harming the patient or delaying the treatment machine. With prior practice of these skills in a virtual reality environment, students should be able to set patients up with increased confidence in a shorter time. Student feedback suggested that a similar application could have a role to play in orientation prior to clinical placements. This should empower students to concentrate their efforts on patient interactions and other clinical skills, maximising the use of time and resources.

A large number of potential treatment sites can be generated for students to practice on, whereas in clinical practice, patient numbers are limited. Additionally, developing psychomotor skills away from the clinical environment will reduce the substantial training burden on clinical staff.

As with any new technology, we must be wary of using new equipment simply because it is there and because it is fun. This study has demonstrated a high level of enjoyment with the application, but as Letterie (2003) commented: “In spite of enthusiastic endorsement and the continued improvements in software, few studies of good design clearly demonstrate an improvement in medical education over traditional modalities”. This may be due to the fact that VR simulators can only ever improve knowledge or technical skills, but the requirement for medical education is to develop clinical skills. This is difficult to achieve without the essential interpersonal communication that characterises the medical professionals. Bergin and Fors (2003) attempted to address this issue by creating a virtual patient who will interact with the user to a limited degree. Until artificial intelligence technology allows more realistic interaction with virtual patients, however, this element of medical education will have to be conducted in the workplace with real patients.

Students were able to benefit from the input of their peers while setting up difficult tumour sites, thus, enabling effective group problem-based learning. In the clinical environment, opportunities for experimentation are clearly limited by the presence of a patient and the afore-mentioned pressures. By presenting a group of students with a challenging scenario, it was found that all members of the group could be involved with the decision-making process and gain in understanding as a result of their interactions. The benefits of a problem-based learning environment are well established, for example by Wang, Lo, and Ku (2004). Further study may determine the optimum group size for learning in this environment.
6.2. Ease of use and realism

The students reported high levels of realism, which correlated to some extent with their performance. The realism was enhanced by the use of a genuine control pendant, along with the fact that the unique environment of the treatment room and task were instantly identifiable to students. Although the technology is perfectly capable of providing a detailed replica of a fully operational treatment room, it is accepted that the situation is not an accurate depiction of working practices. The “patient” is unresponsive and the student is unable to interact physically with them. Although this can be improved upon with AI software coordinating patient responses, it is debatable whether this would add to the value of the application or not. The application is not intended to replace the students’ clinical experience, but to help to prepare them for it. This should not affect the efficacy of the application, since the required psychomotor and spatial awareness skills are identical. Indeed, this study has shown that the level of perceived realism was correlated with student improvement. Of interest may be the observation that when the stereoscopic (3D) function was removed, students found the task more difficult to complete, thus suggesting the relative importance of immersive technology in this situation. More study into the benefits afforded by 3D may be of value here.

There were no unrealistic restrictions on users’ interaction with the environment, although as in real life, it is possible to cause collision of the patient with the apparatus. Although the current application does not notify the student if they have collided, future developments will do, possibly using aural feedback from the “patient”. IVE’s traditionally suffer from lack of realism due to the control systems used (Lindeman, Sibert, & Hahn, 1999). In the case of this study, the user interface is identical to that used in a real-life situation. The use of a real hand-pendant considerably enhanced the realism of the application, and surprisingly, students who have trained with other manufacturers’ products did not report major difficulties. The ability to adapt to different situations and equipment is an essential skill for a radiographer and knowledge of different controls will be advantageous to them in their future careers. Future work on this application will include the use of a range of control systems from different manufacturers so students can experiment with other products.

7. Suggested improvements

7.1. Motion tracking

Although the HIVE offers the ability to track one user’s movement and present a stereoscopic view dependent on their position, other users will view a distorted image. This has been resolved to some extent by using multiple projectors (Omura, Shiwa, & Kishino, 1995) or interspersing personal tracked images and reducing the shutter refresh rate (Agrawala, Beers, Frohlich, & Hanrahan, 1997). Kitamura, Konishi, Yamamoto, and Kishino (2001) developed a novel alternative approach using a mask to present individuals with their personal section of display screen, although the immersive effect will be dramatically reduced with this system. Future development into the use of motion tracking in the HIVE will attempt to assess the impact of view distortion on effective group work.
7.2. Feedback and assessment

The modelling process allowed for measurement to be made of distances between objects in the model. This ultimately enabled a numerical assessment to be made of the quality of the skin apposition that a student achieved. Although this obviously lacked the element of clinical judgement, it did offer a means of testing spatial awareness and grasp of the skin apposition technique. This system was used to compare students’ individual performances for a parallel study, but it is expected that in the future, feedback can be given to the student on time it took to achieve apposition, the evenness of the apposition and the number of adjustments that they had to make in order to achieve it. A traffic-light based system of online feedback as developed by Weidenbach et al. (2004) may help to show the student how well they are doing. A further benefit may be the recording and playback of the student’s performance. Discussing their decisions will be of paramount value in helping them to improve.

Clinical skills are notoriously difficult to assess, and any attempt to compare student experiences in the IVE with those in the real clinical environment will fail in the absence of an interactive patient. Students who are unwilling to engage with the application or who are unfamiliar with the controls will be at a significant disadvantage and may perform worse in this situation than in their own clinical environment.

8. Conclusions and future work

The skin apposition application using a virtual treatment machine has been shown to be both enjoyable and realistic. Students perceive it to have significantly increased both their understanding and confidence with a complicated spatial awareness task. This is largely irrespective of their age, gender or previous clinical experience, but correlates with the perceived realism of the application. Work is ongoing to determine the extent to which the application can enable skill acquisition. Measurement of skill transfer is needed before the application can be used for technical skills training in a teaching environment. Feedback from students suggests that the virtual linear accelerator has a valuable role to play in their future training and as an orientation tool prior to clinical placement. Improvement in understanding was seen, suggesting that its use can be extended to pure academic teaching. Future developments such as motion tracking, feedback and assessment tools and aural feedback are expected to provide further training benefits to radiotherapy students. More study is ongoing in order to determine the true educational value of this and future applications.

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