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# A Usability Study of 3 Radiotherapy Systems: A Comparative Evaluation Based on Expert Evaluation and User Experience

Authors' Contribution:
Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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**Background:** The complex user interface design of radiotherapy treatment delivery systems can lead to use error and patient harm. In this study, we present the results of a comparison of 3 radiotherapy treatment delivery systems now used in China.

**Material/Methods:** We conducted a comprehensive usability study of 3 radiotherapy treatment delivery systems. Expert evaluation was performed through heuristic evaluation with 3 human-factors experts and 1 experienced radiation therapist for each system. User experience was assessed through perceived system usability and workload, using the National Aeronautics and Space Administration Task Load Index and the Post-Study System Usability Questionnaire.

**Results:** For the expert evaluation, 47 usability problems were identified for Varian Trilogy, 75 for Elekta Precise, and 37 for Shinva XHA600E. Most problems were classified as major and minor usability problems, and were found in the process of patient setup and setup verification. For the user experience, radiation therapists presented a lower workload for Varian Trilogy compared to Elekta Precise ($P<0.01$) and Shinva XHA600E ($P<0.01$), and a lower workload for Elekta Precise compared to Shinva XHA600E ($P=0.020$). Radiation therapists perceived a higher system usability for Varian Trilogy compared to Shinva XHA600E ($P<0.01$), and a higher system usability for Elekta Precise compared to Shinva XHA600E ($P<0.01$).

**Conclusions:** This research provides valuable data on how 3 radiotherapy treatment delivery systems compare. The results of this study may be useful for hospital equipment procurement decisions, and designing next-generation products to improve patient safety.

**MeSH Keywords:** **Equipment Design • Equipment Failure Analysis • Equipment Safety • Radiotherapy • User-Computer Interface**

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## Background

A published study suggested that 52% of patients should receive radiotherapy during their cancer treatment [1]. New technologies, such as image-guided radiation therapy (IGRT), have been applied to improve the quality of radiation therapy and prevent treatment errors [2,3]. However, these new technologies can sometimes make the user interface of the radiotherapy system more complex and lead to use error, resulting in adverse events [4,5]. The traditional response to adverse events has been to blame the user for committing use errors. However, patient safety experts confirm that adverse events are often due to the poor usability design of the user interface, which does not take into consideration the ability and limitations of the end user [6–9]. To facilitate use and avert use errors, usability should be considered when designing user interfaces for medical devices and systems [10].

To ensure the safe and effective use of radiotherapy systems, the usability of radiotherapy systems should be evaluated. Proper evaluation of the usability design of a system or a medical device requires usability testing [11,12]. Recently, the usability of medical devices has been addressed, with the U.S. Food and Drug Administration demanding that medical devices meet the use safety requirements prior to regulatory requirements [13]. A number of usability studies have been conducted to improve the usability design of medical devices, such as ventilators [14–16], defibrillators [17], ultrasound workstations [18], laparoscopic devices [19], and inhalers [20]. However, there are few usability studies on radiotherapy systems [21,22]. Heuristic evaluation is a method of usability testing that is usually used to evaluate the usability of user interfaces through investigation. In the heuristic evaluation, 3 to 5 human-factor experts, using require heuristic principles, found 60% to 70% of usability problems occur in the user interface [23]. Moreover, this method relies on the experience and knowledge of the human-factors expert, with no end user involved in the study. Heuristic evaluation is proved to be an efficient method to evaluate the usability of radiotherapy systems [21]. Another method that is commonly used to evaluate usability is user testing, with a number of end users performing key tasks on the user interface in actual use scenarios. The findings of user testing are directly acquired from end users' actual use, which can reflect the usability of the product from the end users' experiences. A published study has proved that user testing can be an effective method to evaluate the usability of radiotherapy systems [22]. Therefore, the present study used both methods to comprehensively evaluate the usability of radiotherapy systems from the perspective of end users (user testing) and usability experts (heuristic evaluation).

With no study to comprehensively compare the usability of similar radiotherapy systems on the market, this study intended to provide empirical evidence of the differences in the usability of 3 radiotherapy treatment delivery systems available in China, namely, the Trilogy® system (Varian Medical Systems, California, USA), Precise Treatment System™ (Elekta Medical Systems, Crawley, U.K.), and XHA600E system (Shinva Medical Instrument, Shandong, China). This study explored the usability of radiotherapy system products in 2 research dimensions, including expert evaluation (based on heuristic evaluation) and user experience (a combination of workload and perceived system usability based on user testing). The methodology, a combination of heuristic evaluation and user testing, used in our study can help end users and hospital procurement decision-makers to clearly understand the differences in usability among the different radiotherapy systems on the market. Furthermore, usability problems in radiotherapy systems were also identified and design improvement recommendations were formulated to improve the usability of user interfaces and strengthen patient treatment safety.

## Material and Methods

### Setting

This study was conducted in 2 cancer centers – Zhoukou Central Hospital (Zhoukou, Henan province, China) and Union Hospital, Tongji Medical College, Huazhong University of Science and Technology (Wuhan, Hubei province, China) – with 3 medical linear accelerator systems used in China. The 3 tested systems were the Trilogy® linear accelerator system (Varian Medical Systems, California, USA), the Precise Treatment System™ (Elekta Medical Systems, Crawley, U.K.), and the XHA600E system (Shinva Medical Instrument, Shandong, China). The Trilogy® system was controlled by the Varian 9.1 control system. It was equipped with a megavoltage (MV) imaging system, a kilovoltage (kV) cone beam imaging system, an on-board imager (version 1.6), a 4D console system (version 13.0), and an ARIA® information management system. The Precise Treatment System™ was controlled by the Desktop Pro™ 7 control system. It was equipped with a megavoltage (MV) imaging system, and iViewGT™ (version 1.4), and MOSAIQ™ (IMPAC Medical Systems, Sunnyvale, CA) was used to connect these software systems. The XHA600E system was controlled by the Shinva XHA600E control system. It was equipped with a megavoltage (MV) imaging system and an image verify system (version 1.3.12.174). It should be noted that the function of the software and hardware in the Shinva XHA600E are simple and are not advanced or richly functional compared to the Varian Trilogy and Elekta Precise, and most tasks are completed by a radiation therapist manually. This study was approved by the Ethics Committee of Tongji Medical College, Huazhong University of Science and Technology (IORG No: IORG0003571).





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**Table 1.** Usability heuristics.

| | Usability heuristic | Description |
|---|---|---|
| 1 | Consistency | Consistency and standards: Users should not have to wonder whether different words, situations, or actions mean the same thing. Standards and conventions in product design should be followed |
| 2 | Visibility | Visibility of system state: Users should be informed about what is going on with the system through appropriate feedback and display of information |
| 3 | Match | Match between system and world: The image of the system perceived by users should match the model the users have about the system |
| 4 | Minimalist | Minimalist: Any extraneous information is a distraction and a slow-down |
| 5 | Memory | Minimize memory load: Users should not be required to memorize a lot of information to carry out tasks. Memory load reduces users' capacity to carry out the main tasks |
| 6 | Feedback | Informative feedback: Users should be given prompt and informative feedback about their actions |
| 7 | Flexibility | Flexibility and efficiency: Users always learn and users are always different. Give users the flexibility of creating customization and shortcuts to accelerate their performance |
| 8 | Message | Good error messages: The messages should be informative enough such that users can understand the nature of errors, learn from errors, and recover from errors |
| 9 | Error | Prevent errors: It is always better to design interfaces that prevent errors from happening in the first place |
| 10 | Closure | Clear closure: Every task has a beginning and an end. Users should be clearly notified about the completion of a task |
| 11 | Undo | Reversible actions: Users should be allowed to recover from errors. Reversible actions also encourage exploratory learning |
| 12 | Language | Use users' language: The language should be always presented in a form understandable by the intended users |
| 13 | Control | Users in control: Do not give users that impression that they are controlled by the systems |
| 14 | Document | Help and documentation: Always provide help when needed, ideally context-sensitive help |

Adopted from Zhang et al. [24] and Chan et al. [22].

### Field observations

The researchers performed 1 week of field observations for each medical linear accelerator system at the 2 cancer centers in order to obtain a comprehensive understanding of its treatment delivery process and how these radiotherapy systems work. The radiation therapists at the 2 cancer centers knew about our study, and they were informed that they would be observed while they worked. When the radiation therapists operated the radiotherapy system to treat a patient during work hours, the researcher recorded each system's workflow and the key tasks that they performed in the treatment delivery process, as well as the way that radiation therapists interacted with each user interface of the radiotherapy systems.

### Expert evaluation

According to the results of the field observations at the 2 cancer centers, a list of representative key tasks for each radiotherapy system that the radiation therapists often performed during their daily work in treatment delivery were developed. In this study, 3 human-factors experts conducted this heuristic evaluation in the 3 radiotherapy systems. All of them participated in the field observations of the 3 radiotherapy systems and were well aware of the treatment delivery process. Usually, these representative key tasks are performed by human-factors experts without involving the users of each radiotherapy system. However, in this study, our human-factors experts were not authorized to perform these tasks on the radiotherapy systems. To carry out this evaluation, for each radiotherapy system, we recruited 1 experienced radiation therapist to perform the key tasks and explain the workflow, while the experts would stand beside to identify the usability problems by their observations. This evaluation was conducted at the radiation treatment room in the 2 cancer centers after work hours.

The user interfaces, such as the software operation interface and control panel, that the radiation therapist used to complete the key tasks were evaluated, and the usability problems were recorded for each user interface. The usability problems that violated the heuristics were generated by each expert according to the usability heuristics described in Table 1.





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**Table 2.** Severity of usability problem in heuristic evaluation.

| Severity | Definition |
|---|---|
| 4 | Usability Catastrophe – imperative to fix this problem |
| 3 | Major Usability Problem – important to fix, so should be given high priority |
| 2 | Minor Usability Problem – fixing this should be given low priority |
| 1 | Cosmetic Problem Only – need not be fixed unless extra time is available on project |
| 0 | No Problem – I don't agree that this is a usability problem at all |

Adopted from Nielsen [13].

For example, if different terminologies were used to indicate the same function, such as "delete" and "del," this was noted as violating the "Consistency" heuristic, and if proper feedback was not given, such as the user modified the treatment plan, it was noted as violated the "Feedback" heuristic. It was important that the experts conducted their evaluation independently in order to eliminate the bias. After the evaluation, the researcher compiled the list of usability problems for each radiotherapy system generated by the experts. Overlapping usability problems were edited out off each list. The edited list was subsequently given back to experts who then independently evaluated the severity of each usability problem based on the scale described in Table 2. The experts' severity ratings of each usability problem were then averaged. The identified usability problems were then classified by severity. We divided the severity ratings into 4 levels. Severity ratings equal to or greater than 3.5 were defined as catastrophic usability problems. Severity ratings equal to or greater than 2.5 but lower than 3.5 were defined as major usability problems. Severity ratings equal to or greater than 1.5 but lower than 2.5 were defined as minor usability problems, and severity ratings equal to or lower than 1.5 were defined as cosmetic usability problems. We also assessed tasks associated with patient information review, patient setup, setup verification, and beam delivery, and identified violations of the heuristics under assessment. The experts also developed recommendations for usability problems.

### User experience

User experience was measured through the workload and perceived system usability. Workload was assessed by the U.S. National Aeronautics and Space Administration task load index (NASA-TLX) [24] which has been used as a valid indictor to evaluate the workload of users in objective and subjective tests [25,26]. The NASA-TLX workload evaluation relies on 6 subscales that are involved with mental workload, including mental demand, temporal demand, physical demand, performance, frustration, and effort. The NASA-TLX is widely used in healthcare to evaluate the user interface of medical devices, such as ventilators [16], infusion pumps [27], and monitoring displays [28]. The result of the NASA-TLX is a score from 0 to 100. The higher the NASA-TLX score is, the higher the workload, with the user interface been thought of as difficult to use.

The perceived system usability was assessed by the post-study system usability questionnaire (PSSUQ), which is a 16-question survey that measures the users' perceived satisfaction with a product or system [29]. The PSSUQ is already used in healthcare for tasks such as anesthesia [30], monitoring [31], and telerehabilitation systems [32]. The output from the PSSUQ is a score that ranges from 1 to 7, where the lower scores are linked to a better perceived system usability.

To test user experience of each radiotherapy system, we needed the end user to operate the radiotherapy treatment delivery system. However, in reality, it is impossible for us to conduct this study on a real patient. In this study, we used a head mold (Type TL-D-T1, TOPSLANE Technology, Shanghai, China) to replace the real patient. We designed an IMRT treatment plan (2 setup fields and 5 treatment fields) of brain cancer, and the images were acquired from the head mold that was scanned by a CT-simulator. For each radiotherapy treatment delivery system, we recruited 19 experienced radiation therapists (for a total of 57 radiation therapists) who were familiar with the treatment delivery system to perform the treatment plan.

The user experience form testing the usability of the 3 radiotherapy treatment delivery systems was conducted independently at 2 cancer centers. For each radiotherapy treatment delivery system, the NASA-TLX and post-study system usability questionnaire (PSSUQ) were applied when the therapist finished performing the treatment plan.

### Data analysis

The usability problems of each radiotherapy treatment delivery system were recorded by human-factors experts, and violations of the usability heuristics were noted by the experts for each usability problem. The severity of each usability problem was also marked by 3 experts, and the results were averaged. Differences in the user experience of the radiotherapy





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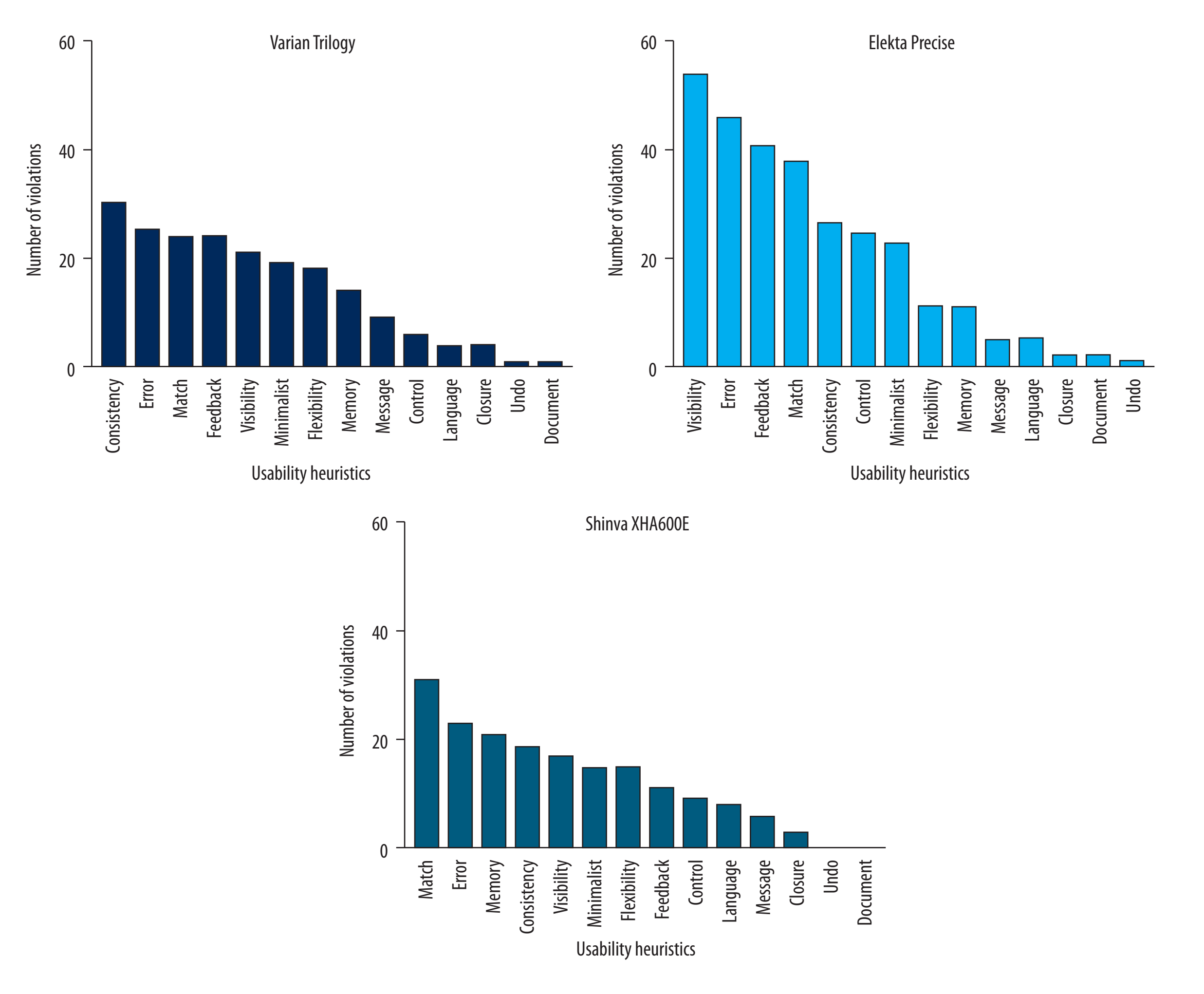


**Figure 1.** Number of heuristics violated by the 3 radiotherapy treatment delivery systems.

treatment delivery systems were explored through the Kruskal-Wallis test. Post hoc multiple comparison tests were performed using the Dunn-Bonferroni test [33]. The values are expressed as the mean ±SD, where P<0.05 was considered significant. The statistical analyses were performed using SPSS 20.0 (IBM, USA).

## Results

### Expert evaluation

Three human-factor experts reviewed the 3 radiotherapy treatment delivery systems using usability heuristics, as shown in Table 1. By the heuristics evaluation, 47 usability problems were identified for Varian Trilogy, 75 were identified for Elekta Precise, and 37 were identified for Shinva XHA600E.

### Usability problem categories by heuristic violations

Figure 1 presents the number of heuristic violations for the 3 radiotherapy treatment delivery systems across the 14 usability heuristics. Because each usability problem violated one or more of the usability heuristics, the number of violations was greater than the usability problem number. For the Varian Trilogy, 200 violations were identified. Consistency was the most frequently violated usability heuristic (30). Error, Match, and Feedback were the next most frequently violated usability heuristics (25, 24, and 24, respectively). Overall, these 4 usability heuristics accounted for 51% of all the violations. For the Elekta Precise, 290 violations were identified by the experts. Visibility was the most frequently violated usability heuristic (54). Error, Feedback, and Match were the next most frequently violated usability heuristics (46, 41, and 38, respectively). These 4 most frequently violated usability heuristics accounted for 61% of all the violations. For the Shinva XHA600E, 178 violations were identified by the human-factors





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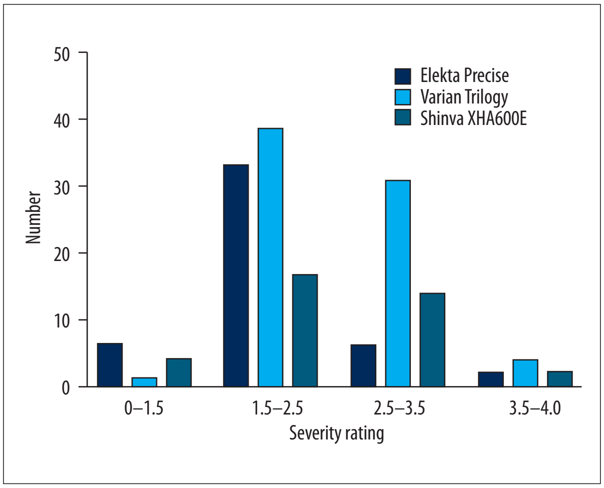


**Figure 2.** Usability problems by severity.

experts. Match was the most frequently violated usability heuristic (31). Error, Memory, and Consistency were the next most frequently violated usability heuristics (23, 21, and 29, respectively). These 4 most frequently violated usability heuristics account for 53% of all the violations.

### Usability problems categorized by the average severity rating

Figure 2 summarizes the average severity of the usability problems identified in the 3 radiotherapy treatment delivery systems. For the Varian Trilogy, there were 2 catastrophic usability problems, 6 major usability problems, 33 minor usability problems, and 6 cosmetic usability problems. For the Elekta Precise, there were 4 catastrophic usability problems, 39 major usability problems, 31 minor usability problems, and 4 cosmetic usability problems. For the Shinva XHA600E, there were 4 catastrophic usability problems, 17 major usability problems, 14 minor usability problems, and 2 cosmetic usability problems. The results of Figure 2 show that the Elekta Precise had a greater number of more severe usability problems than the other 2 radiotherapy treatment delivery systems and thus it is more likely to cause user errors than the others.

### Usability problems categorized by associated task

The usability problems were classified based on the daily work that they performed in the radiotherapy treatment delivery process. In these 2 cancer centers, the radiotherapy treatment delivery process is divided into 4 main tasks, including

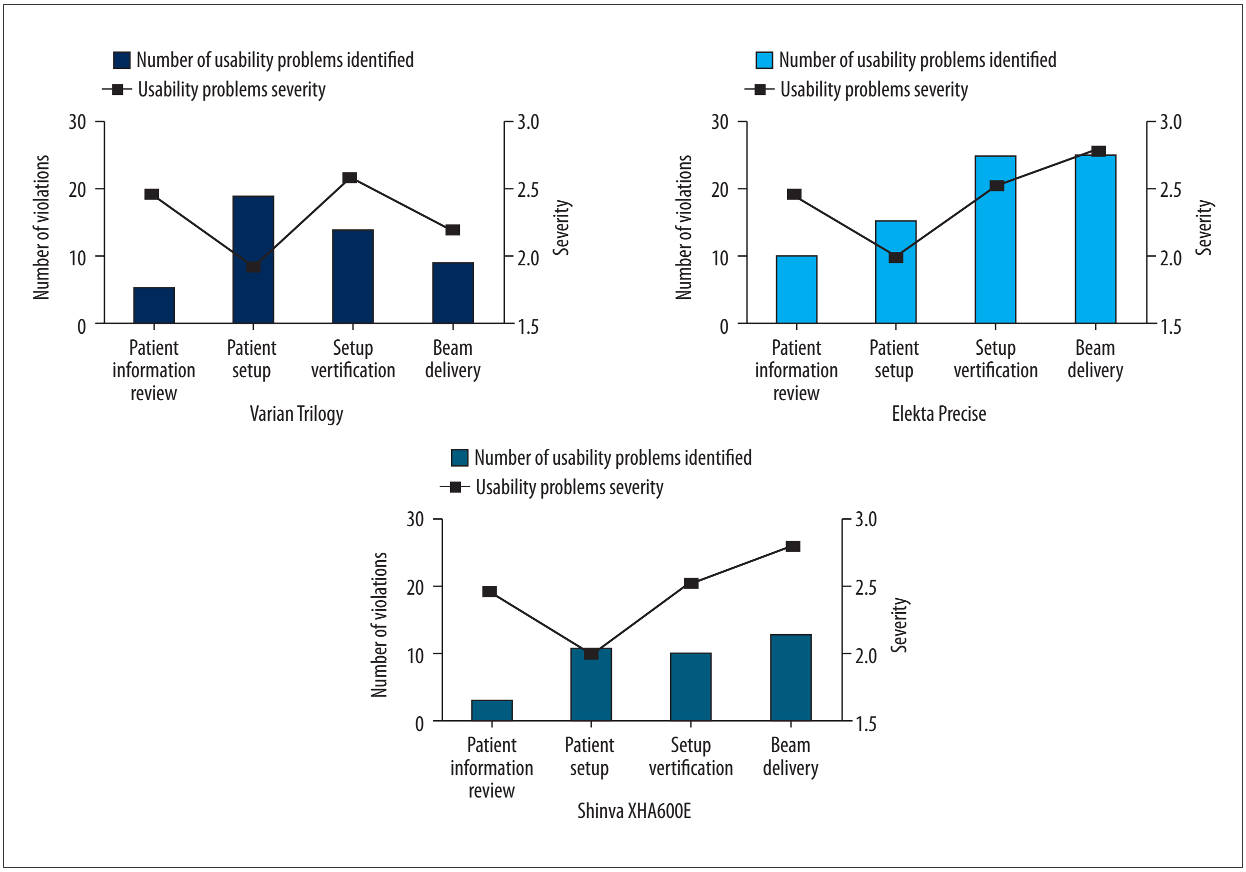


**Figure 3.** Number of usability problems and the average severity ratings associated with main task.





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patient information review, patient setup, setup verification, and beam delivery. The patient information review procedure includes checking the patient's identity and treatment plan information. After the patient information is checked, the patient is positioned on the treatment couch with the relevant accessories. Next, radiation therapists perform the setup verification procedure, where the patient's images are taken to verify the position of the internal organs and target tissue. Finally, the therapist delivers beams, and the patient is monitored during beaming. Figure 3 presents the number of usability problems identified in the 4 main tasks for the 3 radiotherapy treatment delivery systems and the average severity ratings for the usability problems in the 4 main tasks. For the Varian Trilogy, most of the usability problems were identified in the patient setup procedure (19), but with lower severity ratings. The setup verification procedure had the highest severity rating (2.60) among the 4 main tasks, and the number of usability problems (14) was only lower than patient setup. For the Elekta Precise, the beam delivery was associated with the most usability problems (25) and the highest average severity ratings (2.80), followed by the setup verification. For the Shinva XHA600E, the most usability problems were identified in the beam delivery, and the highest average severity rating procedure was the setup verification (2.63). For the 3 radiotherapy treatment delivery systems, most of the usability problems were identified in patient setup, setup verification and beam delivery. The high-severity usability problems were focused on the setup verification and beam delivery.

### Top 3 high-severity usability problems for each treatment delivery systems

Table 3 shows the top 3 high-severity rating usability problems for the 3 radiotherapy treatment delivery systems identified in the heuristic evaluation, and the recommendation for each usability problem was developed by the human-factor experts.

### User experience

Table 4 presents the summary showing how each pair of radiotherapy treatment delivery systems compares, and only the significant pair comparisons are shown. The Varian Trilogy outperformed the other radiotherapy treatment delivery systems in 3 out of the 5 pair comparisons, and the Elekta Precise outperformed the others in 2 out of the 5 pair comparisons. The Shinva XHA600E did not perform better than the other radiotherapy treatment delivery systems.

### Overall radiotherapy treatment delivery system comparison

Table 5 presents the workload of each radiotherapy treatment delivery system on the NASA-TLX scale, and the perceived system usability of the different radiotherapy treatment delivery systems were evaluated by the PSSUQ scale. The Kruskal-Wallis test showed that the NASA-TLX workload ($P<0.01$) and PSSUQ system usability ($P=0.001$) were significantly different between the 3 radiotherapy treatment delivery systems.

### Radiotherapy treatment delivery system comparison pair comparison

Three post hoc comparisons were conducted for each measurement, which ranked the NASA-TLX workload and PSSUQ system usability, as shown in Table 6. The comparisons were the differences in the mean ($M_D$) for each measurement. After performing a Dunn-Bonferroni corrections test, 5 out of the 6 comparisons were significantly different.

For the workload (score ranging from 0 to 100), the radiation therapists showed a lower workload for the Varian Trilogy (42.6) compared to the Elekta Precise (51.16), $M_D$=–3. 3, $P=0.003$, and the Shinva XHA600E (59.4), $M_D$=–6.0, $P<0.001$, respectively. The radiation therapists also showed a lower workload for the Elekta Precise (51.3) compared to the Shinva XHA600E (59.4), $M_D$=–2.7, $P=0.020$.

For the system usability (score ranging from 1 to 7), the radiation therapists presented better usability for the Varian Trilogy (2.8) than for the Shinva XHA600E (3.7), $M_D$=–3.2, $P=0.003$. They also presented a better usability for the Elekta Precise (2.9) than for the Shinva XHA600E (3.7), $M_D$=–3.3, $P=0.004$.

## Discussion

The purpose of this usability study was to evaluate the differences in the system usability of 3 radiotherapy treatment delivery systems that are extensively used in China. Through expert evaluation and a user experience assessment, the results of this study showed that the different user interfaces might have an impact on the system usability and user experience. Furthermore, the results of this study emphasized the importance of the user interface ergonomic design in the radiotherapy treatment delivery system.

Based on the finding from the heuristic evaluation of the 3 radiotherapy treatment delivery systems, most of the usability problems were identified in the patient information review, patient setup, setup verification, and beam delivery procedures. Furthermore, most of the usability problems in the 3 radiotherapy treatment delivery systems were classified as major usability problems and minor usability problems (Figure 2), and several usability problems were even classified as catastrophic usability problems (2 for Varian Trilogy; 4 for Elekta Precise, 2 for Shinva XHA600E). However, the 3 radiotherapy





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**Table 3.** The top three high severity rating usability problems for the three radiotherapy treatment delivery systems.

| Radiotherapy treatment delivery system | Main task | Usability problem description | Heuristics violated | Average severity rating | Recommendation |
|---|---|---|---|---|---|
| Varian Trilogy | Setup verification | When the patient's setup position was incorrect, the On-Board Imager would not enforce the user to move the treatment couch, and the user can override the setup error to perform the delivery beam operation. This may cause the wrong site to be beamed | Error, Feedback, Visibility, Message | 3.67 | The setup error should be corrected before the beam delivery, and the On-Board Imager should informed user to check the setup position information. The beam cannot be delivered when the setup is incorrect |
| | Setup verification | In the user interface of treatment plan selecting, the 4D Console system could not inform the user to review the patient identity information before selecting the treatment plan. Furthermore, the system only displayed the ID number and sex on the main page of the patient's file, and the sex was displayed using "♂" or "♀" instead of text. If the user checks the ID number of patient incorrectly, the wrong treatment may be used | Consistency, Match, Feedback, Error, Message | 3.67 | The system should force the user to check the patient identity information. More patient information should be provided in this system, such as a picture, age and date of birth |
| | Patient setup | At times, the radiation therapists would unlock the treatment couch to move it manually. However, the speed of the treatment couch movement cannot be controlled and it can move fast without limits. It may hit the person near the treatment couch | Visibility, Feedback, Error, control | 3.33 | The maximum moving speed of the treatment couch should be set in this system. When approaching the maximum moving speed, the system should also provide a warning to the user |
| Elekta Precise | Setup verification | The parameter of setup verification field should be entered manually, and the system will not to check the value of parameter if it is correct or with any reminder. Wrong value of parameter may enter for patient setup verification field | Visibility, Feedback, Error, Message | 4.00 | The control system should provide a measure to check the input if it is correct |
| | Beam delivery | If patient have multiple treatment plan for different organs to beam, the all radiation fields are arranged together without classification. It is difficult for the user to identify the field belong to. It may cause the user to use the wrong radiation field to beam the wrong site | Consistency, Visibility, Match, Error, Minimalist | 3.67 | The radiation field should be arranged by classification |
| | Setup verification | When using iViewGTTM to verify the setup position, the system provides no warning for the user with the setup error exceed the tolerance. User may unintentionally ignore this important information. This may cause wrong site to be beamed | Visibility, Feedback, Error, Message | 3.67 | The control system should provide a measure to inform the user to check the setup position whether the setup is correct |



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**Table 3 continued.** The top three high severity rating usability problems for the three radiotherapy treatment delivery systems.

| Radiotherapy treatment delivery system | Main task | Usability problem description | Heuristics violated | Average severity rating | Recommendation |
|---|---|---|---|---|---|
| Shinva XHA600E | Setup verification | When the patient's setup position was incorrect, the treatment couch needed to be moved if the setup position was incorrect. However, in the Image Verify System of the Shinva XHA600E, this procedure can be overridden by a manual operation. Even though the setup position is incorrect, the user can still perform the beam delivery operation | Match, Control, Error, Feedback | 4.00 | If the patient's setup position is incorrect, the user cannot be allowed to perform beam delivery operation. The Image Verify System should force the user to move the treatment correctly, and then the beam delivery can be conducted |
| | Setup verification | The information in the setup verification fields in the Shinva XHA600E should be entered manually by the user, and the Shinva XHA600E control system does not provide any measure to verify the input content or inform the user to check whether the content is correct. This may cause the wrong parameter to be entered | Minimalist, Memory, Control, Error | 3.67 | The control system should provide a measure to check the input if it is correct |
| | Patient information review | The Shinva XHA600E control system does not inform the user to check the patient identification before the treatment. The control system provides limited of patient information (only name and ID number) for the user to identify the patient. It is easy for the user to treat the wrong patient or use the rong treatment plan | Visibility, Match, Memory, Error | 3.67 | The system should provide several reminders for the user to check the patient identification, and more patient information should be provided in the system, such as a picture of the patient |

**Table 4.** Comparative description of how any two radiotherapy treatment delivery system compare*.

| | Lower workload | Better usability |
|---|---|---|
| | NASA-TLX | PSSUQ |
| Varian Trilogy compared to Elekta Precise | Varian Trilogy | |
| Varian Trilogy compared to Shinva XHA600E | Varian Trilogy | Varian Trilogy |
| Elekta Precise compared to Shinva XHA600E | Elekta Precise | Elekta Precise |

NASA-TLX – National Aeronautics and Space Administration Task Load Index; PSSUO – Post-Study System Usability Questionnaire.
* Only statistically significant results after Bonferroni corrections are presented.

treatment delivery systems are widely used in many cancer centers at the present time in China, and there is a considerable possibility that these identified usability problems take place, indicating a considerable potential threat to patient safety during cancer treatment. According to Figure 3, most of the usability problems were identified in the patient setup, setup verification, and beam delivery processes (Figure 3), in which the procedures include most interactions between the systems and the user. Even though hospitals have taken many measures to guarantee patient safety, the results of this study suggest that the user must be reminded that there are numerous user interfaces in the 3 radiotherapy treatment delivery

**Table 5.** Radiotherapy treatment delivery system performance in NASA-TLX and PSSUQ measurements.

| | Radiotherapy system | | | | | | P |
|---|---|---|---|---|---|---|---|
| | Varian Trilogy | | Elekta Precise | | Shinva XHA600E | | |
| | Mean | Standard deviation | Mean | Standard deviation | Mean | Standard deviation | |
| NASA-TLX Workload | 42.6 | 6.3 | 51.3 | 5.9 | 59.4 | 8.1 | <0.001* |
| PSSUQ System usability | 2.8 | 0.8 | 2.9 | 1.0 | 3.7 | 0.9 | 0.001* |

Lower scores on two metrics correspond to better performance. NASA-TLX – National Aeronautics and Space Administration Task Load Index; PSSUO – Post-Study System Usability Questionnaire. * Statistically significant results.

**Table 6.** Mean differences ($M_D$=$Mr_1$–$Mr_2$) between the radiotherapy systems with the results of post hoc contrasts with Bonferroni correction.

| | | Post hoc tests with Bonferroni correction | |
|---|---|---|---|
| | | $M_D$ ($Mr_1$–$Mr_2$) | P |
| NASA-TLX Workload | | | |
| $Mr_1$ | $Mr_2$ | | |
| Varian Trilogy | Elekta Precise | –3.3 | 0.003* |
| Varian Trilogy | Shinva XHA600E | –6.0 | <0.001* |
| Elekta Precise | Shinva XHA600E | –2.7 | 0.020* |
| PSSUQ System usability | | | |
| $Mr_1$ | $Mr_2$ | | |
| Varian Trilogy | Elekta Precise | –0.1 | 1.000 |
| Varian Trilogy | Shinva XHA600E | –3.2 | 0.003* |
| Elekta Precise | Shinva XHA600E | –3.3 | 0.004* |

NASA-TLX – National Aeronautics and Space Administration Task Load Index; PSSUO – Post-Study System Usability Questionnaire. Negative MD values representing $Mr_1$ performing better than $Mr_2$. * Statistically significant results.

systems that they should pay attention to because of the potential use errors. Another problem that should be emphasized is that more than half of the usability problems were minor and cosmetic usability problems, with lower severity, and they may have little impact on patient safety. However, the usability problems that exist in the system can increase the user workload, thus increasing the risk of high-severity usability problems. Hence, lower-severity usability problems also deserve attention, which was also addressed in a previously published study [21].

From the usability heuristics proposed by Zhang et al. [23], "Error", "Feedback", "Consistency", and "Visibility" were the most commonly violated heuristics in the evaluation of the 3 radiotherapy treatment delivery systems (Figure 1). These violations mostly focused on the software systems in the 3 radiotherapy treatment delivery systems. These were reflected in the patient information review, patient setup, and setup verification procedures. In these processes, a majority of the user–machine interactions are completed in a short time, such as checking the patient identification information, reviewing the treatment plan, positioning the patient on the treatment couch, using images to verify the setup position, and editing the treatment plan if the parameter was incorrect. Especially for the checking and reviewing processes, several studies reveal that it is common for medical staff to ignore the check and review processes if they are not compulsory [21,34,35]. These results suggest that measures should be taken to prevent use errors and reinforce the process checking system, and feedback should be provided when users interact with the system (e.g., edit the treatment plan or enter a value for a treatment parameter) regarding whether the system provided is consistent with the user expectations (e.g., the icon shape of the software should be consistent with its function) and whether the status of the system can easily be obtained by the user (i.e., the action that the system is performing).





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Using only the results of the expert evaluation, it was impossible to comprehensively evaluate the usability of the 3 radiotherapy treatment delivery systems. Hence, it is important to also collect the evaluation data on user experience from the end user to further enrich the usability study. The user experience of the 3 radiotherapy treatment delivery systems was compared through the Kruskal-Wallis test, and the results showed statistically significant differences for 2 indicators: NASA-TLX workload and PSSUQ system usability. These results further enriched our study to discriminate the usability of the radiotherapy treatment delivery systems. The results of the expert evaluation were further supported by the results of the user experience. The outcome in Table 4 shows that the Varian Trilogy outperformed the other radiotherapy treatment delivery systems in 3 out of 6 comparisons. These results suggest that the perceptions of the Varian Trilogy's superior system usability from the end users were reflected in the data of the user experience and expert evaluation collected in this usability study. The Varian Trilogy presented a lower perceived workload compared to any of the other radiotherapy treatment delivery systems but showed better perceived system usability compared to the Shinva XHA600E. The Elekta Precise outperformed the Shinva XHA600E both in the perceived workload and system usability. The Shinva XHA600E did not outperform any of the other radiotherapy treatment delivery systems in this usability study. As introduced in the Setting section, the Shinva XHA600E showed better results in the expert evaluation. However, because the function of the software and hardware in the Shinva XHA600E are simple and not advanced or richly functional compared to that of the Varian Trilogy and Elekta Precise, most tasks must be completed by the radiation therapists manually. Therefore, this increased the user workload, and a poor result was obtained in the user experience evaluation (workload and perceived system usability).

This study provided a comprehensive method to evaluate the usability of radiotherapy treatment delivery systems through expert evaluation and user experience. By using qualitative data and quantitative data, we presented comprehensive results of the usability for each radiotherapy treatment delivery system. Heuristic evaluation [21,23], NASA-TLX [24–26], and PSSUQ [30–32] have shown their capacity for evaluating the usability of medical devices, as well as ranking the usability of the radiotherapy treatment delivery systems now being used in China. Ultimately, the methods used in this study were also useful to support the design and hospital procurement decisions regarding radiotherapy treatment delivery systems on the market.

There are several limitations to this usability study of 3 radiotherapy treatment delivery systems. First, the end users in our study were experienced radiation therapists, the sample population only represented 1 category of end user, and other the end users (e.g., novice radiation therapist, radiation physicists, and maintenance engineers) were not considered in this study. Therefore, the study results cannot represent all end users of radiotherapy treatment delivery systems. Second, the radiotherapy treatment delivery system can perform more functions than we tested. However, in our usability study, we only evaluated the treatment function. Finally, it is acknowledged that a new generation of radiotherapy treatment delivery systems has been developed by vendors, such as TrueBeam® Radiotherapy System for Varian, and Synergy® for Elekta. However, the new-generation products were unavailable for our usability study, and some usability problems that were addressed in our study may have been solved in the new-generation products.

## Conclusions

This study provides valuable evidence on how the usability of 3 radiotherapy treatment delivery systems compared and highlights the importance of the ergonomic design of the user interfaces of radiotherapy treatment delivery systems. The Shinva XHA600E performed better in the expert evaluation, with 37 usability problems and 178 violations of usability heuristics, followed by the Varian Trilogy. For the results of user experience, the Varian Trilogy had a lower workload and a better perception system usability from end users (42.6±6.3, $P<0.001$; 2.8±0.8, $P=0.001$; respectively), followed by the Elekta Precise. Based on the qualitative and quantitative data collected in our study, the differences in results of the expert evaluation and user experience were illustrated by the ergonomic design of the user interface, the influence of the product technology on the users' experience, and the ease of the interaction for the user and system. Ultimately, this study provides a comprehensive usability testing methodology for identifying the most usable radiotherapy treatment delivery system now being used in China, and the results of the study also support the design of the next generation of devices to reduce use errors and reinforce patient safety.

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### Conflict of interest

None.





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