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Radiation Dose Tracking in Computed Tomography Using Data Visualization

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Abstract: Radiation dose tracking is becoming very important due to the popularity of computerized tomography (CT) scans. One of the challenges of radiation dose tracking is that there are several variables that affect the dose from the patient side, machine side, and procedures side. Although some tracking software programs exists, they are based on static analysis and cause integration errors due to the heterogeneity of Hospital Information Systems (HISs) and prevent users from obtaining accurate answers to their questions. In this paper, a visual analytic approach is utilized to track radiation dose data from computed tomography (CT) through the use of Tableau data visualization software. The web solution is evaluated in real-life scenarios by domain experts. The results show that the visual analytics approach improves the tracking process, as users completed the tasks with a 100% success rate. The process increased user satisfaction and also provided invaluable insight into the analytical process.

1. Introduction

Recent advances in technology have led to the evolution of data sources, forms, and structures in healthcare. This evolution has made healthcare a source of big data. One of the many available sources of data includes computerized tomography (CT) scans and other imaging modalities. However, the equipment used to generate such imagery exposes patients to harmful ionizing radiation [1], though it can produce numerous pieces of information about the patient's body parts, protocol, images, and radiation dosage. Even though a single dose may be small, radiation exposure is cumulative [2,3]; hence, there is a risk of overdose. The cohort under study in [4] had a higher baseline risk of cancer due to the cumulative doses of repeated CT scans.

Radiation dose tracking has, consequently, become increasingly important owing to the popularity of CT scans. Several variables affect the tracking dose, such as the patient's age, the size of the body part being scanned, the total size of the body, the scanner model and pitch, and the scanning protocol [5]. For example, for a chest CT scan, the patient lies on a flat bed, and then the machine circulates around him/her, emitting a beam that goes through the patient's body (in this case, the chest). When the machine completes a full cycle, it creates a slice that is a 2-D image of the lungs and the inside of the chest. The number of slices is determined based on the study protocol, and a computer processes these images to be displayed on the monitor, and they may even be rendered in a 3-D form [6]. In radiology, a study means all the procedures a patient underwent to obtain a specific scan protocol.

Tracking radiation dosages is an important and mandatory practice in healthcare facilities [7]. In some facilities, teams are assigned to carry out this task manually or by using commercial software, such as DoseTrack (version 1.0) by Sectra [8]. Manual tracking is unfeasible and has the potential for human error. However, commercial tools are based on static analysis, which limits the possibilities of exploring data due to problems such as

predefined reports, no interwind filters, and complex interfaces for inexperienced users [9]. In addition, this commercial tracking software can create integration errors, such as errors while extracting data from the PACS. PACS is a technology used in healthcare facilities for storing, retrieving, presenting, and sharing images produced by medical hardware [10] thanks to the heterogeneity of Hospital Information Systems (HISs) [11].

Using visual analytics to track radiation dosages will allow users to track a single patient or cohort of patients, will include temporal information, and will enable one to observe patterns over time, find trends, and even optimize the practices in use through gained insights.

In this paper, we propose a visual analytical dashboard called VATrack to track radiation dose data for CT scans through employing visual analytics techniques. It monitors the radiation dose in patients undergoing CT scans. The dashboard processes multivariate temporal data and identifies any radiation overdose while reducing human intervention in the radiation dose tracking process and enhancing the performance in terms of accuracy and time. Domain experts have evaluated the proposed dashboard.

The remainder of this paper is organized as follows. Section 2 discusses some background information and sheds light on existing solutions for radiation dose tracking. Section 3 presents the proposed solution for applying visual analytics to monitor the radiation dosage for patients undergoing CT scans and the experimental design in more detail. The performance evaluation of the proposed solution is discussed in Section 4 and the results are presented in Section 5. Section 6 discusses the results. Finally, Section 7 concludes the thesis and provides suggestions for future research.

2. Related Work

Visual analytics is not the same as data or information visualization, even though they have a similar goal, which is to provide insight to the end-users so that they can make good and informed decisions. Visual analytics was first defined by Thomas and Cook as "The science of analytical reasoning facilitated by interactive visual interfaces" [12]. Data visualization is the representation of information or data using visual elements, with no regard to how to manage and process the data.

Therefore, when the problem is not simple or clear enough to be modelled using automatic analysis, the need for human cognitive abilities arises; hence, the use of visual analytics becomes necessary. Visual analytics has attracted considerable interest because it aids in gaining an understanding of problems and solutions; hence, it has been adopted in several application areas such as space, healthcare, social networks, deep learning, and many more.

There are available tools to track radiation doses. Kovacs et al. proposed an engine that calculates radiation exposure from a CT scan with several analysing schemes called the "RE3-Radiation Exposure Extraction Engine" [13]. The engine was integrated within the hospital's PACs to recover radiation dose data using image data and DICOM headers. This integration could, however, create several problems, such as errors in data extraction from different DICOM sources or other integration errors, whereas our solution is completely independent.

The authors in [14] used SharePoint (2013) to create a report generator to monitor the radiation dose in digital mammography and digital breast tomosynthesis. It supports different user roles and operates in a mixed imaging environment. In addition, it was integrated within DICOM and the PACS. However, it provides information as static visualizations to support decision making and quality assurance, whereas the proposed solution provides interactive visuals that support explanatory analysis in addition to the basic functions of monitoring.

Finally, the authors in [15] used the commercial software DoseWatch (version 1.3) (GE Healthcare). They confirmed that commercial dose tracking software is not sufficient on its own, even though it is true to what the developers claim in terms of tracking and monitoring, but inexperienced or busy users require additional time and effort because the tools are static and not interactive; thus, the user feels less motivated to search for answers.

3. VATrack Dashboard

To the best of our knowledge, there have been no applications of visual analytics in diagnostic imaging radiation dose tracking. Therefore, in this paper, a web solution is presented that provides tracking functionality and an exploratory environment for CT scan radiation dose data. The solution is based on visual analytics techniques and Tableau software. The proposed dashboard was evaluated using use case scenarios. To build the proposed dashboard, there were four phases, as follows [16].

- Phase 1: Conducting interviews with domain experts to collect and analyse the requirements.
- Phase 2: Abstraction of data and requirements; our data are multivariate temporal data.
- Phase 3: During this iterative phase, we conduct the following:
    - Generate multiple designs;
    - Develop and implement the selected design;
    - Evaluate prototypes;
    - Improve the design based on user-required improvements.
- Phase 4: Deploy the dashboard and interview users and domain experts for feedback [17].

3.1. Requirement Analysis

To collect the requirements, several meetings with domain experts were held. During this process, the required functions were defined as follows:

- Automate the tracking process and reduce human intervention as much as possible.
- Identify high-dose studies according to European DRLs (Diagnostic Reference Levels).
- Search by patient ID.
- Study comparisons.
- Grouping study protocols into three categories (Head, Chest, and Abdomen).
- Redefine age classes to be:
    - 0–3 months;
    - 4 months–1 year;
    - 2–5 years;
    - 6–16 years;
    - 16+ years.
- Reduce study attributes to provide good tracking and summary information—we chose only 13 relevant attributes. These attributes were chosen based on domain experts' opinions and reviews of what and how the radiology department performed the tracking process and what they used for their tracking process.

    Additionally, we were able to ascertain our user characteristics:

- Educational level: Bachelor or higher;
- Experience: they are experienced in the field but not in the tracking process;
- Disabilities: No visual disabilities such as colour blindness or loss of vision;
- Technical expertise: Basic level of computer skills.

    Finally, we determined the following general constraints:

- No integration with HIS is required;
- No data pre-processing by users;
- Platform-independent.

3.2. CT Radiation Tracking Dataset

Data records for 2019 were obtained from the Radiology Department at King Abdulaziz University Hospital, Jeddah, Saudi Arabia. They are multivariate data generated by Dosewatch software, not raw data from medical scanners, exported into an Excel file format. The dataset consisted of 98 columns. The number of rows varied depending on the patient count and the type of CT scan protocol conducted. It included patient information,

such as Patient ID, date of birth, age class, sex, weight (kg), height (cm), and BMI. It also contained information pertaining to the study performed, such as study protocol name, study time, series type, mean CTDI, DLP, the operator, and the imaging machine.

The sample consisted of 2755 records that represented 946 patients. Data were adversely affected by user input errors, such as entering the wrong file number as a study ID or the wrong date of birth. Unfortunately, patient size, BMI, and weight data are missing, which has created an obstacle in tracking and identifying radiation overexposure cases. This will affect tracking of chest and abdominal CT scans, as head CT scan dosage limits are determined by age, as shown in Table 1.

Table 1. European diagnostic reference levels [18].

| Exam | Age or Weight Group | EDRL | |
		CTDI vol, mGy	DLP, mGycm
Head	[0 ≤ 3 months]	24	300
	[3 months ≤ 1 year]	28	385
	[1 ≤ 6 years]	40	505
	[≥6 years]	50	650
Thorax			
	<5 kg	1.4	35
	[5 ≤ 15 kg]	1.8	50
	[15 ≤ 30 kg]	2.7	70
	[30 ≤ 50 kg]	3.7	115
	[50 ≤ 80 kg]	5.4	200
Abdomen			
	< 5 kg		45
	[5 ≤ 15 kg]	3.5	120
	[15 ≤ 30 kg]	5.4	150
	[30 ≤ 50 kg]	7.3	210
	[50 ≤ 80 kg]	13	480

Table 1 represents the European Diagnostic Reference Levels (DRLs) followed by King Abdulaziz University Hospital and is used to identify any study that exceeded the radiation limits to be investigated in more detail. It covers three main areas: Head, Chest, and Abdomen. For head-related CT scans, it classifies the safe dosages by age, while for chest-related CT scans and abdomen-related CT scans, it uses weight for classification purposes.

Data pre-processing and cleaning was carried out by defining the conditions in Tableau that would be applied to the extracted data when uploaded. First, data were cleaned by removing records with missing patient IDs, invalid ID numbers, or invalid values in basic patient attributes (such as no gender given or an unrealistic date of birth provided). Subsequently, data aggregation occurred for studies with protocols that consisted of more than one step. Some CT scan protocols consisted of more than one step; hence, in the dataset, there were as many records for a study per patient as the number of protocol steps. This situation proved problematic because there were also some protocols with an unknown number of steps, meaning they could not be defined in the system because the physician decided how many steps there would be at the time of the procedure. To overcome this problem, VATrack aggregated each study using the patient ID, Study ID, and protocol name (local study description) to ensure that the protocol steps (series description) were covered.

3.3. Design

The dashboard must be easy to use and intuitive since our users will have only a basic level of computer skills and limited time to learn or be trained due to busy schedules, yet it still must be able to provide users with summary information at a glance. A dashboard that is capable of this is shown in Figure 1.
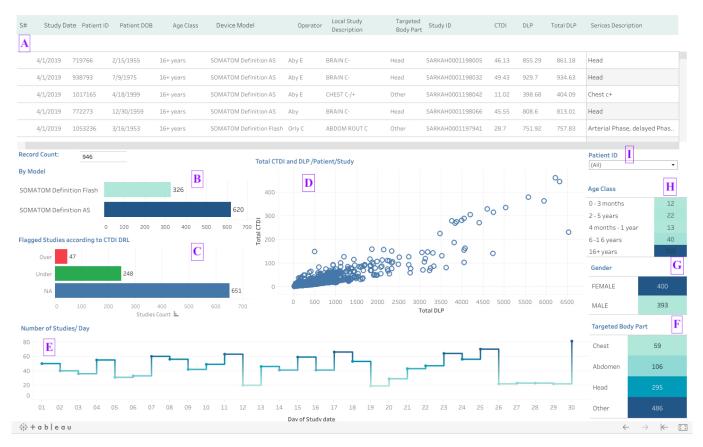
Figure 1. VATrack: Radiation dose tracking and monitoring interactive visual display. (**A**) main view, (**B**) imaging device model, (**C**) flagged studies (red indicates overdose studies and green indicates safe dose studies), (**D**) scatter plot of studies in relation to DLP and CTDI, (**E**) timeline to show the number of studies per day over the selected period, (**F**) study protocols categorized according to the targeted body part, (**G**) gender bar chart, (**H**) age classes using bar chart b, and (**I**) patient ID search bar.

The dashboard consists of:

- Nine coordinated views;
- Search bar;
- Several interaction techniques (filtering, linking and brushing, and details on demand).

Coordinated views are used, whereby clicking on or selecting an area in one view updates the remaining views. In addition, the search bar updates all nine views. The interaction techniques depend on the view, as shown below.
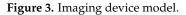
Figures 1A and 2 are the main view of the top third, which is a scrollable table structure wherein the 13 attributes are displayed at the beginning. The table is populated with complete data; each record represents a patient, clicking on a cell will highlight his/her record, and the remaining views will not be updated. In addition, under the table, there is a counter for the records that are currently available.

Figure 2. Dashboard main view.

Figures 1B and 3 are a horizontal bar graph that represents the imaging device model and acts as a filter by clicking on the bars, and the numbers at the outside end of each bar represent the number of studies using each model.

Figure 3. Imaging device model.

Figures 1C and 4 are also a horizontal bar graph that represents red-colour overdose studies, green-colour safe dose studies, and NA for studies that have yet to be categorized. The bar graph also acts as a filter by clicking on the bars, and the numbers at the outside end of each bar represent the number of studies within each category. We used bar graphs as filters to provide the necessary information and to visualize the comparison of data among categories.
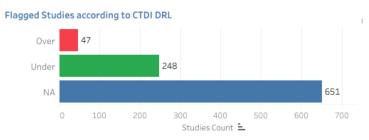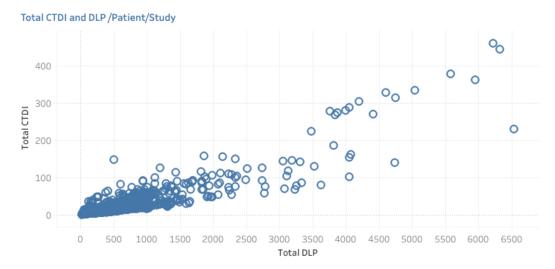

Figure 4. Flagged studies (red indicates overdose studies and green indicates safe-dose studies).

Figures 1D and 5 show a scatter plot that represents each study according to its DLP and CTDI. Users can click on an individual point or use 'sliding' by selecting an area on the plot that will update the rest of the dashboard; also, there are 'infotip' details-on-demand that appear when you rest the pointer on a point. We use a scatter plot to show the relationship between the two variables and allow the user to identify other patterns in the dataset.

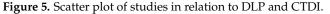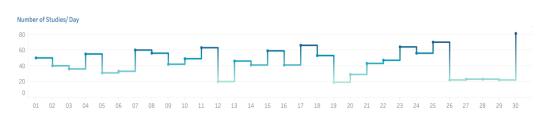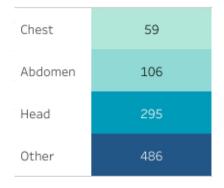**Figure 5.** Scatter plot of studies in relation to DLP and CTDI.

Figure 1E is a dotted-line graph that represents the study date, and the dots represent the number of studies per day. It also has a brushing and linking interaction technique by selecting an area on the graph that updates the rest of the dashboard and 'infotip' details-on-demand, as seen in Figure 6.
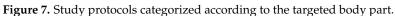
Figure 6. Total CTDI DLP per patient/study.

Figures 1F and 7 are a bar graph wherein each bar represents a group of CT scan protocols related to body area, which also acts as a filter, and the numbers inside each bar represent the number of patients in the category.

Figure 7. Study protocols categorized according to the targeted body part.

Figures 1G and 8 are a bar graph wherein each bar represents a gender, which also acts as a filter, and the numbers inside each bar represent the number of patients in the category.

Figure 8. Gender bar chart.

Figures 1H and 9 are a bar graph wherein each bar represents an age class; it also acts as a filter, and the numbers inside each bar represent the number of patients in the class.

Figure 9. Age classes using the bar chart.

Figures 1I and 10 show a search bar wherein the user can filter the dashboard by patient ID, as shown in Figure 1.

Figure 10. Patient ID search bar.

Using these different visualization components as filters provides insights from an initial look and also conveys as much information as possible without overloading the user with multiple irrelevant records to scroll through. In addition, we used colour-coded views to indicate that the deeper the colour, the higher the number (that is, except for the "flagged studies" filter, which uses a traffic-light colour code to indicate high risk for red and safety for green).

3.4. Implementation

For testing and evaluation purposes, a proof of concept (PoC) implementation of the interactive visual display was developed. Tableau is a visual analytics software platform that provides several functions to individuals and enterprises. It helps with creating interactive and connected dashboards across an organization from pre-processing data, whether from a spreadsheet, SQL database, or in the cloud, to publishing compelling results to provide insights and answers acquired through the analytical process [19,20].

Tableau Desktop (version 2020.4) was used because data visualization and analysis functionalities are its main features, and the researcher(s) have greater familiarity with the software. Tableau was used to build the interactive visual display. The next section describes the steps taken to build the solution depicted in Figure 1.

Data Interaction Components

First, Tableau was connected to a data-source Excel (version 2019) file, as shown in Figure 11. The rules defined in data pre-processing are applied automatically whenever the user uploads new data.

Figure 11. Connecting data source to Tableau software.
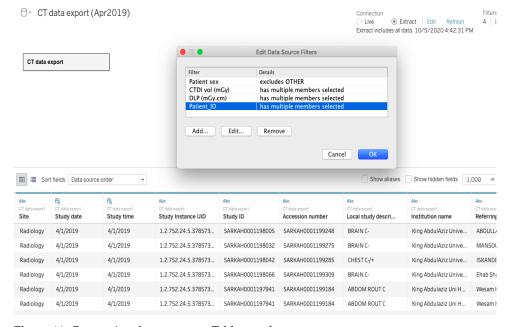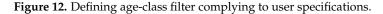
In Figure 1, only 13 different attributes are displayed in the data source rather than 98. The age-class interaction component is created in Tableau, as shown in Figure 12; according to user needs, age classes are split differently. To calculate the age month, which is not available in source data, Tableau subtracts the date of birth from the study date and converts that period

to the number of months; then, the desired classes are applied using conditional statements. In this study, the linking and brushing interaction techniques were used.

Figure 12. Defining age-class filter complying to user specifications.

For the body part interaction component shown in Figure 1, four groups were created, each containing specific scanning protocols, as shown in Figure 13. In addition, there were eight other data interaction components:

- Model (B in Figure 1): a bar graph shows the number of studies performed using different devices. In addition, it acts as a cross-filter based on the medical scanners used.
- Flagged studies according to CTDI and DLP (C in Figure 1): a bar graph represents studies based on the total radiation dosage per study; hence, for each study per patient, the software sums the CTDI and DLP values then compares the total to the standard used in Figure 1. If it is over the standard, then it is in the red category, while if it is under the standard, then it is placed in the green category. In addition, it acts as a cross filter, which updates the dashboard based on whichever bar is clicked on.
- Number of studies/day (E in Figure 1): a dotted line graph represents the number of studies performed each day. In addition, it acts as a cross-filter when sliding and linking a group of days or selecting a single day. Further, it has an infotip feature.
- Gender (G in Figure 1): a bar graph shows the number of patients according to gender—female or male. In addition, it acts as a cross-filter when clicked on.
- Patient ID (I in Figure 1): a search bar filters data based on entering the patient ID in the search bar or by selecting a patient ID from a single-value drop-down list.
- Total CTDI and DLP/patient/study (D in Figure 1): this is a scatter plot wherein each point represents a study showing the radiation dose in CTDI and DLP measures. In addition, it acts as a cross-filter when sliding and linking a group of points or by selecting a single point. Further, it has an infotip feature.

To remove what the user may think of as redundancies, a field called "series description" was created, as shown in Figure 14. Each scanning protocol consists of a different number of steps, and each step has its own radiation dose value in the DLP field. For example, in Figure 14, a protocol with four steps actually appears four times in the data source, but in Figure 14, it appears as a single record, and the aggregate value of the radiation dose is in the DLP field.

All charts and input boxes in Figure 14 are cross-filters that can be applied simultaneously. The table at the top displays the records available after applying the data interaction components. Users can click on several interaction components and immediately inspect the dashboard. On the scatter plot and the timeline at the bottom, the user can either click on a single value/day or slide a group of dots or days.

Figure 13. Defining body-part filter based on scanning protocols.

Figure 14. Listing all protocol steps in a single record.

All charts and input boxes in Figure 1 are cross-filters that can be applied simultaneously. The table at the top displays the records available after applying the data interaction components. Users can click on several interaction components and immediately reflect on the dashboard. On the scatter plot and the timeline at the bottom, the user can either click on a single value/day or brush a group of dots or days.

4. Evaluation

The evaluation focused on use-case scenarios, completion accuracy, and time. We also used a questionnaire-based evaluation. A usability test was conducted to evaluate, measure, and improve the usability of the proposed solution. The usability test examined the user-friendliness of the solution. According to Jakob Nielsen, a renowned usability expert, usability consists of five components: learnability, efficiency, memorability, error minimization, and satisfaction [21]. A "User and Task Observation" test method was chosen.

4.1. Study Design

An on-site usability test was conducted at King Abdulaziz University Hospital. It took place at participants' offices on Sunday 17 October 2021 from 8:30 a.m. to 2:45 p.m. There were some waiting periods between the test sessions since a number of participants were working. The test started by greeting the participants and explaining the goal of the study, which was to assess the usability of VATrack interface design and interactivity. Four test users who worked as medical physicists in the department participated; they were responsible for monitoring radiation doses and exposure in all forms at the hospital, including tracking radiological procedure doses.

It was difficult to include additional participants since the remainder were technicians who were operating the scanning machines, and it would have been very difficult to suspend the workflow. Then, a consent form was signed by each participant to obtain his/her agreement to conduct the study. Then, the observer introduced VAtrack as a

dashboard web-based solution that served as a medium to track and analyse radiation doses of CT scans retrospectively.

The dashboard also performed data pre-processing and provided users with easy access to tracking information and efficient interactivity that allowed users to answer related questions. Subsequently, scenarios were provided to test users one by one. Each individual session lasted approximately one hour, during which test users performed the scenarios both ways. The first participant started by using the current existing process and then VATrack, while the remaining participant started with VATrack then the current existing process. We made the switch in order to ensure the completion of the test because the first test participant became reluctant, tired, and kept checking the time. All participants had the same order of scenarios.

4.2. User and Task Observation

In this usability testing method, a tester observed a test user performing a given task while documenting and timing the process. Any success or failure was recorded. In addition, the test users were not coached. User success was measured by the percentage of tasks completed correctly and the time taken to complete the task.

4.2.1. Identifying Users

This study illustrates how visual analytics enhances the radiation dose tracking process in the radiology department at King Abdulaziz University Hospital. To identify the user group, we started by looking at who was going to use the dashboard: the radiologists at the hospital. We then had to identify their characteristics, so we interviewed radiologists at the hospital to get their thoughts about the current tracking method deployed there, the problems they faced, their needs, and what they felt should be changed. During the conversations, we also learned about their technical skill levels. Four users working in the radiology department volunteered to participate in the testing phase. One of them who was responsible for the tracking task was involved in VATrack's data collection phase. Two of them were female and the other two were male. Three of them were in their late twenties to mid-thirties and one was in his/her early forties.

4.2.2. Task Scenarios

To create the test scenarios, we first listed three basic tasks that needed to be completed regularly by the end users plus two additional related tasks. We determined these tasks by reviewing department tracking files and discussing their contents with domain experts in the Radiology Department at the hospital. These scenarios were completed both ways—the current process and using the proposed dashboard—to compare the two solutions fairly. The task scenario activities were as follows:

- Participating users needed to provide a quick summary presentation of studies and patients from April 2019 that included patients' total counts and distributions within the three main categories of CT scan studies (head, chest, and abdomen) by age classes using both the VATrack dashboard and the process currently used to obtain that information.
- Participating users needed to create a report that showed gender and age distributions within chest CT scan studies using both the VATrack dashboard and the process currently used to obtain that information.
- Participating users needed to know why the patient with ID 1054533 had received a high dosage that was over the limits of the European Diagnostic Reference Levels using both the VATrack dashboard and the process currently used to obtain that information.
- Participating users needed to create a report of adult head CT scan studies performed with a device model "Somatom Definition AS" using both the VATrack dashboard and the process currently used to obtain that information.
- Participating users needed to create a report of overdose studies in children aged 0–3 months for the month of April 2019 using both the VATrack dashboard and the process currently used to obtain that information.

To complete Activities 1 and 2, test users had to explore the data and complete Activities 3 and 5. Further, the data had to be analysed. Finally, to complete Activity 4, participants had to compare the data. In addition, any age criterion was based on the standard used by the department. Age classes were as follows:

- 0–3 months;
- 4 months–1 year;
- 2–5 years ;
- 6–16 years;
- 16+ years.

5. Results

Using the VATrack dashboard, all participants successfully completed the five task scenarios shown in Table 2. However, while following the current procedure used in the department of radiology, 10% of the tasks were completed correctly, 45% were completed with errors, and 45% were not completed (Figure 15).

Table 2. Task completion time. NA means the task hasn't been completed.

VATrack	Test User 1	Test User 2	Test User 3	Test User 4
Activity 1	00:47.23	00:07.50	00:11.60	00:19.00
Activity 2	00:21.17	00:39.50	00:04.52	00:19.95
Activity 3	00:28.47	00:39.51	01:24.91	00:21.90
Activity 4	03:16.84	01:22.95	00:17.50	00:25.10
Activity 5	02:19.99	01:54.65	00:01.00	00:01.00
Total	07:13.70	04:44.11	01:59.53	01:26.95
Current Process	**Test User 1**	**Test User 2**	**Test User 3**	**Test User 4**
Activity 1	09:32.83	01:20.00	02:14.64	NA
Activity 2	01:37.60	03:46.32	02:04.42	NA
Activity 3	03:00.47	02:15.91	00:00.00	NA
Activity 4	03:55.97	04:03.25	01:13.85	NA
Activity 5	19:35.28	03:30.87	04:30.05	NA
Total	37:42.13	14:56.35	10:02.96	00:00.00

For completion time, Figure 16 compares the total times the test users took to perform each activity both ways. As depicted in Figure 16, the activities performed using VATrack took less time to complete with a 100% success rate. On the other hand, being familiar with the current process did not have a significant impact on the time required to complete each activity. Activity 1 represented a basic task the users performed in the department every month. This activity had the longest completion time of 27 min and 36 s, and it was one of the activities that users either did not complete or completed with errors. The test user who already performed this task monthly stopped after approximately 20 min because it would take the entire morning to perform correctly.

In contrast, performing the same Activity 1 using VATrack took around 4 min and 17 s for this particular user, and it took two test users a second to complete, with them noting: "no need to do anything, it is clear by looking at the dashboard".
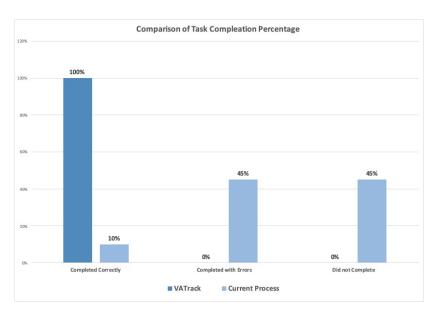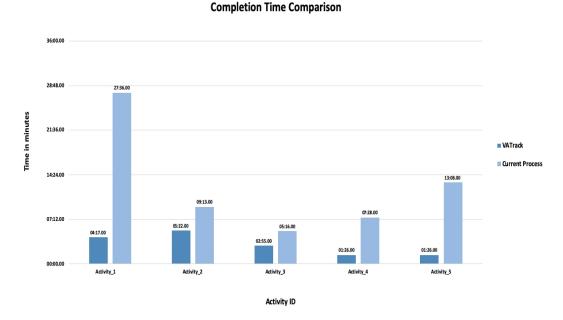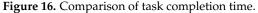
Figure 15. Comparison of task completion percentage.

Figure 16. Comparison of task completion time.

Activity 2 took five minutes and 16 s using VATrack and had a 100% success rate, while following the current process took nine minutes and 13 s with a 0% success rate, putting it into the categories of 'completed with errors' and 'did not complete'. Some of the user errors in this activity occurred during data filtration in Excel; for example, a user chose scanning protocols with "chest" in the name but did not know that "thorax" was an alternative name for the chest. Another user did not complete the task because he was confused by the amount of data.

Activity 3 took two minutes and fifty-five seconds using VATrack with a 100% success rate. Following the current process, it took five minutes 16 s while falling into the three categories 'completed correctly', 'completed with errors', and 'did not complete'. Some of the user errors in this activity while following the current process involved guessing the answer based on his/her knowledge and experience. A user who did not complete this activity knew that he/she needed to compare information against certain standards but did not know what they were.

Activity 4 took one minute and twenty-six seconds using VATrack with a 100% success rate. Using the current process, it took seven minutes and twenty-six seconds and also fell into the three categories 'completed correctly', 'completed with errors', and 'did not complete'. Some of the user errors in this activity while following the current process involved included any scanning protocol with the words 'head' and 'adult' in the name. Additionally, one user used "Series description", not "Study Protocol Name", which was usually used.

Finally, Activity 5 using VATrack took one minute and twenty-six seconds with a 100% success rate. The current process took 13 min and 8 s with a 0% success rate.

Many human errors occurred while following the current process, such as missing records while aggregating the dosages of a single study or adding a CT scan protocol that was not included in a given category; in addition, there were mistakes when recalculating age groups or not calculating them at all. The same went for the use of diagnostic reference levels. In general, looking at the raw data while working with the current process led to the test users becoming reluctant and confused.

Questionnaire

After the test users completed the required tasks, they were asked to contribute and answer an electronic questionnaire that summarised their experience and the usability of the new solution. The first question, as shown in Figure 17, asked users to choose, after trying both methods, which they felt performed each activity better, and 100% chose VATrack.
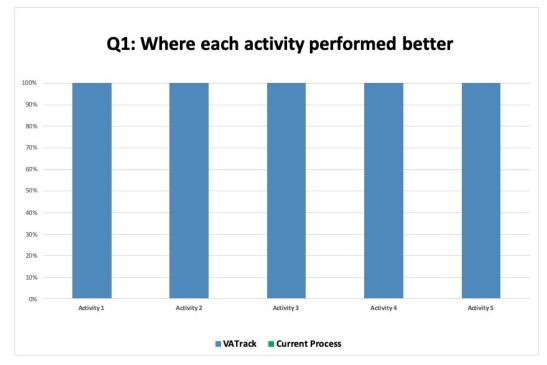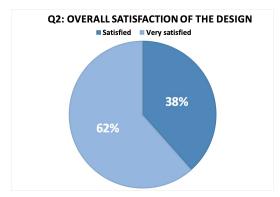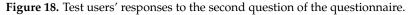

Figure 17. Test users' responses to the first question of the questionnaire.

The second question was about the overall satisfaction with the VATrack design according to the clarity of information, comfort of usage, visual appeal, and usefulness. In general, the responses fell into two categories, as seen in Figure 18: 62% of participants were very satisfied, and 38% were satisfied.

Q2: OVERALL SATISFACTION OF THE DESIGN

■ Satisfied ■ Very satisfied

38%

62%

Figure 18. Test users' responses to the second question of the questionnaire.

The third question was about VATrack's ability to minimise errors while performing tasks or in data pre-processing. All test users, as shown in Figure 19, agreed that VATrack minimised errors. In addition, all test users, as shown in Figure 20, agreed with this.

Q3: VATrack offer minimization of Errors

■ Yes ■ No

0%

100%

Figure 19. Test users' responses to the third question of the questionnaire.

Q4: How easy it was to navigate VATrack?

100%

0%   0%   0%   0%

Very easy   Somewhat easy   Easy   Somewhat difficult   Very difficult

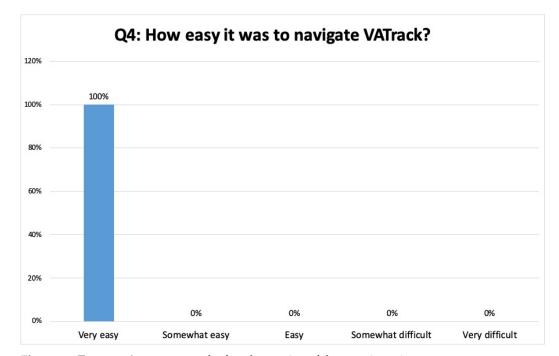**Figure 20.** Test users' responses to the fourth question of the questionnaire.

The remaining question was about what particular aspect(s) VATrack users liked or disliked and what they thought would improve VATrack. In general, users liked the speed of obtaining the required answers and that the ease of use—interacting with it—was

intuitive. In addition, they liked not having to constantly check the DRLs since they were built-in.

In addition, the users liked several simultaneous filters. One complaint was that even though VATrack was much faster than the current process, it needed a better internet connection to perform smoothly. This could be solved using a desktop version of VATrack. Second, if it is possible to change the used Diagnostic Reference Levels (DRLs).

For the suggested improvements in general, users were very happy with their experience with VATrack. One user suggestion was to allow multiple DRLs such as American DRLs and Saudi DRLs in addition to the European DRLs. This point will be added in our future work to support different DRLs.

Users needed more flexibility than commercial radiation dose-tracking software offered, and age classes had to be redefined in accordance with standards used in a user environment, which cannot be done with Dosewatch software. In addition, users needed to be able to customize the view to display CT scan protocols as groups of the targeted body part and to aggregate multi-step protocols into a single record. Plus, users needed to be able to dig deeper once they had identified which patient had been exposed to high radiation doses and answer some important questions such as: 'Why?', 'Which device?', 'Who was the operator?', 'Was it a cumulative or single-dose?', and many more.

6. Discussion

Due to the current increased use of CT scans, patients are increasingly prone to radiation overdose hazards, such as an increased risk of developing cancer [2]; hence, there is a need to keep track of every possible venue where a person might be exposed to radiation, and one of these venues is the hospital.

For example, in [22], the cumulative radiation dose from diagnostic imaging such as a CT scan measured over a partial period—from diagnosis until radiotherapy planning—was 71.5 mSv (range: 11.9–131.9 mSv) for breast cancer patients; this is not negligible. It is also important to note that monitoring is not only to track the cumulative dose but also to support the justification and optimization of procedures.

Before proceeding in detail, we must differentiate between radiation exposure tracking and radiation dose tracking. According to Rehani [2], exposure tracking involves tracking all radiological examinations a patient has undertaken regardless of the dose, whereas radiation dose tracking takes into consideration the dose of each examination.

Healthcare providers, policymakers, regulators, researchers, industries, and, most importantly, patients can benefit from radiation exposure and dose tracking. For instance, in terms of patient safety to avoid/reduce instances of radiation exposure overdose, healthcare providers can benefit from such tools in decision support, resource savings, and better-quality radiation datasets for researchers.

When tracking, patients may be tracked as individuals or groups. In addition, one might track radiological procedure types and counts if a patient has undergone several procedures, the radiation dose data of those procedures, or both. Tracking diagnostic imaging approaches is not an easy task: one of the main difficulties is that radiation dosage varies for the same examination type depending on the scanner, protocol, part of the body to be imaged, and total body size, even if it is the same scanner.

Using the proposed solution shown in Figure 1, users can start by filtering cases using the "flagged studies" filter on the left, examining data more closely on the scatter plot, or viewing detailed patient and study information from the table at the top. In addition, each filter is colour-coded such that the darker/more intense the colour, the higher the radiation count.

7. Concluding Remarks

In this study, we have addressed several problems associated with radiation dose tracking software solutions, including lack of flexibility, ineffective analysis support, and poor interactivity, which tend to decrease user satisfaction with such solutions. The main contributions of this work include:

- Design and develop the proposed visual analytics dashboard to track radiation doses to which patients are exposed.
- Clean the data and organize it automatically in an interactive dashboard.
- Apply several filters simultaneously to the data using several interactive styles. Additionally, the versatility of different filters allows users to explore and manipulate data to answer specific questions.

The aim of this study was to provide a generic, flexible, and easy-to-use visual analytics display tool for radiation dose data from medical scanners and to implement a proof-of-concept prototype that proves our design. The results show that the visual analytic approach improves the tracking process, as users completed the tasks with a 100% success rate.

In future work, we will utilize VATrack exploratory data analysis to allow users to create their own radiation dose benchmarks. They can then include them with other diagnostic reference level standards by providing patient cohort comparison features to emphasize trends and patterns. In addition, to overcome the limitation of a retrospective analysis style, VATrack will have a built-in predictive model that can predict future scenarios based on user-defined criteria and generate alerts based on the radiation dose. Furthermore, VATrack can be used with other diagnostic imaging types where tracking is required, such as nuclear imaging. More, we will make VATrack customizable in a way that allows the user to determine protocols within each targeted body category because this cannot be automated based on protocol names considering there is no standard naming convention in the department. Finally, we will create a desktop version of VATrack to ensure reliability and availability, thus avoiding internet connection issues.

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Abbreviations

BMI	Body Mass Index
CTDI	Computed Tomography Dose Index
CT Scan	Computerized Tomography
DICOM	Digital Imaging and Communication in Medicine
DLP	Dose Length Product
EMR	Electronic Medical Record
HIS	Hospital Information System
PACS	Picture Archiving Communication System

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