JSESD005: Development and Implementation of a Low-cost Source-to-surface Distance (SSD), Collimator Rotation and Gantry Angle Verification Device and its Implications in the Medical Field

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Abstract

The demand for radiotherapy services in developing countries cannot be overemphasised; an increase in cancer cases has been observed and governments have invested heavily in cancer treatment through procurement, maintenance and service of radiotherapy equipment and accessories. The availability of such equipment facilitates the management of various cancer cases by offering services ranging from diagnosis to palliative and cure. However, quality control devices would be required for the treatment machines to operate according to specified standards. These verification devices are so expensive that most developing countries can only buy entry point devices. The basic verification devices in most hospitals are mechanical apparatus like the magnetic front pointer (for source to source-to-surface distance) and spirit level for gantry angle verification. In this study, a linear accelerator (Linac) gantry collimator angle and source-to-surface distance (SSD) verification device was developed and implemented. The physical parameters (distance and angle) are measured using sensor modules. The Atmega 328 microcontroller is used as the main controller for this device. Low-cost and locally-available materials are used in the development of the device. The device can also measure time and temperature, making it a four-in-one multi-purpose QC verification device. The device was tested and calibrated with reference to secondary standards in a local government

hospital setup. A linear relationship was observed between the device and equipment readouts, and the device was then characterised to match the actual measurements. To facilitate inferences, a comparison of results was done using the appropriate statistical tools. Correlation of 99.9996% and a confidence level of 99.98% were observed between the data sets. Through the use of the device, about 81% and 19% was observed in time savings for distance and angle measurement, respectively. The usage of this device brings various operational features such as accuracy, ease of use and increased productivity.

***Keywords**:* collimator rotation measurement, gantry angle, source-to-surface distance (SSD), QC verification device

Introduction

This document is a presentation of the research aimed at improving quality assurance for medical linear accelerator (Linac) machines which are used in external beam radiation for the treatment of tumours. A low-cost microcontroller-based instrument that can measure/verify the source-to-surface distance and gantry angle for a Linac machine was developed. The instrument is a mechanical quality assurance device and has been designed to show digital readings with an accuracy of +/-1 and+/-0.8 for gantry angle and source-to-surface distance, respectively. The current verification methods used in the mechanical quality assurance tests are too manual, and calls for instruments such as spirit levels (for angle verification), and the analogue readings obtained pose a challenge to accuracy. The accuracy of the readings from the apparatus depends on several variables (the reader, placement of apparatus and analogue measurements). The microprocessor-based instrument shows digital readings which are more accurate and faster to read. Operationally, this saves time and gives better accuracy. The two parameters (SSD and gantry angle) are critical, for quality control as they affect the energy delivery to the targeted tumour(s). They are used in the calculation of dose and, as such, have to be very accurate. The development of the instrument took the normal development cycle from the breadboard prototype and, finally, the packaged product. To facilitate the usability and accuracy of the device, calibration was done in accordance to prevailing standard(s). Various tests (qualitative and quantitative) were done on the instrument data to come up with specific operating parameters.

Background

Quality and accuracy are key parameters in planning the treatment of cancer, and this calls for proper maintenance of machinery for the attainment of high service delivery standards. According to Chang et al. (2000), for one to be able to perform the mechanical quality assurance (QA) of a linear accelerator, it is important to find the actual zero-degree angle of the gantry. This implies that the accuracy, safety and quality of treatment are also hinged on the gantry distance (source-to-surface distance/source-to-axis distance) and the angle. This research addresses quality control tests in terms of verification methods and time reduction in carrying out the quality control tests. Several documents have been developed by the World Health Organisation (WHO) as an attempt to conscientise and prioritise quality care in the health sector. Quality control (QC) is periodically carried out for radiotherapy machines and equipment.

However, in Zimbabwe and elsewhere, parameters such as source-to-surface distance (SSD) and gantry angle are manually measured and compared to the digital readouts on the Linac console. However, this approach has its merits and demerits. Considering the fact that we are now living in the digital world, there is a need to digitalise the apparatus or verification instruments. With the advent of the Internet of things, microcontroller devices have found a lot of relevance in various ways by facilitating the processing, storage and retrieval of data from and to devices either directly or indirectly. The microcontroller has been deemed appropriate for the development of this device due to its size, open-source software and upgradability.

Statement of Research Problem

The purpose of this study is to improve on the current mechanical quality control verification on a source-to-surface distance and gantry angle. The current verification methods used by medical physicists (in Zimbabwe and other developing countries) in the mechanical quality control tests are too manual. Instruments in use are spirit levels (for cardinal angle verification) and magnetic front pointers (for source-to-surface distance). The quality control tests for the measurement of such critical parameters therefore take more time, and analogue readings obtained pose a challenge to accuracy and, ultimately, the dose delivered to the patient. Skinner et al. (2019) indicated that although quality assurance (QA) is critical for linear accelerators, the procedures involved are so time consuming that they take the time for other tasks that are supposed to be carried out by medical physicists. This can lead to stress and fatigue which can eventually lead to mistakes, incidents and accidents. As a way of addressing this issue, the development of the SSD and gantry angle verification device is an attempt to come up with improved

workflows, higher reading accuracies and more productivity.

Aim and Objectives of the Research

The research aimed to develop a low-cost microcontroller-based SSD and gantry angle verification device with the following specific objectives:

a) To design and develop a SSD and gantry angle verification device
b) To measure the implication of device usage on productivity

Significance of the Research

Khan (2014) emphasised the need to keep radiotherapy equipment in a healthy state through QA in order to be able to deliver high quality patient care. To carry out the QC for QA, verification/ measurement devices play a critical role. Merwe et al. (2016) emphasised the importance of accuracy in all steps of radiotherapy treatment, and this starts from QA. Quality Assurance procedures and methods need continuous improvement and, in some cases, may be out of date (Williams et al., 2007). The main focus of the research is to improve on accuracy and reduce time spent conducting QC tests, in particular, SSD and gantry angle verification. Skinner (2019) indicated that medical physicists spend a lot of time on QA such that they do not have ample time to do other tasks. According to Podgorsk (2005), QC helps to provide best treatment through the reduction of uncertainties, errors and accidents, as well as facilitating inter-comparison of results. The aspect of full exploitation of technology is also addressed through QC and the associated devices and instruments used. Podgorsk (2005) also indicated that incorrect dose is a resultant of geometric uncertainty like systematic errors. Such errors emanate from field position and block position relative to target volumes or organs at risk. It is in this regard that this verification device is designed and implemented with its key features (affordability, accuracy and reliability), and its suitability in developing countries. Radiotherapy equipment and associated instruments are generally very expensive. The use of a microcontroller as a controller brings countless possibilities such as easy upgrades and Internet of things (IoT) possibilities, whence having such a device will be having a device for the future. The development of the prototype serves in manifesting and concretising the design idea. From a broader perspective, the contribution of this research to the body of knowledge is both prescriptive and deductive.The instrument design and implementation gives some instructions in the use of the device, and uses theory to explain the basic science involved in the measurement of the concerned parameters.

Literature Review

Quality Assurance (QA) in Radiotherapy

In line with quality assurance, considerable work has been done by various researchers/ writers. Chang et al. (2000) looked at critical mechanical QA tests but were more focussed on the surface on which the spirit level is positioned. They used the term 'good surface' to refer to the surface on which the level is supposed to be mounted. Hence, the contribution was more focussed on improving the existing procedure through the use of the spirit level, but in a consistent manner. Welsh et al. (2002) came up with a geometric and mechanical device for medical Linacs called Mini-GARD (shown in Fig. 1), that could be used for daily and monthly QC checks.

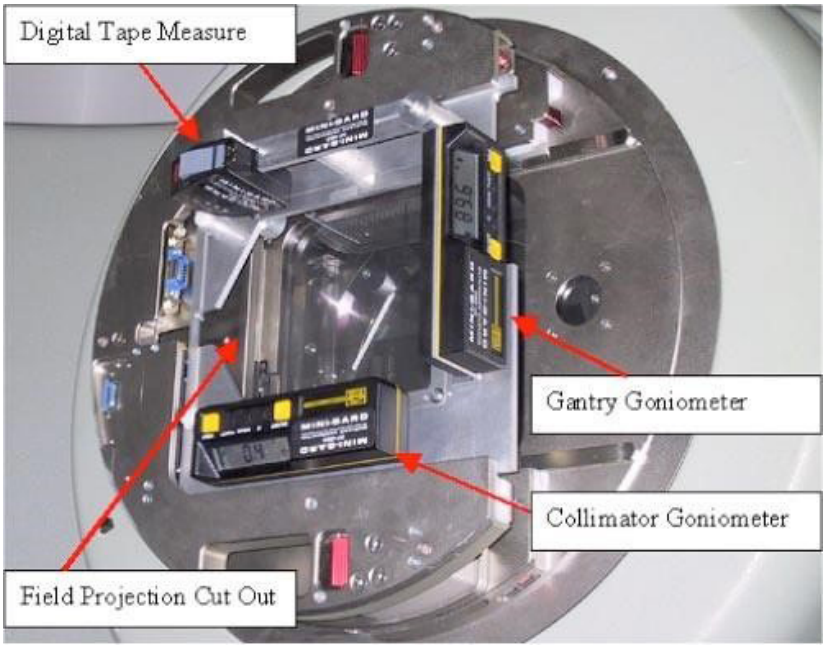


Figure 1: Mini-Gard (Welsh et al., 2002)

The instrument verifies the digital readouts on the machine. It measures gantry angle, collimator angles and field sizes. In addition, it tests optical distance indicator and patient laser alignment. In some related work, Rowshanfarzad et al. (2012) used inclinometers (NG360) in gantry angle measurement. The

sensing unit was basically liquid capacitive-based, and had the ability to measure gantry angle over the range of 360° with an accuracy of ± 0.25°. Hwang et al. (2016) focussed on a new method to align the patient setup lasers. McCowan et al. (2014) developed methods to assess the accuracy of the gantry potentiometer for Linacs. Reinstein et al. (2003) invented a QC device for Linacs, and this instrument could measure a multitude of parameters like gantry angle, optical distance indicator (ODI), collimator angles, radiation of field size and alignment of the lasers.

From the little literature that has been produced, it seems not much has been done in terms of coming up with new methods and instruments for the verification of Linac SSD and gantry angle. This device is different from those that are currently on the market in that it will be measuring or verifying just two parameters (gantry angle and SSD). It will be microcontroller-based and, as such, brings in endless possibilities in terms of future developments and easy integration to other existing systems without necessarily making huge changes. Most modern hospitals have taken the paperless technology path through the use of hospital information systems and, in line with this, the data collected by such a device can be stored or retrieved if the device becomes a component of the hospital information system.

Methodology

The building blocks of this project falls into hardware and software. The hardware is as shown in the respective figures in this study. C language was used for the project software development.

System Hardware Components

The verification device is composed of five parts/blocks: the microcontroller, the gyromagnetic sensor, the ultrasonic sensor, the power supply and the display. Fig. 2 shows the block diagram of the device.

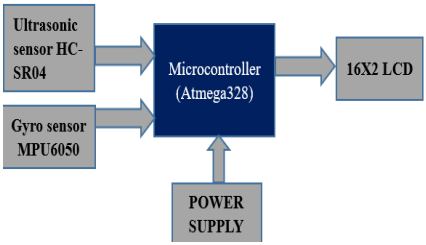


Figure 2: SSD, gantry angle verification device block diagram

Interfacing Microcontroller and Ultrasonic Sensor (HCSR04): Software
Through the use of the relevant data sheets, the SSD/ distance calculation was done as follows:

According to Shrivastava (2010), *from distance = speed x time*
And *velocity/speed = 340+0.6(t-15) m/s* ……..... (1)
where t: temperature in °C.

a) The following assumptions were made:
   i) Room temperature of 20°C was assumed, hence the velocity of ultrasound in the air was taken as 343 m/s.
   ii) In calculating the distance, the 343m/s is taken as the universal speed of ultrasound and this is incorporated in the computation.

b) Total distance was calculated as:
   i) $Total\ distance = 343 * Time\ of High(Echo) pulse/2$ ……..…..…..(2)
   ii) $Distance\ (in\ cm) = echo\ pulse\ width\ (in\ microsec)/58$ ……..(3)

Interfacing Microcontroller and Gyro-sensor (Software)

Time/Counter
This has been coded as value = millis (). This code basically counts the number of seconds since the programme started running. This has been converted into minutes and fractional minutes by multiplying by a factor of 0.1667, hence finally ending up with:

$j = \frac{millis()}{1000} * 0.01667$, and this number will overflow after about nine hours.

Temperature sensing
On the gyroscope sensor, the temperature formula incorporated in the programme was taken from the sensor datasheet as:

$$tx = Tmp + tcal \text{ ……..... (4)}$$

The conversion of temperature into degrees Celsius was done using the following relationship which was also obtained from the datasheet:

$$t = \frac{tx}{340} + 36.53 \quad \text{..... (5)}$$

Device Characterisation

The device readings were compared with those on the machine and gave variances which were then corrected. The results are herewith presented before and after correction.

SSD

After the statistical analysis of the device and Linac data, a constant of 66.64 cm was obtained which was then used as a correction factor. The final line code was therefore entered in the programme as D=66.64+distance, where D is SSD and distance is as in equations (2) and (3).

Gantry angle

There was no correction factor incorporated as the data obtained and analysed had about 99.98% accuracy.

Software and Hardware Layout and Casing

Fig. 3 shows how the components were wired and placed in the device casing. Terminations to the peripherals were connected through soldered connections and block connectors. Main modules were also connected to the controller through buses.

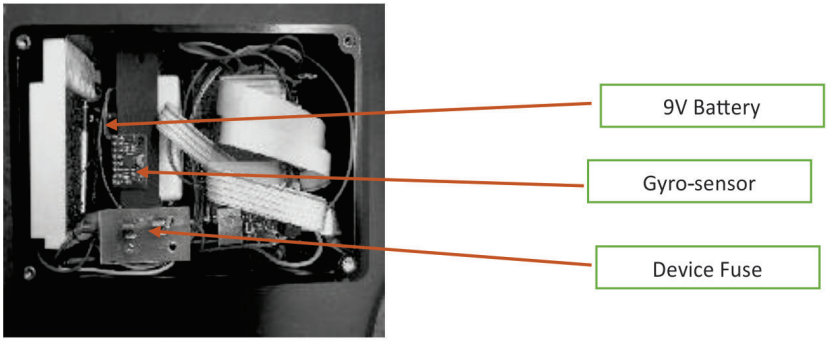


Figure 3: Hardware and software testing

Field Measurements/Verifications

Fig. 4, Fig. 5, Fig. 6.1 and Fig. 6.2 show the various position mountings of the device to verify various parameters in a hospital setup.

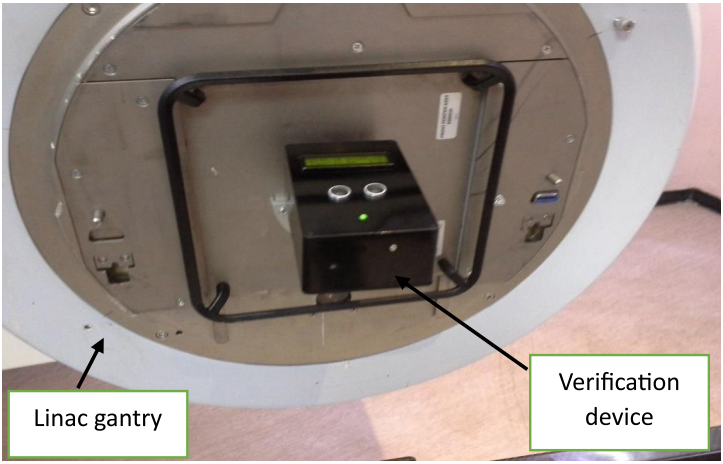


Figure 4: Collimator rotation measurement on Linac machine

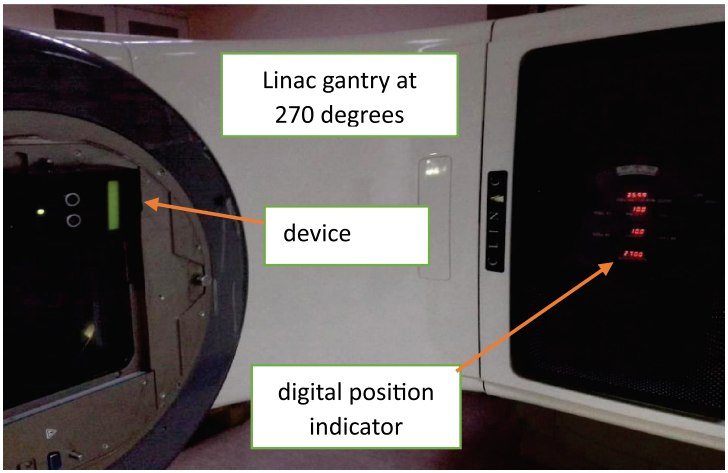


Figure 5: Device mounted for gantry angle measurement

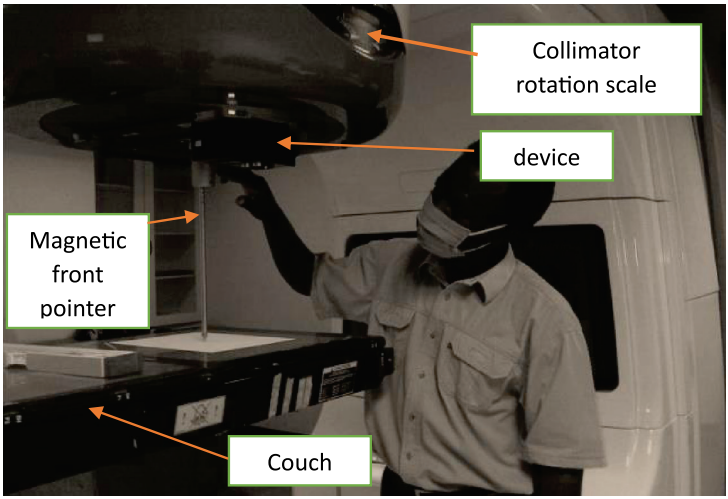


Figure 6.1: Device mounted on Linac gantry-SSD measurement

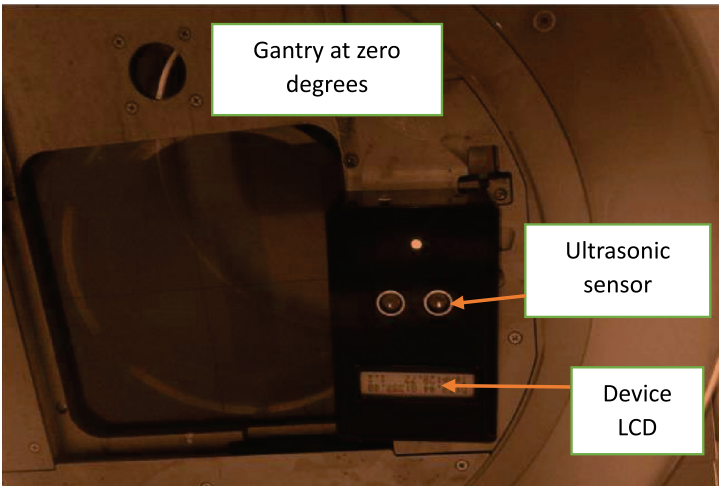


Figure 6.2: Device mounting on Linac gantry (SSD and gantry angle measurement)

Implications of Device Use in the Medical Field

A qualified medical physicist was observed carrying out SSD and gantry angle QC on the Linac. Each parameter measurement and verification was done three times. The average time was then considered for each process.

Comparisons of the time taken for the two methods were done, tabulated and represented on pie charts as shown in Section 5.3 of the results.

Measurement data was taken, tabulated and statistical tools used to facilitate presentation and inferences. Multiple data analysis techniques were employed as a way of achieving objectivity.

Results And Analysis

Results/Measurements after Incorporation of Correction Factors

Source-to-surface distance (SSD)

A linear relationship was obtained between the device and the Linac readings as shown in Fig. 7.

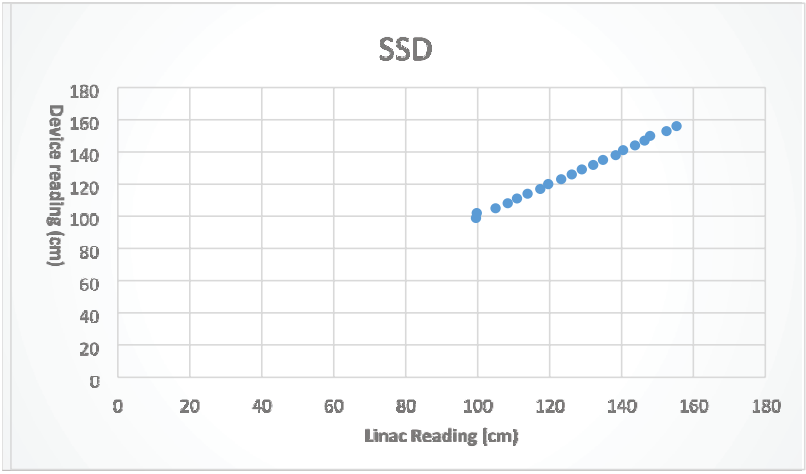


Figure 7: Linac readings versus device readings

The variations on device readings were plotted against the residuals, and the results obtained are as shown in Fig. 8. The graph shows peak residuals/errors at about 104 cm and 150 cm, and this may be attributed to the detection angle of the ultrasonic sensor and some surrounding obstacles in the bunker.

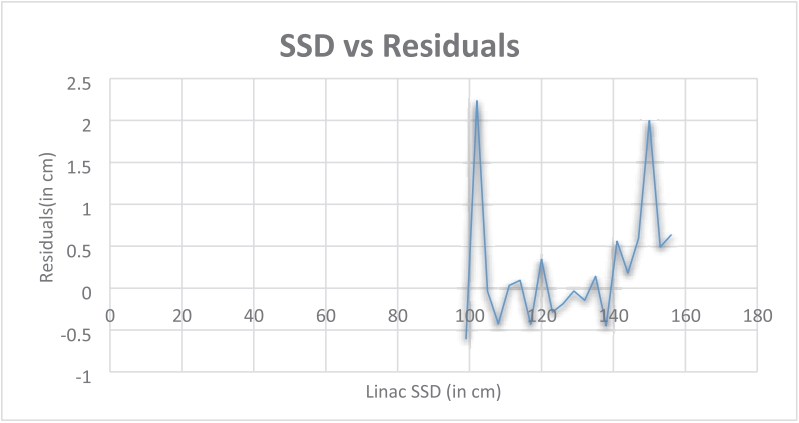


Figure 8: Linac SSD versus device error

Gantry and collimator rotation

The relationship between the Linac and device readings was plotted on the same axis, and a linear relationship was obtained as shown in Fig. 9. Through the use of statistical analysis, the gradient of the line was almost 1 (0.99).

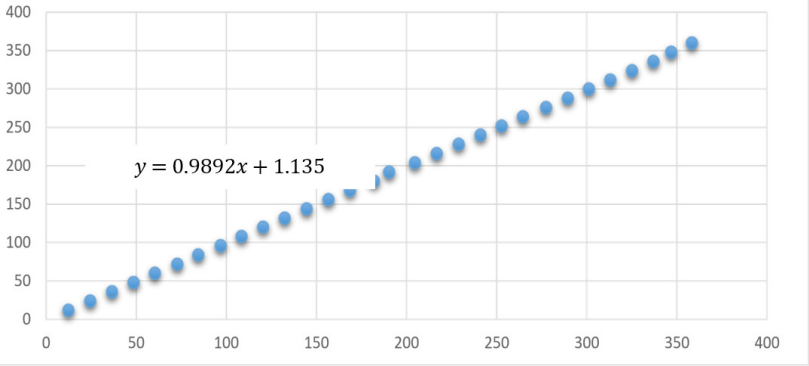


Figure 9: Linac versus device angle readings

Fig. 10 shows a more detailed relationship on variation of error with machine readings. Considerable overshoots were observed at points A, B and C and, overall, the error was observed to sit at about +/-0.5 degrees.

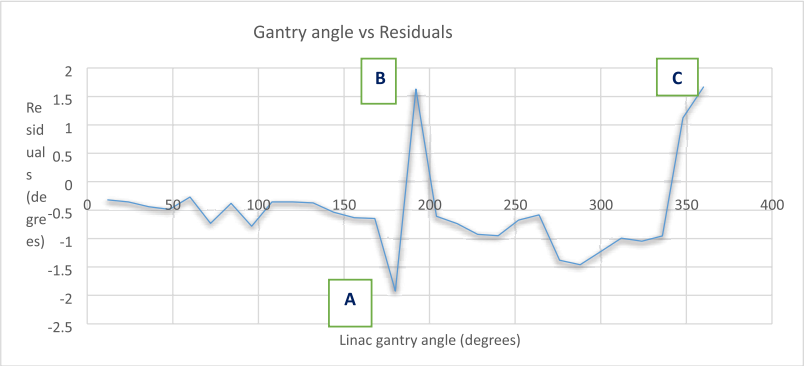


Figure 10: Linac gantry angle versus residuals

Collimator rotation

For the collimator rotation, the same analysis as the one for the gantry angle was done. A convenient sample was taken at 0; 90; 180 and 270 degrees.

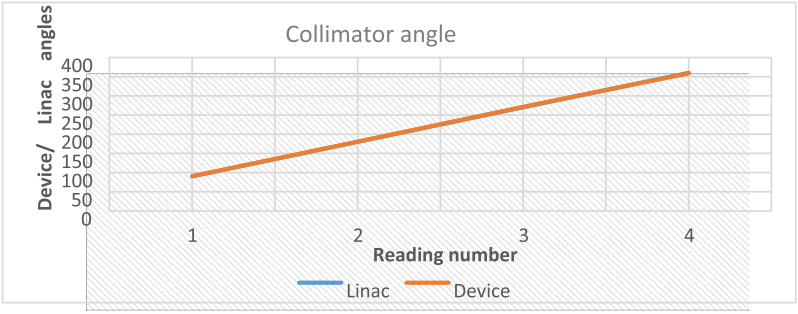


Figure 11: Device and Linac collimator angle

Fig.11 shows the relationship between device and Linac collimator angles; the two graphs are almost in phase, indicating that the angles from the two are almost the same. This figure resembles the gantry angle results shown in Fig. 9.

Device Technical Parameters

Accuracy/Error, maximum values and the number of decimal places were considered in coming up with device specifications.

a) Gantry angle: accuracy = 99.72%
Accuracy as percentage of maximum range = 99.85%

b) SSD: correction = $True\ value - Measured\ value$
100 − 33.36 = 66.64 cm
(i) Distance measurement and threshold(s): calculating the distance:
$distance = 66.64 + duration * 0.0342/2$

(ii) Setting threshold: if (distance >= 450||distance<=81){lcd.set Cursor (0,0); lcd. Print ("**Out of Range**");

c) Significant figures: Float data type was incorporated in the declaration and calculation of all parameter readings and readings were given to two decimal places, which is an indication of the precision of the device; the more the significant figures, the more the precision**.**

Implications of Use of Device on SSD and Gantry Angle Verification

Fig. 12 and Fig. 13 represent the results obtained after carrying out the procedures in Section 5.3.

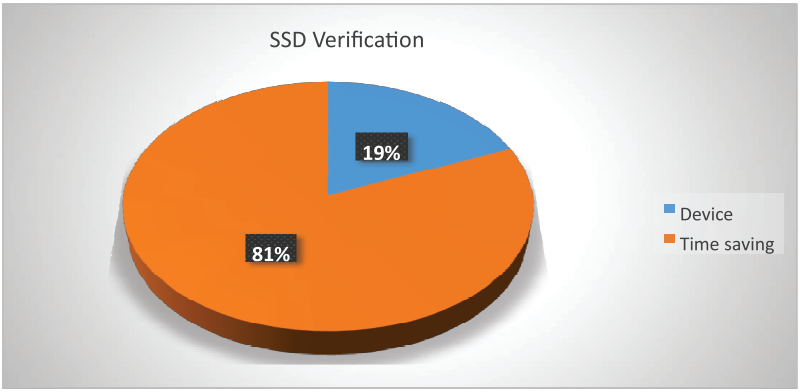


Figure 12: Time reduction on Linac SSD verification

Fig. 12 shows that for SSD verification, 19% of current practise time is required. This results in 81% time savings.

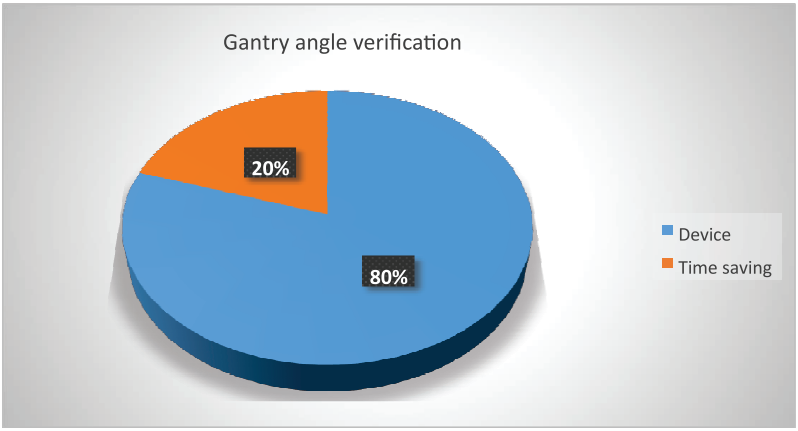


Figure 13: Time spent on Linac gantry angle verification

Fig. 13 shows that for gantry angle verification, 80% of current practise time is required. As a result, there is 20% time savings.

Descriptive Evaluation

The components of the device were interfaced successfully both in hardware and software. The objectives generally touched on designing, developing, calibration, characterisation and measurement, including noting implications on productivity.

Unlike the GARD system that was developed by Welsh et al. (2002), this device has a very big advantage in that it is a single multi-parameter device. However, the GARD system had an additional parameter (field size) that it could measure. Both devices (the GARD and the microcontroller-based device) measure SSD, gantry and collimator rotation. The microcontroller controlled device has two additional parameters (counter and temperature) that it displays. Rowshanfarzad et al. (2012) also came up with a similar device but could only measure the gantry angle. Although the instrument was accurate, it, however, has some demerits when used in the field; it only verifies one parameter. Such an instrument would be very relevant and appropriate in calibrating other instruments because of its high accuracy.

However, in real life situations, it would be best to have one multi-purpose device when carrying out Linac QC, for this saves time. Further, in terms of operations, as has already been revealed in this study, only one person can carry out the QC. Reinstein et al. (2003) also invented a QA device

for Linacs, and the instrument could measure a multitude of parameters like gantry angle, ODI, collimator angles, radiation of field size and alignment of the lasers. The multi-parameter aspect in this regard would bring countless advantages over devices that can verify one or a few QC parameters. Another most important aspect is that the device has to be affordable. For instance, if we look at developing countries, the prices for the multi-purpose QC devices is on the high side. This then leaves the countries/institutions with no option but to go for entry level devices, which are still expensive. The verification device developed in this project is affordable (costs about US$80-US$100) and is made from locally available components and materials.

Analytical Evaluation

One of the objectives of this study was to find out the implications of using the device as opposed to the current practice. In pursuing this objective, overall, when the procedure was done for the four machines at a government hospital in Harare, a total time saving of about 12 minutes was observed. However, the current practice requires two people to carry out the SSD and gantry angle QC. From a human resources perspective, the total time saving will be in man-hours, and if this is translated to monetary terms, it has a greater impact on remuneration. The contributing factors to the general time saving are the fact that the microcontroller-based device is a multi-parameter device, is microprocessor controlled and gives a digital readout, is magnetically mounted at the respective recommended points, and instead of getting multiple apparatus to perform QC, one only needs a single device.

Just like any other instrument, the device has technical specifications. The calculated errors in gantry angle and SSD measurement were 0.282% and 0.1843%, respectively. This translates to accuracies of 99.72% and 99.82%, respectively. This shows that the instrument readouts are fairly accurate and lie within the tolerances set by world standards and in the respective procedures (2 mm for SSD and 1 degree for gantry angle). In line with accuracy, the number of decimal places plays a big role. The device gives readings to two decimal places, which is more accurate as opposed to rounded off readings; the decimal aspect gives better resolution.

Limitations of the Study

The microcontroller-based device could not be calibrated to secondary standards. Instead, it was calibrated to sub-standard, that is, with reference to a secondary standard and, as such, may not be used to calibrate other equipment or devices falling under its category. All calibrations and

measurements were done on machines at only one government hospital. It would have been best if verifications were also done at other centres to get more information pertaining to the instrument parameters.

Significance of the Results

The results obtained in this research show that this instrument is functional, reliable and time saving for the Linac SSD and gantry angle verification. The tests and verification have been done in a clinical setup, and this makes the results and inferences authentic. However, in the event that the project needs to be taken to another level (which could be further development or production), these results can be used or be referred to when the need arises before the instrument is put to a field test.

Conclusion And Recommendations

Conclusion

The aim of the project was met and exceeded; the verification device was developed and implemented using option(s) that could address the aim and objectives. The cost of the device is about US$95, and the device has been developed using locally-available materials/components. If labour and other costs are factored in, the selling price of this device could be around US$120. The device has also been tested and found to be very accurate in the measurement/verification of the stated parameters. Further, it has three extra parameters that it can measure or show (collimator rotation, temperature and timer/counter). Each and every objective was looked at during the course of the research and addressed accordingly. The stated objectives were addressed as follows:

To design and develop an SSD and gantry angle verification device

From the various design options through the use of various components and with the guidance of the stated objectives as well as the consideration of the merits and demerits, the device was successfully designed and implemented using the Atmega 328 microcontroller. The design included both hardware and software as well as the interfacing. The available literature assisted in the attainment of the required knowledge. The development of the prototype also included prototype casing, chosen based on availability and cost. The device was also characterised and gave accuracy levels above 98%, as indicated in the results. A very important aspect is also the LCD which shows measurements to two decimal places, which also has a bearing on accuracy. The use of MEMS sensor technology-based modules (as in accelerometer/

gyroscope sensor) resulted in high levels of accuracy. On the other hand, the ultrasonic sensor also improved on distance measurement in terms of accuracy as it is not very much affected by factors such as colour and other environmental conditions.

To assess the implication of using the device in carrying out QC for SSD and gantry angle verification

Having developed, implemented, tested and calibrated the device, a timed exercise was used in the use of the device (as indicated in the methodology and results sections), and the time durations compared with the current procedures. It was noted that there is a lot of time savings when using this device as compared to the current practice. For SSD and gantry angle verification, the use of the device reduces time by about 81% and 20%, respectively. This impacts on various aspects of productivity and, as such, becomes critical and interesting from a human resources perspective. For instance, the medical physicist will take less time to carry out this important exercise while having more time to perform other critical issues.

The development and implementation of the device has been a success, and all objectives have been met and even exceeded. This project can be categorised under innovation, which is in line with Zimbabwe's new Education 5.0 Philosophy. Further development of this prototype into a marketable product will address a lot of challenges that we are currently facing as a country in relation to radiotherapy equipment operations, maintenance and, to some extent, repairs. This is a low-cost product that can positively impact taking measurements and improving productivity.

Recommendations

Radiation protection/screening of electronic components

There may be need to use the device for a reasonable period of two or so years, and then make an assessment of the variance of the readings obtained from the instrument. From both a theoretical and practical point of view, the components will change their specifications due to exposure to certain levels of temperature and radiation (Golunov et al., 2019). Such variance will therefore call for periodic calibrations to make sure that the readings from the device are correct to a chosen reference.

Device casing

This can also be made smaller and lighter so as to facilitate its mounting on the gantry to take measurements. A heavy device will need a stronger

fixing mechanism to mount it on the gantry. If magnets are used as fixing mechanisms, stronger magnets are required for heavier devices.

Measured parameters

This device is only able to measure three parameters. It would be best to have a device that can measure more parameters to address issues of convenience and cost cutting.

Angle measurement

The gyro-sensor used in the development of this device is capable of giving x, y and z values and, as such, its use can be extended to various situations where 3D coordinates or measurements are required, for instance, in object flatness tests/verification.

Mounting plate

The device mounting plate/surface needs to be firm and flat so that correct measurements, especially for gantry angle, can be obtained. During verification, as the gantry rotates, the device will be subjected to force of gravity, and if the mounting system is not strong enough, this would be a source of errors.

In terms of continuous improvement, these recommendations are just some of the few possibilities of improvements that can be made.

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