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LANDAUER® TECHNOLOGY WHITE PAPER

microSTARii™ – A new system for medical dosimetry: *Part I: Technology & Initial Performance*

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Executive Summary

The new microSTARii™ from LANDAUER® represents a significant step forward in making fast, accurate and repeatable point-dose measurements in medical dosimetry. The microSTARii™ features innovations in electro-optical, mechanical and software design, including new technology developed for the US Army RadWatch™ OSL dosimetry system, which was designed to monitor radiation exposure to battlefield personnel. These technological innovations significantly improve signal-to-noise in dosimetric measurements. In addition, the microSTARii™ uses state-of-the-art manufacturing techniques and aerospace-grade materials and coatings to improve durability and to increase dosimeter positioning accuracy. Initial results indicate that the microSTARii™ is exceptionally stable and measurements are highly repeatable. The intrinsic stability was measured using the PMT and a Photodiode, and the coefficients of variation were 0.017 and 0.008 respectively. Precision was evaluated using stationary and moving repeatability measurements. Repeat measurements of the same nanoDot™ without removing it from the reader were within 0.53% and repeat measurements of the same nanoDot™ after moving it were within 0.59%. The lower limit of detection is less than 0.020 mGy. The microSTARii™ software is also tightly integrated with the reader's operation to dramatically improve workflow and to automate quality assurance tracking. This paper describes the new technology and measurement techniques that were used in the microSTARii™ to provide a new level of performance for medical dosimetry.

Introduction

Design Goals: Improved Workflow and Accuracy

The LANDAUER® microSTARii™ combines state-of-the-art electro-optics with contemporary design in order to achieve superior performance in medical dosimetry applications using nanoDot™ optically stimulated luminescence (OSL) dosimeters. The purpose of this paper is to describe the improved accuracy and workflow that were the key design goals of the new microSTARii™, the technology innovations that were developed to meet the design goals, and the performance that was subsequently achieved.

Figure 1: microSTARii™ Medical Dosimetry System

The accuracy and reproducibility of measurement of the new microSTARii™ were improved using a number of technological innovations. For example, the microSTARii™ uses a redesigned, state-of-the-art electro-optical engine and embedded microprocessor for pulsed LED stimulation, luminescent light collection and on-board data collection [Yoder (2010), Akselrod (2013a), Akselrod (2013b)]. A new readout technique was also developed that uses pulsed optically stimulated luminescence (POSL) to improve the signal to noise of nanoDot™ measurements and improve measurement accuracy and reproducibility. New methods of measuring intrinsic reader performance were developed and integrated into the software to facilitate quality assurance analysis. The mechanical design was optimized for accurate and precise measurements of nanoDot™ dosimeters, and measurement precision was further improved through custom optimization of each reader's measurement settings. Reliability and durability were improved through the use of aerospace-grade coatings and self-lubricating plastics.

The workflow of the microSTARii™ was significantly improved through additional hardware and software design innovations. For example, a new drawer was developed that can be quickly loaded and easily slid into position, which enables faster reading of nanoDots™. The drawer was designed with a new nanoDot™ positioning feature such that the nanoDot™ is opened and positioned very consistently, which significantly improves the precision of repeat measurements. The reader and software were designed in tandem to complement each other and enable new automatic reading features that were not previously possible. In addition, new software features make it possible to perform multiple measurements without moving the nanoDot™ which provides better dose reproducibility than the original microStar. The automation of the multiple read processes enhances the workflow by eliminating the need to manually initiate the read process multiple times. Furthermore, the software recognizes repeat readings of the same nanoDot™ so it is unnecessary to rescan the serial number for each reading.

The remainder of this paper describes the technology innovations that were developed to meet the design goals, and the measurement performance that was subsequently achieved.

Technology Innovations

New Intrinsic Measurements for improved Quality Assurance

The automation features of the microSTARii™ facilitate the collection and analysis of data for clinical quality assurance programs. For example, the new microSTARii™ software automates the collection of most of the measurements required for daily quality assurance. In the original microStar™ this required the physicist to turn a mechanical knob as many as 80 times, but the new microSTARii™ software accomplishes this with one mouse click. After the automatic intrinsic measurements and multi-read QC analysis have been completed, the average reading and coefficients of variation are automatically calculated and checked against the performance specifications. This feature eliminates the need to export measured data, and to manually perform spreadsheet calculations in order to track the intrinsic stability of the reader as part of an ongoing clinical quality assurance program.

The new design, combined with new optical filtration, allows for spatial separation of the excitation light from the luminescence light. The change in the readout from Continuous Wave Optically Stimulation Luminescence to Pulsed Optically Stimulated Luminescence reduces the background noise to a level approaching the dark counts in the photomultiplier tube (PMT).

In the microSTARii™, the PMT and the photodiode are used to measure the LED, which enables intrinsic measurement of the stability and magnitude of both the PMT and the LED over time. The microSTARii™ offers three such Intrinsic Performance measurements (formerly known as standard measurements). The Intrinsic Performance measurements include the Dark Count, the PMT Count, and the Photodiode Count measurements.

The Dark Count measurement is a measure of the PMT background noise and light-tightness of the reader enclosure. The Dark Count is recorded for a time equivalent to the read time of a standard dosimeter read with the LED off.

The PMT Count is a measurement of the LED with the PMT. Due to the differences of POSL and CW-OSL, the technique for recording the PMT response differs between the microSTARii™ and the original microStar™. In the original microStar™, a filter was mounted on a movable arm that was shifted out of the optical path during the LED measurement. With CW-OSL, the LED is on throughout the dosimeter read, so the LED measurement is the same as a standard read (other than the removed filter). In contrast, the POSL measurement technique used by the microSTARii™ does not record counts during the LED pulse for normal dosimeter reads. A special algorithm was developed for the microSTARii™ LED intrinsic measurement to enable measurement of the LED during the pulse.

The Photodiode Count measurement is a new measurement technique used in the microSTARii™ and made possible by the new Photo-Optical Engine. Figure 5 shows the basic layout of the optics in the microSTARii™. The photodiode is placed opposite the PMT. The glass backside of the central LWP filter acts as a beam sampler directing a small portion of the LED light into the photodiode.

Another innovation in the microSTARii™ is the elimination of the C14 radioactive source that was used in the original microStar™ for PMT standard measurement. Lastly, the Photo-Optical Engine used in the microSTARii™ has no moving parts, which further improves reliability and reproducibility.

State-of-the-Art Electro-optics and Pulsed Measurement

The new microSTARii™ uses advanced electro-optics technology, and an improved readout technique to significantly improve the signal-to-noise of the luminescence measurement. The advanced optical design combines focusing lenses with a shorter optical path to increase luminescence collection. The new design, combined with new optical filtration, allows for spatial separation of the excitation light from the luminescence. The change in the readout from Continuous Wave Optically Stimulated Luminescence to Pulsed Optically Stimulated Luminescence reduces the background almost to the level of dark counts in the PMT. For the microSTARii™, LANDAUER® used a new, patented, pulsed optically stimulated luminescence (POSL) measurement technique with a reflective geometry. POSL electro-optics with reflective geometry were originally developed by LANDAUER® for the US Army as part of the RadWatch™ OSL dosimetry system that is now used by the US Army for monitoring radiation exposure to battlefield personnel.

In conventional, continuous-wave optically stimulated luminescence (CW-OSL), the illumination source is used to stimulate luminescence while, simultaneously, the luminescent signal is collected by a photomultiplier tube (PMT). The illumination light is a potential source of background noise, thus filtration is required to both prevent the illumination light from reaching the PMT, and to allow the signal to be collected. In CW-OSL, there is a trade-off between the background noise and the signal, which reduces the overall signal-to-noise of the system. With aluminum oxide dosimeters, however, it is not necessary to continuously provide optical stimulation because the aluminum oxide crystals continue to luminesce for approximately 35 msec after the stimulation beam has been shut off [Markey (1995)]. The pulsed optically stimulated luminescence (POSL) technique takes advantage of this relatively long luminescence decay of aluminum oxide. Using the POSL technique, the illumination source is pulsed on to stimulate luminescence, and then briefly turned off, during which time the luminescence signal is measured. When short pulses are used, more than 90% of the luminescence is emitted after the pulse. Thus, the background noise from the illumination source can be eliminated by separating the period of illumination from the period of luminescent light collection. After the illumination pulse, there is a short delay that allows the illumination source to completely turn off before the luminescence is collected. Separating stimulation and luminescence in time also reduces the amount of filtration that is required in the optical chain, which further increases signal relative to background noise.

The microSTARii™ uses a Super Bialkali Photomultiplier Tube (PMT). The Super Bialkali PMT uses a new photocathode from Hamamatsu that improves the spectral response characteristics of the PMT and boosts its quantum efficiency by 45% at its peak wavelength. The higher quantum efficiency of the PMT in addition to POSL measurement technique increases the signal to noise response of the microSTARii™.

Mechanical Innovations

In designing the microSTARii™, LANDAUER® used contemporary industrial production methods, such as 3D printing, rapid-prototyping, and state-of-the-art technology originally developed for the US Army, to design and develop a reader that is significantly smaller and lighter than the original microStar™. The new case has a contemporary look-and-feel that compliments the high performance internal electro-optics and precision mechanical components.

The microSTARii™ was designed to simplify the nanoDot™ reading cycle as much as possible. The new mechanical design of the microSTARii™ reduces the number of moving parts in the reader by a factor of 5 relative to the original microStar. For example, the action of inserting the drawer is all that is needed to position the nanoDot™ into the read position. The drawer is constructed from precision-machined aluminum with an aerospace-grade, hard anodized coating for smooth operation and high durability.

Figure 2: microSTARii™ drawer

The durable construction and small number of moving parts in the drawer ensures a long life of reliable operation. In addition, the drawer is a separate part from the reader that can be removed for field cleaning and maintenance. It is also possible to use multiple drawers with the same reader to further speed the work flow. As shown in Figure 2, the drawer is modular and contains the only moving parts of the reader, which results in increased measurement accuracy and precision, greater reliability, improved ease-of-use, and improved serviceability. The interior nanoDot™ positioning mechanics were designed to precisely position the nanoDot™ for reading with special locating features and tight tolerances.

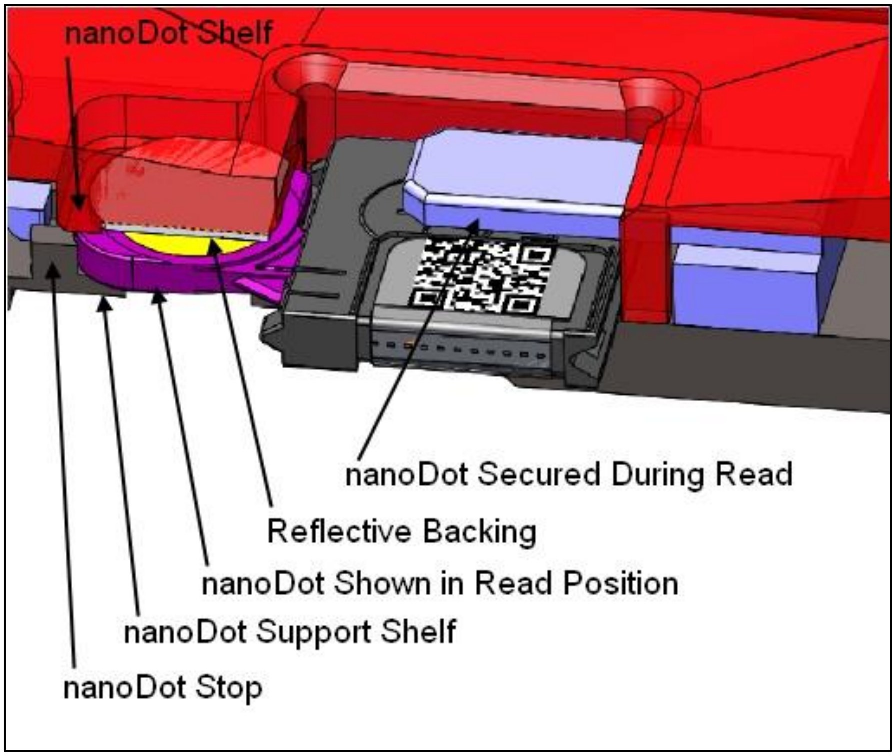

Figure 3: nanoDot™ positioning in drawer

As shown in Figure 3, the nanoDot™ is held in place on all sides, and the action of inserting the drawer into the reader moves a pin that opens the nanoDot™ and extends it until it hits a semicircular hard stop. The pin maintains pressure on the nanoDot™ throughout the read to insure there is no variability in positioning during the read. There is also a bar parallel to the pin that secures the nanoDot™ in place during the read. Below the nanoDot™ there is a support bed and above the nanoDotTM there is a shelf. The combination of the support bed and the edges of the shelf ensure that the nanoDot™ element is coplanar to the optical aperture. The center of the shelf is slightly recessed to allow a reflector to be inserted. The reflector has several purposes. First, it reflects the stimulation light that has passed through the element back onto the element to generate more luminescence. Second, it reflects some luminescence back through the element so it can be measured by the PMT. Third, it reflects the stimulation light during intrinsic measurements to increase the counts of the measurement.

The advantage of the reflection geometry in the microSTARii™ over the transmission geometry used in the original microStar™ is that the reflection geometry significantly reduces the physical size of the optical components. The transmission geometry used in the original microStar™ is characterized by the illumination LEDs sitting on one side of the dosimeter and shining onto and through the NanoDot™ element. On the opposite side of the dosimeter the luminescence and the excess LED light are collected by the PMT. In contrast, the reflection geometry used in the microSTARii™ places the PMT and the LED on the same side of the dosimeter. This configuration allows the optical chain of the reader to be significantly reduced in size. Figure 4 illustrates the size difference between the transmission and reflection geometry.

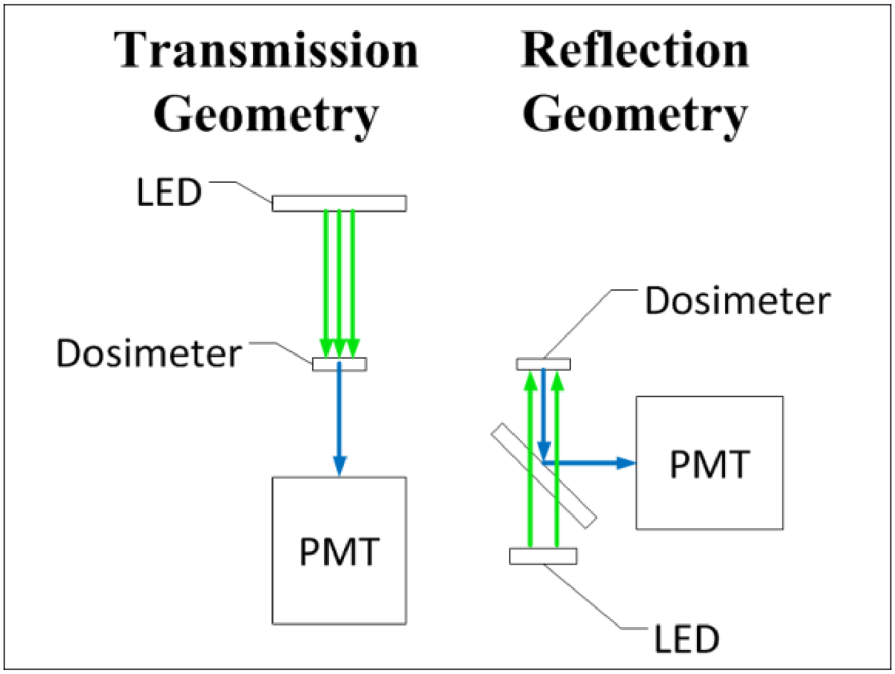

Figure 4: A comparison of Transmission and Reflection Geometry

The microSTARii™ uses the same Photo-Optical Engine that was designed for use in the RadLight™ readers with the RadWatch™ dosimeter. The Photo-Optical Engine is a single unit with a reflective geometry OSL readout optical chain that consists of a small, light-weight and robust aluminum housing containing the LED, PMT, photodiode, filters and focusing optics. The Photo-Optical Engine introduces several design improvements over the original microStar™ optics and electronics. For example, the microSTARii™ uses a single, high-powered LED in place of the 38 LED array of the microStar™. The beam profile of the high-powered LED is very consistent from reader to reader. The microSTARii™ also uses a new PMT that is smaller, more sensitive and has a higher dynamic range than the PMT from the original microStar™. The microSTARii™ also introduces a new photodiode to monitor the stability of the LED.

Figure 5 illustrates the optical chain and operation of the Photo-Optical Engine. During the LED pulse, light is emitted from the single, high-powered LED. That light is directed through a long wavelength pass LED filter that blocks out the blue portion of the LED spectrum. The LED light then passes through another filter with a long wavelength pass edge transmission coating. Then the dosimeter is illuminated. The dosimeter immediately begins luminescing, however the luminescence is not recorded until the LED illumination pulse has terminated. The luminescence returns from the dosimeter and the long wavelength pass filter coating reflects the shorter blue wavelength into the PMT. Even though the PMT is not in a direct line with the LED, the filtration is still needed to protect the PMT from stray LED light during the pulse. The photodiode is illustrated in Figure 5 on the left side of the Photo-Optical Engine. The glass substrate of the LWP coated filter acts as a beam sampler directing a small amount of the LED light into the photodiode.

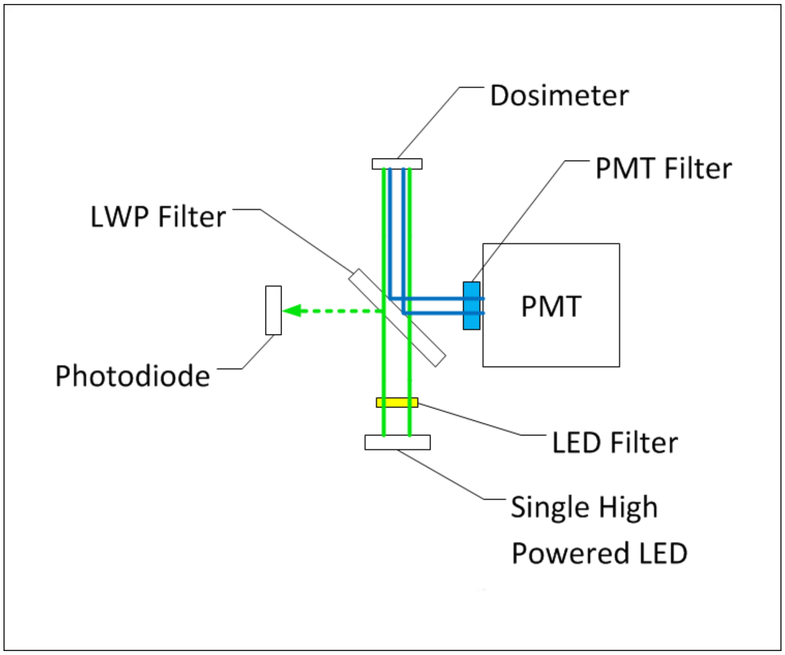

Figure 5: Photo-Optical Engine layout

Results

Initial results indicate that the new microSTARii™ is exceptionally stable and measurements are highly repeatable. The intrinsic stability of the new reader was evaluated using intrinsic measurements of the PMT and Photodiode counts from nine readers. The average coefficients of variation of the PMT and Photodiode counts measured using nine different readers were 0.017 and 0.008 respectively. In contrast, the coefficient of variation for LED standard measurements of the original microStar™ were 0.028 on average, and the coefficient of variation for PMT standard measurements were 0.022 on average.

The precision of the new reader was evaluated using tests of stationary and moving repeatability. The stationary repeatability test measures a reader's ability to reproduce a reading without removing the dosimeter from the drawer. This is important because the microSTARii™ software can make multiple measurements of the same nanoDot™ without moving the dosimeter. The moving repeatability test measures the precision of reading the same nanoDot™ after the dosimeter is removed and replaced before each read. All repeatability tests were performed using nanoDots™ exposed to 50 cGy of Cs137. Measurements from nine readers resulted in an average stationary repeatability within 0.53% and an average moving repeatability of 0.59%.

The microSTARii™ also delivers improved lower limits of detection (LLD) compared to the original microStar™ and, for low dose measurements, approach 0.010 mGy. The average lower limit of detection (LLD) measured using nine microSTARii™ readers were less than 0.020 mGy for the strong beam and 0.055 mGy for the weak beam. The original microStar had a strong beam LLD of approximately 0.040 mGy on average (the weak beam LLD was not normally calculated). These improvements in the LLD are due to the reduction of background noise made possible by the new POSL technique (through the temporal separation of optical stimulation and luminescence measurement).

microSTARii™ Comparison to the Original microStar™			
	microStar™	microSTARii™	
Intrinsic Measurement			
LED	0.028	0.017	PMT
CAL	0.022	0.008	Photodiode
Repeatability (@ 50 cGy Cs137)			
Stationary	NA	0.53%	
Moving	0.67%	0.59%	
Lower Limit of Detection (mGy)			
Low Dose	0.040	0.017	
High Dose	NA	0.054	

Table 1: Comparison of the new microSTARii™ to the Original microStar™

The performance comparison results, as shown in Table 1, demonstrate a significant improvement in the performance of the microSTARii™ over the original microStar™. Stationary repeat measurements are a new feature of the microSTARii™ that were not possible with the original microStar™.

During the development of the microSTARii™, it was found that individual readers could be optimized to minimize the coefficient of variation of successive readings of the same nanoDot™. The optimization improves measurement repeatability by compensating for variances in the optical performance of the LED and filters of the Photo-Optical Engine. This is a departure from the original microStar™ that used a predefined read time of 1 second regardless of the optical performance. The fixed settings of the original microStar™ lead to a large range in operating performance between readers in terms of Calibration Factors, Depletion, Standard Measurements and Read Variability.

Tests performed during development demonstrated that the best repeatability for each reader could be obtained by balancing counting statistics with higher signal and increased depletion. Figure 6 illustrates the relationship between depletion and the coefficient of variation of multiple reads for the microSTARii™. Each microSTARii™ has been optimized for the best reader repeatability without depletion correction.

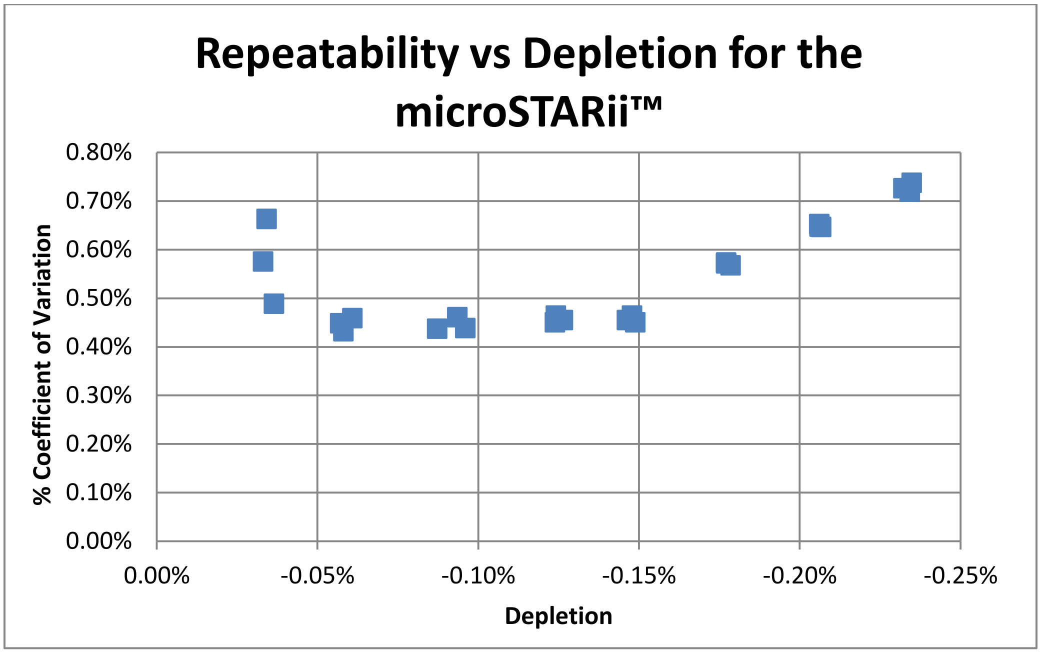

Figure 6: Finding the optimal depletion for the minimum repeatability

The excellent repeatability of the microSTARii™ was achieved through mechanical design, material selection and precision machining. The drawer was designed with a hard stop for the nanoDot™ element extension and the pin that opens the nanoDot™ maintains constant pressure on the element to insure repeatable placement each time the nanoDot™ is inserted into the reader. In addition, support bars above and below the nanoDot™ element hold the nanoDot™ such that the element is perpendicular to the optical axis. All of the critical mechanical parts use aerospace-grade anodized aluminum or self-lubricating plastics for a long life of precision movement.

Discussion

Advantages of the microSTARii™ over the original microStar™

The first generation microStar™ was originally designed to read LANDAUER® InLight™ whole body dosimeters for occupational dosimetry and emergency response applications. Medical dosimetry using OSL dosimeters was made possible by the development of the LANDAUER® nanoDot™ OSL dosimeter, and an adaptor that allowed nanoDots™ to be inserted into the microStar™ reader. However, the adaptor was prone to wear and had to be replaced after repeated use.

The microSTARii™, in contrast, was designed specifically for medical dosimetry applications using nanoDot™ OSL dosimeters. The microSTARii™ electro-optical and mechanical systems were optimized for repeat measurements of the nanoDot™. For example, the microSTARii™ uses fewer moving parts than the original microStar™ and it uses aerospace-grade, hard anodized coatings to ensure smooth actuation with minimal wear.

The original microStar™ also used continuous wave optically stimulated luminescence, which resulted in an elevated background from the leakage of stimulation light through the PMT filtration. This leakage increased the lower limit of detection and acted as a bias between consistent measurements across several systems. The microSTARii™ leverages patented, state-of-the-art POSL technology with reflection geometry that was developed for the US Army in order to eliminate background noise from the LED and achieve superior signal-to-noise characteristics. As a result, the microSTARii™ provides a new level of accuracy, precision, reliability, ease-of-use and cost-effectiveness that was not possible with the original microStar™.

Lastly, the original microStar™ software was developed for occupational dosimetry and emergency response applications, and later modified to provide the basic functionality required for medical dosimetry. The microSTARii™ software was designed and developed specifically for medical dosimetry. The new software introduces many new features that significantly improve the workflow of clinical measurements, while providing automated quality assurance features that facilitate best practices in clinical medical physics. These will be described in Part 2 of this White Paper series.

Advantages of the microSTARii™ over other medical dosimetry options

Although a number of dosimetry systems have been developed for in vivo radiotherapy dosimetry, including thermoluminescent dosimeters (TLDs), solid-state diodes, and metal-oxide-semiconductor field effect transistors (MOSFETs) [Mijnheer (2013)], few of these systems offer the unique capabilities, performance and value provided by the nanoDot OSL dosimeter and the new microSTARii™ reader. TLD's, for example, are more energy dependent than OSL dosimeters, and TLD's must be heated under controlled conditions for accurate dose measurement, which requires large, expensive and difficult to operate readers. In addition, the TLD read-out process is destructive so a TLD dosimeter can only be read one time.

Most diode-based and MOSFET dosimeters developed for point-dose measurements have greater energy dependence, greater angular dependence, and are more temperature sensitive than OSL dosimeters. For example, commercially available diode-based systems were found to have ±12% change in sensitivity depending upon the angle of incidence of radiation [Jursinic (2009)]. Diode and MOSFET leads are also prone to break, which decreases the reliability of the device and increases the cost of operation. In addition, in all current commercially-available diode-based and MOSFET dosimeter systems, the detector leads are attached to wires that must be routed to the read-out electronics.

The performance and clinical application of OSL dosimeters for in vivo radiotherapy dosimetry have been extensively reported in the peer-reviewed literature [Jursinic (2007); Yukihara (2010); Mrčela (2011)]. These studies have shown that LANDAUER®'s nanoDot™ OSL dosimeters, in contrast to TLDs, MOSFETs and diodes, have little energy dependence in the range of energies used in radiotherapy, have relatively little angular or temperature dependence, can be re-read multiple times, are durable and reliable, and are small and convenient to use.

Conclusion

The new microSTARii™ offers users a faster, more accurate and more precise medical dosimetry system in a new, compact, contemporary design. The new technology in the microSTARii™ reader increases the accuracy and repeatability of measurements, improves the lower limit of detection, and decreases reader to reader variability. The new microSTARii™ uses fewer moving parts to improve durability and reliability, and uses a modular drawer design that decreases service costs. It also includes new features to quickly and easily measure intrinsic reader performance, to improve and streamline measurements, and to implement an improved quality assurance program. Initial results indicate that the new reader is exceptionally stable, that measurements are accurate and highly repeatable, and that a lower limit of detection of less than 0.020 mGy can be achieved. The LANDAUER® nanoDot™ OSL dosimeter and microSTARii™ reader offer a level of performance, reliability, convenience and cost-effectiveness that is unmatched by existing medical dosimetry systems.

This paper described some of the technological innovations in the microSTARii™ that were developed to achieve superior performance and improved workflow for medical dosimetry. Future LANDAUER Technology White Papers will describe the radiation dosimetry performance of the microSTARii, the new clinical quality assurance program and software developed to facilitate physics QA, and experience gained in using the microSTARii in specific clinical applications.

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