A novel beta source design for uniform irradiation in dosimetric applications

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Abstract
A novel beta radiation source, specifically developed for the lexsyg luminescence system, was studied by radiochromic film. A circular arrangement of miniaturized sources creates a homogeneous radiation field, with a variation of 2% of radiation dose across the central 8 mm diameter of the target irradiated. While this arrangement is very efficient to achieve homogeneous irradiation, it also allows the simultaneous luminescence detection of radio-fluorescence through the hole in the source body. The geometry of the irradiation set-up, in particular the material, the size and the shape of the substrate carrier affect the actual dose distribution and dose rate at the target site to a larger extent than any inhomogeneity of this source itself.

Introduction
In dosimetric applications the uniformity of laboratory irradiation is crucial. While this can be easily achieved by photon irradiation with rather homogeneous irradiation fields (e.g. by ^{137}Cs or ^{60}Co γ-sources), such are often not available, or simply not feasible, for example in the application of the single aliquot regeneration (SAR) protocol to reconstruct the response of material to radiation. Radiation fields of sources used in luminescence dating applications are mostly reported with concentrically decreasing dose-rates away from the centre of the target (e.g. Spooner and Allsop, 2000). For typical diameters of 6 - 10 mm the radiation field of ^{90}Sr/^{90}Y beta sources has been reported to vary spatially at least between 3% for a distance of 9.75 mm from a 4 cm^2 active area (Sanderson & Chambers, 1985), 10% for a 1 cm^2 active area (e.g. Bailiff, 1980; Veronese et al., 2007) and 30-40% (Spooner & Allsop, 2000). For larger areas of interest (8 - 10 mm diameter) the field inhomogeneity was found to vary sometimes by a factor of two and additionally sometimes shows a skewed concentric pattern in the radiation field (e.g. Ballarini et al., 2006), if the widely used ^{90}Sr/^{90}Y beta sources (SIF and SIP type) are considered.

Larger distances between the source and sample provide more homogeneous irradiation fields, as do sources with active surfaces which are larger than the target surface (Aitken, 1985). Furthermore a large distance also reduces the effects of the dependence on distance of approximately 10% mm^{-1} (Aitken, 1985).

Inhomogeneities of irradiation can be reduced by moving the sample in a small circle during irradiation (e.g. the "jitter" facility of the Littlemore 9022A irradiator), or by moving the grains constantly during irradiation on a vibrating plate (Valladas and Valladas, 1982).

As a consequence of inhomogeneities of the artificial radiation field in luminescence dating the individual grains on multiple grain sample carriers will receive different individual doses, requiring the calibration of each individual grain position in single grain applications (e.g. Veronese et al., 2007), which is a tedious and error-prone procedure. Any effects of calibration sample dependencies, sample translucency, etc. will be enhanced by an inhomogeneous radiation field, which could be responsible for several second order effects and artefacts of the interaction between the sensitivity distribution within samples and the artificial radiation field. We here consider an irradiation as homogeneous if the absorbed dose variation is 3% or better for the area of interest, which is lower than the associated uncertainty for β-source calibration (Aitken 1985).

The homogeneity of an irradiation with a β-emitter is a function of source uniformity, source diameter, distance of active surface to area/volume to be irradiated, shape, and size of the latter, as well as any material close enough to be included in any bremsstrahlung and backscatter effects (e.g. source housing, target substrate, etc.). These variables also determine the relationship between source strength and dose rate at the sample. From a luminescence dating application point of view, the former should have a low surface activity to minimise radiation safety concerns, while the latter should be large in order to maximise efficient use of luminescence readers and increase laboratory throughput, especially with respect to the SAR protocol. The desire to increase dose rates from sources of modest activity has led to closer coupling between source and sample, resulting in an inhomogeneous irradiation field, and potentially exacerbating the effects of heterogeneity of the activity distribution across radiation source with small active areas.

The main component of the resulting radiation field of a beta source encased in a housing is direct beta radiation from the source. Depending on the design of the source, the source holder etc., the radiation field will be significantly affected by scattered beta radiation and bremsstrahlung as well. The latter is produced by beta interaction within the material of the source, its housing, and shielding (Liritzis and Galloway, 1990). Furthermore, the material to be irradiated and its substrate as well as any material within the range of beta or bremsstrahlung also influence the radiation field (e.g. Ingram et al., 2002) and are therefore important parameters to be consider if homogeneous irradiation is required.

In developing the lexsyg luminescence measurement system one of the design requirements was to allow easy and direct radiofluorescence (RF) measurement. This is normally achieved with a source placed underneath the sample (e.g. Erfurt et al., 2003), which limits other uses of the source; or with a source above the sample and luminescence measured via a light guide (e.g. Bøtter-Jensen et al., 2003; Lapp et al., 2012), with a potentially significant loss in efficiency. An alternative approach is to use a ring source design with an opening for direct light collection to a detector, which has the added advantage of providing a more uniform radiation field than could be achieved using a conventional disc source. As indicated above, homogeneous irradiation is highly desirable in dosimetric and dating applications, where secondary effects of non-uniformity may be hard to quantify. It is also important in developments in single grain or surface area luminescence detection. The purpose of the current paper is to present data on the radiation characteristics of a novel beta radiation source developed for the lexsys reader, and to discuss parameters affecting the radiation field quality while applied to luminescence measurements. The radiation field produced by the new source has been measured using radiochromic films and dependency on the geometry of surrounding materials in the reader, and the sample substrates of the irradiated material have been investigated for a fixed source to sample distance.

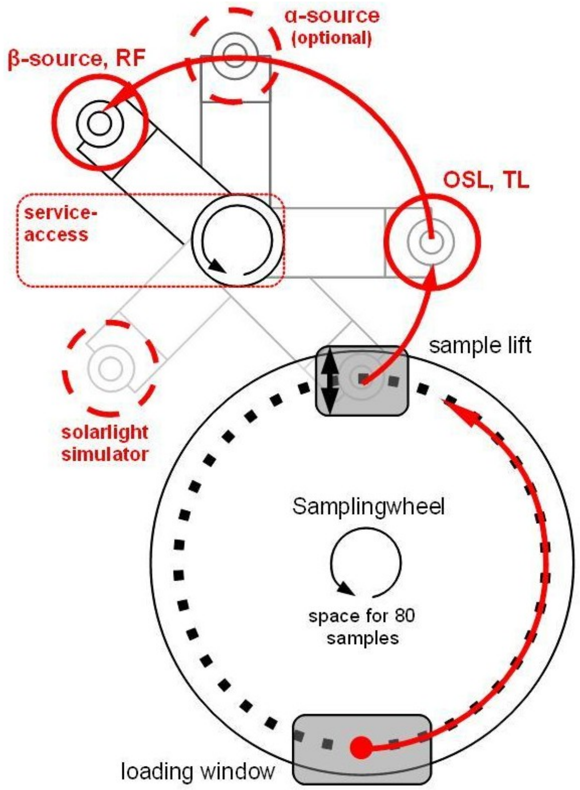

Figure 1: *Schematic setup of a lexsyg system, where the sample wheel is separated from the measurement/stimulation or irradiation.*

The lexsyg luminescence system

In the modular lexsyg luminescence system the samples are placed in a circular sample holder accommodating 80 positions. During the measurement sequence the sample to be analysed is moved from the sample wheel to separate irradiation positions and measurement stations as required using a pick-and-place system, illustrated as an arrow in Fig. 1. There are no other samples in the vicinity of the sources used for irradiation, and the irradiation takes place away from illumination sources used in luminescence measurements. Therefore, light exposure of other sample aliquots is absent and radiation cross talk is negligible due to the large separation between the radiation source(s) and the sampling wheel. However, because the sample disc/cup stays on the heating plate all the time during standard (i.e. SAR) measurement cycles and is neither lifted nor itself moved, neither the grains nor the sample carrier move their (relative) positions on the disc/cup or the heating plate. This has been verified for 10 times of movements between source and measurement positions. In fact, it does not appear to be necessary for the grains to be fixed by silicone oil.

A new β-source

In order to achieve direct radiation while measuring RF and to obtain a homogenous radiation field which also would allow spatial luminescence analysis without error prone differential area calibration, a new β-source has been developed for the lexsyg system.

Design of the ^{90}Sr/^{90}Y-source

The beta source is intended for the direct irradiation of samples for RF as well as for TL/OSL applications and therefore the design in the form of a ring is most feasible, with a hole in the centre of the source body (activity carrier). This allows efficient, simultaneous light detection during RF. The design of the beta radiation source features a circular arrangement of miniaturized, sealed beta sources (Fig. 2). In order to create a homogeneous radiation field at the target site (sample, aliquot), each individual source is pre-selected according to its activity (<5% variation), before being mounted into a circular groove (14 mm diameter) of a stainless-steel source body. Thus, a circular activity distribution is formed. A stainless steel foil is micro-laser welded to the source body to fix the miniaturized sources in the grove. The field characteristics at irradiation distance are mainly governed by the diameter of the ring of activity, the material of the source body, the shape of the grove and the thickness of the cover foil.

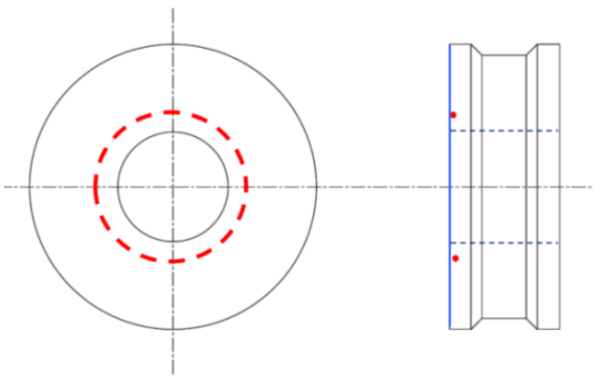

Figure 2: *Schematic drawing of the source: dotted line– circular arrangement of miniaturized sources forming an active "wire", bold line – radiation window (stainless steel foil)*

Characterization of the radiation field of the ^{90}Sr/^{90}Y-source

The radiation field at the target site was investigated using radiochromic, self-developing films (GafChromic film type HD-810 from ISP, Inc.). This type of radiation detector provides high-resolution, two-dimensional information on the dose distribution. The purpose here is a qualitative determination of the spatial variation of absorbed dose. These are investigated for dependencies on source as well as sample carrier geometry.

The optical density of the irradiated films was determined by an LED scanner NIKON CoolScan IV ED at 300 dpi resolution. Calibration in terms of soft tissue equivalent dose was achieved through a NIST calibrated reference β-source (Sr-90, type QQ251). Note that the current investigation primarily deals with radiation field uniformity rather than dose rate, thus the tissue equivalent dose rate has been used to gather this information. The field distributions and profiles are shown as normalized absorbed doses.

Experimental setup

Due to the limited size of the lexsyg sample carrier (heating plate) it was considered to be too difficult to reproduce the entire area occupied by samples with radiochromic films placed within the lexsyg luminescence reader. Thus, the geometry of the reader was mimicked as closely as possible in a special experimental set up. Challenges here are the necessity to hold the films planar and stabilize a film of a size large enough in order to guarantee enough space between the unusable area at the film edge (1-2 mm rim) and the area of interest (sample area size of ~8 mm diameter). Furthermore, the geometry and material of sample targets/holders have an influence on the dose distribution. Additionally, sample geometries obviously can have effects as well, but are not the purpose of this study and are therefore not considered here.

Experiments were repeated at least three times with exposure periods between 50 and 70 minutes, always providing the same results and representative figures (Fig. 3-5) are shown for all experiments.

Three different experimental settings were employed, while keeping the source to heating plate distance of 7.7 mm constant. First, the uniformity of irradiation was measured in a 'free in air' experiment where all materials needed to hold in place the radioactive source were minimized and the film placed on a wide acrylic glass substrate to avoid the influence of edge effects from the backscatter caused by the substrate and the source holder. This allows the evaluation of the dose distribution created by the source exclusively, with the least influencing geometry factors (Fig. 3A) and provides insight in the variation exclusively caused by the geometry of the

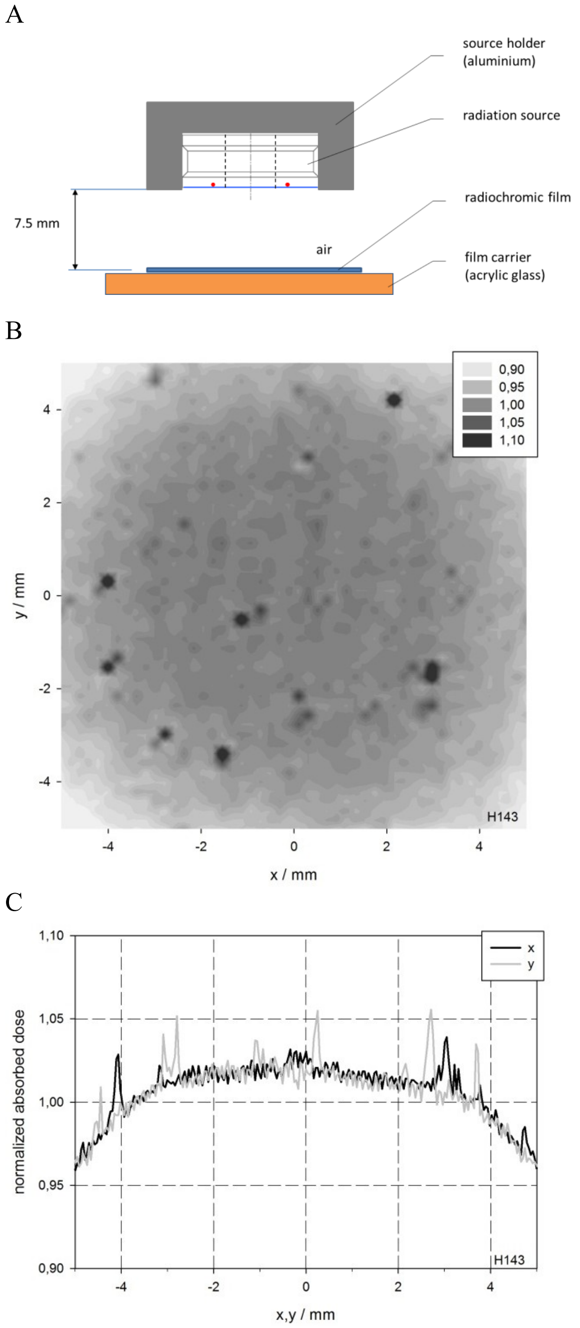

Figure 3: *'Free in air' experiment with minimized influence of other materials. (A) geometry with film on a large area substrate and radioactive source mounted with minimized material, where the source holder isn't shown for the sake of simplicity (not to scale); (B) contour plot of normalized spatial dose distribution for the irradiated area within the limits of the usable area of the film; (C) normalized absorbed doses for two profiles (x and y) perpendicular to each other. The actual range of interest is between -4 and +4 mm, which corresponds to the available area of 8 mm inner diameter of cups, intended for use in the lexsyg systems.*

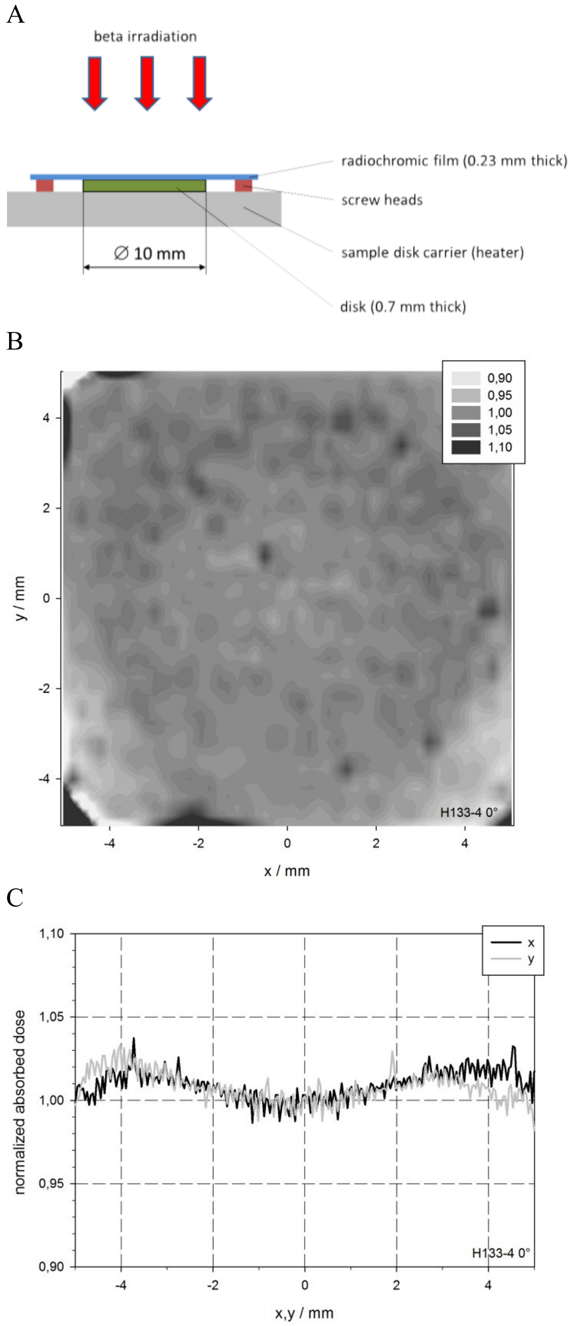

Figure 4: *Experimental setup to mimic the irradiation of a sample on a flat disc in a lexsyg reader. The geometry of the source mounting and film placement was identical to the actual situation in a reader by using e.g. an original heater plate on arm. (A) Geometry; (B) contour plot of normalised absorbed dose; (C) normalized absorbed doses for two profiles (for more details see Fig. 3 caption).*

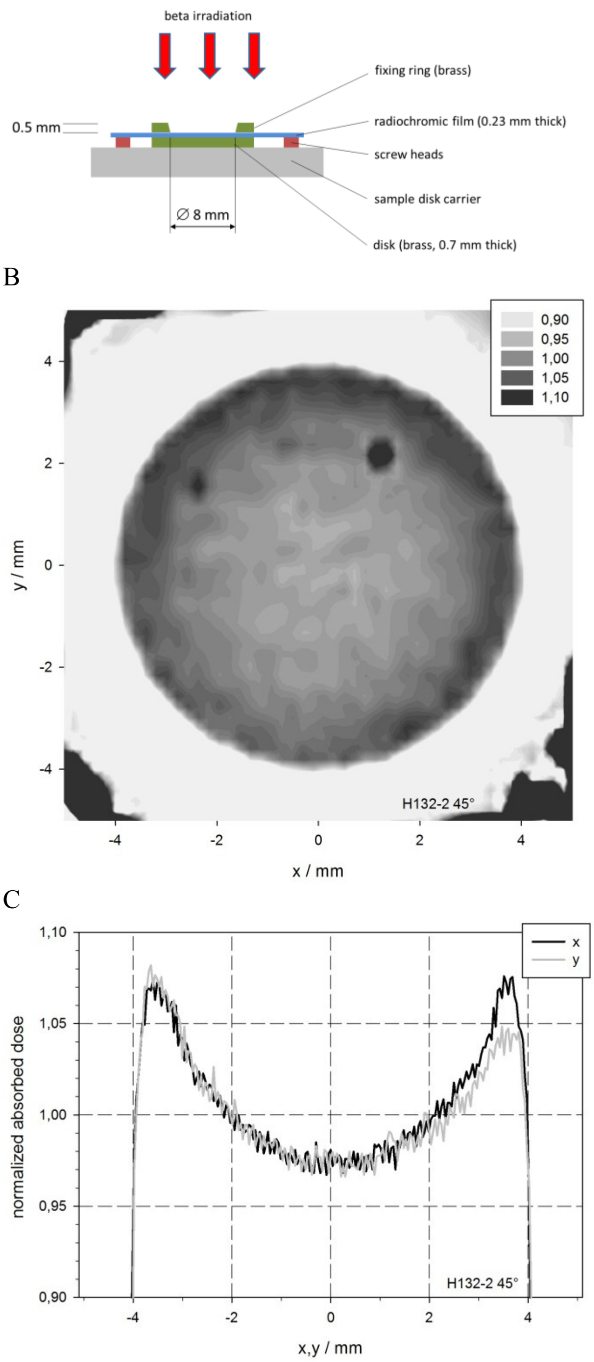

Figure 5: *Experimental setup to mimic the irradiation of a cup in a lexsyg reader. The geometry of the source mounting and film placement was identical to the actual situation in a reader by using e.g. an original heating plate mounted on an original arm, but a ring was placed on top of the film with a disc underneath to mimic the rim of a cup. (A) geometry; (B) contour plot of normalised absorbed dose; (C) normalized absorbed doses for two profiles (for more details see Fig. 3 caption).*

source in its housing. However, the actual irradiation in a measurement system takes place in a more complex geometry, and includes backscatter effects which affect the radiation field.

The laboratory setup to mimic the geometry in the lexsyg system allows reproducible experiments under optimized conditions, with the film placed on a heating plate mounted on an arm as used within a system. The film here takes the place of a sample on a carrier substrate, while the radioactive source in its housing is mounted the same way as in the lexsyg system, but easy access is possible. In one of such experiments the film is placed on a disc which is only slightly thicker than what is commonly used as sample carrier (Fig. 4A), but thick enough to ensure backscatter saturation.

In the other experiment a ring of the outer diameter of such a disc and 0.5 mm thickness is additionally placed on top of the film to mimic a 'cup' as sample carrier (Fig. 5A) and investigate the influence of the form of the sample carrier on the radiation field. It is not possible to perform reliable measurements with a film within an actual sample 'cup' because the areas close to the edges of a film is unusable for analysis. The rim of a cup limits the size of the film which can be placed and thus only an area smaller than the actual area of interest of the radiation field would be available.

Furthermore, measurements were performed for four different substrate materials (brass, aluminium, nickel and two different stainless steel) placed as 10 mm diameter discs of 1.0 mm thickness each underneath the film (film is thus at sample position).

Results of film measurements

The results are presented as contour plots (B of Figs. 3-5) of the relative absorbed dose for the irradiated area within the limits of the usable area of the film. The actual variation can be better visualized as normalized absorbed doses for two profiles (x and y) perpendicular to each other (C of Figs. 3-5). Note the limited scale of only 0.9 - 1.1 of the normalized dose for all graphs. Even though the practical range of interest is between -4 and +4 mm from the centre, which is corresponding to the available area of 8 mm diameter within the cup/discs used in the lexsyg systems, a wider x-y range is displayed for informative purposes. Local inhomogeneities of the film material caused by handling of those unusually small film pieces are responsible for the peaks/spikes observable especially in the dose profiles. Such apparent 'hot spots' are artefacts of the radiochromic film and do not correspond to the groove which holds the sources. Furthermore, slight asymmetries, which are likely caused by film positioning (film not lying perfectly flat on the substrate material), are noticeable.

All distributions show either a maximum or a minimum of the absorbed dose at the centre of the irradiation field. When the film is placed on a material of a size much larger than the irradiated area, a maximum value in the centre is observed (Fig. 3C). This contrasts with a minimum in absorbed dose if the edge of the substrate is close to the area of irradiation (Fig. 4C).

In a “basic” geometry, i.e., the source simply positioned over a film while minimizing the amount of surrounding material to minimize (backscatter) effects, the variation in absorbed dose is about 2% over the area of interest of 8 mm diameter and about 6% for 10 mm diameter (Fig. 3C). An even wider homogeneous irradiation field appears to be obtainable when a tube of a diameter slightly larger than the active area is located underneath the source (not shown), which appears to slightly increase Bremsstrahlung and thus promotes homogeneity of the radiation field. While placing such a tube is certainly not feasible in automated irradiation, it might provide an opportunity for further developments in irradiation fields.

For a geometry identical to the one in a lexsyg luminescence reader and a flat disc of 10 mm diameter as substrate, the variation is about 3% over the entire area with a small edge effect noticeable (Fig. 4C). For the identical set up and the geometry of a 'cup' with a ring placed on top the film, the edge effect becomes rather pronounced, leading to a variability of 10% of the area of 8 mm diameter where sample material can be placed (Fig. 5C). Variation is less than 2% when only the central 4 mm diameter area is employed in this geometry.

The newly designed β-source delivers approximately 0.0375 Gy s^{-1} GBq^{-1} at a distance of 7.45 mm from the source to the top of the 0.5 mm thick target disc in the lexyg system.

The absorbed doses were similar for discs made from brass, nickel and two different varieties of stainless steel, but approximately 15% lower for aluminium. Only for the latter material the dose profile exhibits a different pattern with a pronounced continuous increase in dose starting at ~0.8 mm distance from the rim, whereas the other materials show similar patterns as in Fig. 3A, where a maximum is reached towards the edge with a subsequent decrease in dose.

Discussion and conclusions

The uniformity of β-irradiation at sample position is shown to vary between 2 and 8% for areas of 8 and 10 mm diameter centred around flat sample discs, respectively. The variation obtained is significantly lower than some recently reported values (e.g. factor 1.4 in Ballarini et al., 2006), and is considered satisfactory for luminescence dating applications.

For the present source design the reported uniformity could only be achieved by pre-selection of individual miniaturized sources and ensuring a variation in activities of less than 5%. Because of the special source design, in RF application the luminescence signal can be efficiently collected through adapted lens optics without any need for a light guide. The gain in signal intensity is contrasted by an increased dark count due to the proximity of the β-source to the light detector (i.e. PMT or EMCCD).

The 'free in air' experiment, where little influencing material is close to the source, shows the significance of the actual geometry of the irradiation, which includes not only the housing and surrounding materials, but the shape of the substrate as well.

While the radiation field from the source itself was shown to be very homogeneous, inhomogeneities are mainly caused by backscatter effects. Obviously, the material of the sample carrier matters, but the size and shape of sample carrier as well as of the heating plate are influential parameters in the dose distribution. The presence/absence of a rim of the sample carrier has been shown to have a large influence on the homogeneity of the radiation field. Employing a sample carrier with a 0.5 mm rim has a pronounced effect on the homogeneity of the irradiation, leaving only the central 4-6 mm diameter area (of the original 8 mm) available, if homogeneous irradiation is required. Not investigated here are effects arising from the material which is irradiated, as well as from its shape and size.

In any case, it is advisable for irradiation with any non-photon source not to employ the entire surface of a disc/cup in order to avoid inhomogeneities which appear to increase usually towards the edge of the irradiation area (e.g. Spooner and Allsop, 2000). Given the observed influence of the rim when cups are used (Fig. 5), it appears to be prudent to minimize the rim of the cup in order to minimize its effect on the variation of absorbed dose.

The influence of inhomogeneous artificial irradiation on luminescence dating results would merit further investigation and especially with the further developments in small scale luminescence measurements, like single grain and spatially resolved luminescence, such influences are becoming more important. Some of the overdispersion observed in luminescence dating might be attributable to such non-uniformity of β-irradiation. Because of the sufficiently small variation in dose delivered by the current ring source, the lexsyg system does not need to be calibrated for single positions (e.g. single grain measurements) and allows a single grain approach, areas of interest of single grains from multiple grain aliquots or for solid samples by e.g. EMCCD luminescence analysis. Due to the uniformity of the radiation field any random displacements of the sample carrier or sample grains during sample handling in the measuring system are less crucial with respect to absorbed dose, provided the grains are spherical.

Experiments have shown that the commonly observed bell shape of the dose distribution over irradiated area (e.g. Spooner and Allsop, 2000) is mainly due to geometric effects of the irradiation, where the centre is being irradiated by the entire active areas and a uniform irradiation appears to be obtainable when the activity is less in the centre of the source, as is the case with the ring source in the LEXSYG system. The main advantage of the present source design is the homogeneous radiation field as well as the ability for efficient fluorescence light collection through lens optics for RF application.

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Reviewer
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Reviewers Comment
Uniformity of radiation fields used in calibrating luminescence systems remains of critical importance to analysis and reduction of overall dating errors. Here the idea of using an annular source design instead of a disc based source is discussed. The dose mapping results here are highly encouraging and confirm that this approach partly compensates for the centre-weighted dose distributions achieved with disc sources. The new geometry also offers added potential for observing RL through a central aperture in the source. It will be interesting to see how such systems perform in comparison with existing geometries over a range of dating samples.