A dedicated high-resolution PET imager for plant sciences

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Abstract
PET provides an \textit{in vivo} molecular and functional imaging capability that could be valuable for studying the interaction of plants in changing environments at the whole-plant level. We have developed a dedicated plant PET imager housed in a plant growth chamber (PGC), which provides a fully controlled environment. The system currently contains two types of scintillation detector modules from commercial small animal PET scanners: 84 microPET\textsuperscript{®} detectors, which are made with scintillation crystal arrays of 2.2 mm\textsuperscript{3} × 2.2 mm\textsuperscript{3} × 10 mm\textsuperscript{3} crystals to provide a large detection area; and 32 Inveon\textsuperscript{™} detectors, which are made with scintillation crystal arrays of 1.5 mm\textsuperscript{3} × 1.5 mm\textsuperscript{3} × 10 mm\textsuperscript{3} crystals to provide higher spatial resolution. The detector modules are configured to form two half-rings, which provide a 15 cm-diameter trans-axial field of view (FOV) for dynamic tomographic imaging of small plants. Alternatively, the Inveon detectors can be reconfigured to form quarter-rings, which provide a 25 cm FOV using step-and-shoot motion. The imager contains two linear stages that move detectors vertically at different heights for multisection scanning, and two rotation stages to collect coincidence events from all angles when using the step-and-shoot acquisition. The detector modules and mechanical components of the imager are housed inside a PGC that regulates the environmental parameters. The system has a typical energy resolution of 15\% for the Inveon detectors and 24\% for the microPET detectors, timing resolution of 1.8 ns, and sensitivity of 1.3\%, 1.4\% and 3.0\% measured at the center of the FOV, 5 cm off to the larger half-ring and 5 cm off to the smaller half-ring, respectively (with a 350–650 keV energy window and 3.1 ns timing window). The system’s spatial resolution is capable of resolving rod sources of 1.25 mm diameter spaced...
2.5 mm apart (center to center) using the ML-EM reconstruction algorithm. Preliminary imaging experiments using soybean and wild type and mutant maize labeled with $^{14}$CO$_2$ produced high-quality dynamic PET images that reveal the translocation and distribution patterns of photoassimilates. This system can be used to provide an *in vivo* molecular and functional imaging capability for plant research.

Keywords: 87.57.uk positron emission tomography (PET), 87.80.-y biophysical techniques (research methods), 87.57.U- nuclear medicine imaging, 87.57.C- image quality, 29.40.Mc scintillation detectors

(Some figures may appear in colour only in the online journal)

1. Introduction

Rapid population growth and global climate change have led to an unprecedented challenge to the sustainable supply of food and energy. One of the key components in the overall solution is innovation in plant sciences, which may produce new crops that are more resistant to biotic stresses (insects, viruses and microorganisms) and abiotic stresses (drought, temperature extremes, nutrient limitation, etc). Although advances in molecular biology have made genetic modification of crops easily available, the actual yield of crops is determined not only by the genotype of the plant but also by the growth environment. As a result, phenomics has become a critical element in plant research and innovation (Yang *et al* 2013). While most high-throughput phenotyping systems are based on visible light-based imaging techniques, x-ray computed tomography (CT) and magnetic resonance imaging (MRI) have also been adapted to image the inner structures of a plant or its roots under soil (Mooney *et al* 2011, Borisjuk *et al* 2012). In addition to the aforementioned structural imaging tools, imaging methods that reveal physiological information non-destructively are of great value to enrich the tool sets for future plant phenomics (Fiorani *et al* 2012, Dhondt *et al* 2013).

Positron emission tomography (PET) is a molecular and functional imaging technique that can provide *in vivo* measurement of a dynamic radiotracer distribution in an object non-invasively. Combined with tracer kinetics modeling technologies, PET allows one to probe biochemical processes and physiological responses quantitatively, with a spatial resolution of the order of millimeters. Clinically, PET is commonly used for diagnosis of cancer, neurodegenerative diseases and cardiac diseases (Phelps 2000). High-resolution (HiRes) PET scanners are also widely applied in preclinical research for establishing human disease models or measuring pharmacokinetics of new drugs using small animals (Cherry and Gambhir 2001).

Using short-lived radioisotopes such as C-11 and N-13, PET offers an opportunity to observe the underlying mechanisms of carbon and nitrogen utilization in whole plants in real time. This unique probing and phenotyping capability has attracted plant scientists to revisit the application of PET in plant research. Early studies of photosynthate transport in plants using C-11 labeled CO$_2$ started in the 1960s (Moorby *et al* 1963). Sugar transport from source to sink in a plant could be modeled in real time to establish multi-compartment source–sink models (Minchin and Thorpe 2003). With the recent surge of interest in studying plants using PET, some research groups opted to use clinical PET/CT scanners to image plants (Garbout *et al* 2011) despite their limited spatial resolution. Most PET scanners built specifically for plant imaging research are based on HiRes PET detectors commonly used in small animal PET or organ-specific human PET systems. For example, planar detector modules with a large detection area are used to acquire projection images of plants in the PETIS system in Japan.
(Uchida et al 2004), as well as in the PhytoPET system in the Jefferson Lab (Kiser et al 2008, Weissenberger et al 2013). A partial ring plant PET scanner based on eight ClearPET™ detector modules mounted on a rotation stage was developed by a research group in Germany to provide tomographic PET images within a 10.1 cm field of view (FOV) (Ziemons et al 2005, Beer et al 2010). A full-ring plant PET scanner under development at Brookhaven National Laboratory is based on the RatCAP PET detector technology (Woody et al 2004) with a scanner bore diameter of 10 cm and 18 mm in height (Budassi and Stoll 2012). These efforts demonstrate the increasing interest in PET for plant research in recent years (Nakanishi et al 1999, Kiyomiya et al 2001, Jahnke et al 2009, De Schepper et al 2013, Agtuca et al 2014).

Unlike human or small animal imaging where the object size is somewhat fixed, the size of plants to be investigated may vary greatly in shape during the course of their development, which means the scanner may need to provide either a large FOV or high spatial resolution, depending on the application. In terms of temporal scale, the imaging time may range from several minutes when using short half-life isotopes (11C, 13N and 15O) to many days when using long half-life isotopes (64Cu and 22Na). As a result, the ideal plant PET scanner should have high sensitivity to support studies with a wide radioactivity range. Since most plants grow vertically, a PET scanner dedicated to plant imaging should have a vertical bore to provide the most natural imaging position. As plants are very sensitive to environmental changes, a well-controlled environment for growing, administering the tracer and imaging the plants under investigation is likely to be beneficial. To address the above issues for functional plant imaging, we have developed a dedicated plant PET imager with unconventional geometry and features, as described below.

2. Materials and methods

2.1. System design overview

The functional plant PET system has been developed with two major features in mind: (1) high spatial resolution and sensitivity, with configurable system geometry to accommodate plants of different sizes and shapes and (2) the ability to control the environment in which the
plants will be studied. To achieve these goals, the system is composed of high-performance modular detectors that are commonly used in small animal PET scanners. The geometry of these modular detectors can be reconfigured to acquire projection or tomographic images of plants with different sizes. These modular detectors are mounted on translation and rotation stages, which are controlled by a computer remotely to image different sections of plants. The above components are installed in a plant growth chamber (PGC), which provides full environmental control. A radiotracer delivery system was also developed to enable simultaneous labeling and imaging capability for plant imaging studies. Figure 1 shows the whole-plant PET system and the details of the main components.

2.2. Detector modules and readout electronics

We use two types of detector modules (shown in figures 2(a) and (b)) in the imager with different geometries to accommodate different imaging needs. The first group consists of microPET detector modules, each containing four position-sensitive photomultiplier tubes (PS-PMTs) to read out four lutetium oxyorthosilicate (LSO) arrays. Each LSO array contains 8 × 8 crystals each measuring 2.2 mm³ × 2.2 mm³ × 10 mm³ with a 2.4 mm pitch (Knoess et al 2003). For imaging large plants, 21 microPET modules are used to build a detector panel with large
solid angle coverage. The second group consists of eight Siemens Inveon detector modules, each containing four PS-PMTs to read out four LSO crystal arrays. Each LSO array contains 20 × 20 crystals each measuring 1.51 mm³ × 1.51 mm³ × 10 mm³ with 1.59 mm pitches. In general, the cross section of the scintillation crystals determines the image resolution of a PET system, while the length of the crystals (10 mm in this case) affects the detector efficiency.

Siemens QuickSilver™ (Newport and Siegel 2006) electronics is used to digitize detector signals and to process coincidence events. Figure 3 illustrates the data flow of the QuickSilver readout electronics system. Two segments of flat flexible cables (with a total length of 3.5 m) are used to connect the detector output to the QuickSilver electronics through a custom designed junction board mounted on the PGC. Figures 2(c) and (d) shows the flood histogram of a typical Inveon detector and a multiplexed microPET module read out by the system electronics. No observable signal degradation is seen with these long cables.

2.3. Reconfigurable geometry and positioning system

Using the above modular detectors, the system can be configured to form different geometries in order to accommodate plants of different sizes and shapes. Figure 4 shows three
potential configurations with the corresponding imaging FOV listed in table 1. In all three configurations, 21 microPET–microPET detector modules (84 blocks) are arranged to form a half-ring of 140.7 mm radius. In the half-ring + half-ring configuration, the eight Inveon modules (32 blocks) are arranged to form a half-ring of 86.1 mm radius to provide high-resolution and dynamic imaging capability within an imaging FOV of 15 cm diameter by 10 cm axially (figure 4(a)). In the HiRes quarter-ring + half-ring configuration, the Inveon modules are arranged to form a quarter-ring (figure 4(b)) of 166.6 mm radius. By rotating both the Inveon detectors and the object, complete sampling of the object can be acquired using rotate-then-acquire data motions as demonstrated previously (Tai et al 2008). If the distribution of radioactivity in a plant does not change significantly within the time frame required for the rotate-and-acquire acquisition, 3D tomographic images can be acquired for objects up to 25 cm in diameter. In the half-ring + planar configuration (figure 4(c)), the Inveon modules are arranged in a plane to acquire projection images of even larger objects up to 40 cm in cross section.

The two groups of detector modules are supported by two aluminum platforms, which can be moved vertically by two translation stages. This allows multisection imaging of plants taller than the axial imaging FOV (ranging from 8–12 cm among the three configurations), similar to human whole-body PET imaging through multi-bed positions. Additionally, there are two concentric rotation stages in the system. The bottom rotation stage supports and rotates the linear stage that supports the Inveon detector modules, while the top rotation stage rotates the object independently during the rotate-and-acquire motion in the HiRes quarter-ring + half-ring configuration in order to acquire coincidence data from all angles for tomographic image reconstruction. All components above are mounted on an optical table (60 cm × 90 cm) installed inside the PGC. The motion controllers of all four stages are daisy-chained and connected to the host computer via a RS232 serial cable.

### 2.4. Imaging console software

Custom imaging console software was developed based on the application framework provided by Microsoft Visual Studio to support detector module and system setup, as well as automated data acquisition when using the HiRes quarter-ring + half-ring configuration. The detector module setup includes setting the variable-gain amplifier in the front-end application-specific integrated circuit, and creation of crystal lookup tables, energy lookup tables and time alignment lookup tables. Since the system consists of two types of detector modules, the supplied high voltage is different for the Inveon and microPET modules (700 and 800 V, respectively). For Inveon modules, the three types of lookup table are generated automatically. The setup of the microPET modules requires a little manual effort to ensure correct identification of corner crystals. For data acquisition, a user specifies the radionuclide used, imaging frame duration and number

| Configuration | Imaging FOV | Imaging type | Geometry/Radius (mm) |
|---------------|-------------|--------------|----------------------|
|               | Axial       | Transverse   |                      |
| 1             | 10 cm\(a\) | 15 cm        | 4D                   |
| 2             | 8 cm\(a\)  | 25 cm        | 3D or 4D\(b\)        | half-ring/86.1 half-ring/140.7 |
| 3             | 12 cm\(a\) | (up to) 40 cm| 2D projection        |

\(a\) Larger axial FOV (up to 60 cm) can be achieved with multisection scanning.

\(b\) Depends on the kinetics of radiotracer in plants.

### Table 1. Geometric parameters for different configurations.
of sections needed before starting the scan in the half-ring + half-ring configuration. For the HiRes quarter-ring + half-ring configuration, the same user input parameters are used to pre-calculate the duration at each scanning angle before the console software sends commands to the motion controller and scanner to acquire data automatically in the rotate-then-acquire data motion. The status information of the rotation and the linear stages is sent to the console software by decoders mounted on the stepping motors’ axes to ensure the completion of the requested motions.

2.5. Image reconstruction

The list-mode data is collected with QuickSilver electronics and sorted by custom sorting codes to form a sinogram data set. As multiplexing is used to map four microPET detector modules in one flood histogram, re-mapping codes were developed to convert the crystal index of microPET detectors to their actual physical location based on predefined system geometry. Reconstruction of PET images is based on the maximum likelihood expectation maximization (ML-EM) algorithm (Mathews et al 2013). The system matrix is factorized into a geometric component, a normalization component and an attenuation component. The geometric component is computed by subdividing the detector crystals to form sub-lines of response (LORs) joining the sub-crystals. Using Siddon’s algorithm, the average intersection length of these sub-LORs with each voxel is computed and divided by the square of the total length of a LOR to obtain the weights of the emission system matrix (Keesing et al 2012).

Currently, the system does not offer transmission imaging capacity or provide CT images of the subject to estimate the attenuation component. If there is no attenuation coefficient, the recovered radionuclide concentration is underestimated in the middle of a plant. Transmission imaging provides structural information about the object, enabling correction of attenuation coefficients. For plants that have narrow stems and thin leaves above the soil level, the amount of attenuation is insignificant. For the section of plants under the soil level, a calculated attenuation correction can be implemented for a given soil type and container size. Component-based normalization was implemented to estimate parameters that are not modeled in the system matrix (e.g. a detector’s nonuniform response). We scanned a uniform Ge-68 phantom of known activity concentration for 3 h and estimated the normalization factors of individual components through a maximum likelihood approach (Bai et al 2002, Keesing et al 2012). The estimated components include the weights of microPET–microPET, microPET–Inveon and
Inveon–Inveon data, as well as the detection efficiency of individual crystals. Random and scatter coincidence estimates are additive in the forward model of the reconstruction. The random event rate is estimated through a delayed window approach. Scatter is estimated using a single scatter simulation (Watson et al 1996, Komarov et al 2010). All these efforts are to ensure the quantitative accuracy of PET images that truthfully represent the radioactivity concentration in an object such that tracer kinetic modeling can be applied to establish biological models.

2.6. Growth chamber and tracer administration system

In order to provide a controlled environment during the administration of radiotracers and imaging of the plants, we designed the plant PET imager to be integrated into a PGC. The PGC (Conviron, S10H) has exterior dimensions of 200 cm × 85 cm × 200 cm (W × D × H) and an interior 0.93 m² growth area. The growth environment can be controlled with a temperature range from 4 °C–45 °C, light intensity up to 1000 µmol m⁻² s⁻¹, humidity level from 40%–90%, and CO₂ level from the ambient level to above. The entire system is located in a plant imaging lab above our cyclotron facility for easy access to a wide range of radionuclides and tracers. Gaseous radiotracers are delivered via dedicated tubing directly from the cyclotron facility. After labeling, the waste radioactive gases can be flushed back to the cyclotron facility where they can decay in storage. Custom labeling chambers of different sizes and shapes have been made using polyvinyl chloride (PVC) or acrylic tubes. The radioactive gases can be delivered directly into a labeling chamber inside the PGC or to the fume hood next to the PGC for manual labeling of plants if necessary.

3. Results

3.1. Basic performance measurements

All performance measurements were acquired using the half-ring + half-ring configuration shown in figure 4 as it is the most used configuration. The detector block energy resolution was measured using a Ge-68 line source, and was found to be 15.1 + l − 1.4% and 23.8 + l − 6.2%

![Figure 5. System sensitivity measured with two different energy windows (250–750 keV and 350–650 keV) at three different positions (center, 5 cm off-center to the larger half-ring, and 5 cm off-center to the smaller half-ring) crossing the axial FOV with 3.1 ns coincidence time window.](image-url)
full-width at half-maximum (FWHM) at 511 keV for the Inveon and microPET detectors, respectively. These results agree with published results (Tai et al 2001, Knoess et al 2003, Bao et al 2009). The coincidence timing resolution between the Inveon detectors and microPET detectors was found to be 1.8 ns FWHM. The coincidence timing window of the system was set to 3.1 ns as a compromise between system sensitivity and random rejection capability. For this particular detector geometry, system sensitivity was much different from conventional full ring systems. The sensitivity of the system, shown in figure 5, was measured with a 2.59 MBq (70 µCi) Ge-68 point source at three different trans-axial positions crossing the entire axial FOV with a 1.6 mm step size. The system sensitivity at the axial center of those three selected positions was 1.3%, 1.4% and 3.0%, respectively, with an energy window of 350–650 keV, and 2.0%, 2.0% and 4.3%, respectively, with an energy window of 250–750 keV using a 3.1 ns time window. The sensitivity along the center axis within a +/- 25 mm offset maintained a peak value, which may be useful for imaging small plants. The system sensitivity is limited by the solid angle coverage of the half-ring microPET modules. For the following imaging experiments, data were acquired using an energy window of 350–650 keV and a timing window of 3.1 ns.

The plant PET scanner is located inside the PGC where the temperature may be varied from day to night. The LSO light output, the PMT gain and quantum efficiency of the photocathode are effected by the environmental temperature (Weber et al 2003, Moszyski et al 2006). This variation may cause a shift of the photon peaks in the detector block’s flood histogram or the crystal energy peaks. Since our current research protocols only call for a 10 °C variation between day time and night time, we use a 2.59 MBq (70 µCi) Ge-68 point source to measure the stability of detectors by acquiring single events at 20 °C and 30 °C. The detector modules were maintained at the two temperature conditions for at least 2 h before data were acquired. Figure 6 shows that the peak location found from the flood histogram acquired at 20 °C matches very well with the peak location found in the flood histogram acquired at 30 °C. Comparing the energy peaks of individual crystals from the two selected detector modules, there was found to be an average of a 2% decrease of the energy peak value for both Inveon and microPET detectors at 30 °C in the energy spectrum, but the energy resolution remains the same. The evaluation shows that the detector module works stably within 10 °C of temperature variation, which should suffice for many plant growth applications. In experiments that require extreme temperatures, special calibration and setup may be necessary.
3.2. Phantom study

3.2.1. Uniform phantom. A 6 cm diameter Ge-68 cylindrical phantom with a uniform activity concentration of 22.8 kBq ml⁻¹ was used to normalize the system. A separate scan of the same phantom (with offset) was reconstructed with normalization and calculated attenuation correction. Images in figure 7 show good uniformity in the center of the FOV.

Figure 7. Reconstructed uniform cylindrical phantom images and their profiles in tangential, radial and axial directions.

Figure 8. Central slice of reconstructed micro-Derenzo phantom image with an inner core diameter of 3.2 cm. The diameters of the rods (in millimeters) are shown in the images. Data were acquired with a typical energy window of 350–650 keV and time window of 3.1 ns.
Figure 9. The first PET imaging experiment with the system: (a) a cucumber plant being labeled with $^{13}$CO$_2$, (b) the plant is being imaged, (c) maximum intensity projection of the 3D PET images of the cucumber plant clearly shows uptake in the leaves and the photosynthetic transported to the petiole, flowers and stem.

Figure 10. Spot labeling of a dwarf soybean plant. The top three leaves (marked with the dotted box) are fixed in a small transparent rectangular labeling chamber. The activity was injected into the labeling chamber through the tubing and washed out with fresh air 5 min later. The bean-pod was removed from the plant after the experiment. The five square boxes in the photo correspond to the VOIs used to measure the average radioactive concentration in the following regions over time: (1) upper burl, (2) stem between two adjacent burls, (3) lower burl, (4) bean-pod and (5) seed.
3.2.2. Derenzo-like phantom. A home-made phantom with a Derenzo-like hot rod pattern was scanned to evaluate the spatial resolution of the plant PET system. The inner core of the phantom has a diameter of 32 mm and contains fillable hot rods of different diameters (0.80, 1.00, 1.25, 1.50, 2.00 and 2.50 mm) arranged into six segments. The distance between adjacent rods in each segment is twice the rod diameter. The phantom was filled with 18.4 MBq (0.50 mCi) of F-18 solution and scanned for 20 min. List-mode data were sorted into 3D sinograms and reconstructed with the ML-EM algorithm. The 3D image size is 200 × 200 × 320 pixels with a 0.4 mm³ × 0.4 mm³ × 0.4 mm³ voxel size. Phantom attenuation and scatter were not corrected in the reconstruction.

The reconstructed transverse slice of the phantom is shown in figure 8. The rods with 2.5, 2.0, 1.5 and 1.25 mm diameter are clearly separated.

3.3. Plant imaging experiments

To evaluate the performance of this dedicated PET scanner for real plant imaging applications, four pilot experiments were conducted using different plants after administering ¹¹C-12CO₂. All of the following images were reconstructed with the ML-EM algorithm with an image size of 400 × 400 × 160 voxels, 0.8 mm³ × 0.8 mm³ × 0.8 mm³ in size.
3.3.1. First plant imaging experiment with a cucumber plant. A young cucumber plant was labeled with 370 MBq (10 mCi) $^{11}$CO$_2$ in a cylindrical chamber (shown in figure 9(a)). The total uptake is approximately 11.1 MBq (0.3 mCi) at the end of the 15 min labeling. The plant was imaged for 10 min. Different parts of the cucumber plant are clearly delineated in the reconstructed image as shown in figure 9(c). The flowers appear to be the sinks of the photosynthates.

3.3.2. Soybean imaging experiment. The top three leaves of a dwarf soybean plant were labeled with 444 MBq (12 mCi) $^{11}$CO$_2$ using a home-made rectangular labeling chamber (figure 10) for 13 min. The total uptake was estimated to be 222 MBq (6 mCi) after correcting for the decay back to the beginning of the labeling time. The plant was imaged at 60, 120, 145 and 200 min post-tracer administration. The 60 min delay was because the high level of radioactivity at $t=0$ created too many random coincidence events.

Five volumes of interest (VOIs) were selected at (1) the junction of leaves and stem, (2) stem, (3) junction of stem and a soybean pod, (4) edge of the pod and (5) a bean inside the pod. Each VOI is 2.4 mm$^3$ × 2.4 mm$^3$ × 2.4 mm$^3$ (3 × 3 × 3 pixels in the image). The maximum value of the 27 voxels is plotted over time and shown as a time-activity curve of the VOIs in figure 11. Most photosynthates were translocated to the seed in the late frames.

3.3.3. Maize root imaging experiment. As shown in figures 12 and 13, young mutant and wild type maize plants (8 days after sowing) were labeled with about 370 MBq (10 mCi) of $^{11}$CO$_2$ inside a custom-made labeling chamber for about 10 min. A high luminosity LED light source...
is mounted on top of the chamber. After the radioactive gas was administered, the chamber was flushed out and the plant was moved into the plant PET imager and imaged for about 2 h. The raw data were binned into 5 min frames. No attenuation and scatter correction was applied to these images during reconstruction. Dynamic images with 5 min frames reveal different translocation and distribution patterns of photoassimilates in the two types of maize plant. The PET images at later time points (after 60 min) clearly show root structures in regular soil. Small hot spots appeared at the tips of roots, which are likely related to the meristem growth of these young roots.

3.4. Dynamic whole-plant imaging capability

Dynamic imaging of whole plants is a critical feature if tracer kinetic modeling is to be used to establish biological models. For plants that are taller than the axial FOV of our scanner, we developed a dynamic multisection imaging protocol that moves the plant up and down multiple times in 8 cm increments. At the early time points, since the radioactivity concentration is high, the imaging duration in a given frame can be as short as 30 s. As the radioactivity decays, the frame duration may need to be increased to compensate. Figure 14 shows an example of a maize plant that was labeled using 370 MBq of $^{11}$CO$_2$ and imaged for 2 h. The plant was only 7 days old after germination on the day of the imaging experiment. The overall length of the plant (shoots and roots) was more than 25 cm and required three sections to include the entire plant (one section for the shoots and two sections for the roots) in the imaging FOV. We used 0.5 min and 5 min per frame for the shoots and roots initially, and increased to 1 min

![Figure 13. Different translocation patterns shown for wild type and mutant maize dynamic PET images, acquired in around 1.5 h. Upper: mutant (131H), lower: wild type (B73).](image-url)
and 10 min per frame for these two different zones at late time points. The images from the three sections were stitched together using a custom program with proper decay correction to compensate for the elapsed time when each scan started (for different time frames and sections). Using this protocol, we demonstrated that dynamic whole-plant imaging with multiple sections is feasible despite the limited axial FOV of the scanner. It should be noted that some fast kinetics may be lost if the plant is tall and many sections are required to cover the whole plant. This is particularly challenging at late time points when the frame duration for each section may be as long as 10–20 min. Nevertheless, the result in figure 14 is promising and we will continue exploring the potentials and limitations of whole-plant dynamic imaging capability in the future.

4. Conclusion

We have developed a dedicated high-resolution plant PET scanner based on two types of detector module from commercial small-animal PET systems. The scanner features a reconfigurable system geometry and full control of the plant growth environment. The system has a sensitivity of 1.3% at the center of the FOV, an average of 18% FWHM at 511 keV, and a time resolution of 1.8 ns FWHM. The image resolution of the scanner is similar to that of the commercial microPET system. Phantom studies and preliminary plant imaging experiments show that high quality 3D tomographic and dynamic PET images can be acquired with the full ring configuration. These initial plant imaging studies also clearly demonstrated the functional imaging capability for plants using the plant PET system. Additional studies using N-13, C-11 and other radionuclides are being conducted by collaborating with regional plant scientists.
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