DICOM SUV calculations for PET imaging

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There are several methods for measuring the rate and/or total amount of radiotracer accumulation in PET images, most commonly the accumulation of 18F-FDG in tumors. PET scanners are designed to measure the *in vivo* radioactivity concentration (Bq/mL), which is proportional to the FDG concentration. Typically, however, it is the relative tissue uptake of FDG that is of interest. The two most significant sources of variation that occur in practice are the amount of injected FDG and the patient size. To compensate for these variations, at least to first order, the standardized uptake value (SUV) is commonly used as a relative measure of FDG uptake. The basic expression for a SUV (g/ml) is:

$$\mathrm{SUV} = \frac{A}{d' w}$$

where A is the radioactivity concentration from a voxel or region on interest (ROI) in the image in units of Bq/cc, d is the injection radioactivity, or 'dose' in Bq. Dose is a common jargon term as we often referred to the radiation dose to the patient (but it is more complicated than that). We decay-correct injection dose to d' to match the time the activity A is measured by the PET scanner, and w is the weight of the patient in g.

Conceptually, if all the injected FDG is retained and uniformly distributed throughout the body, the SUV everywhere will be 1 g/mL, regardless of the amount of FDG injected or patient size.

There are several other factors that can confound the measurement of SUVs that have been well described elsewhere [Boellard, Kinahan, Adams, Pierce]. Here we present the methodology for correctly calculating PET SUVs from DICOM activity-concentration images using the values of the Attributes that describe the procedure, acquisition, correction and reconstruction.

There are variations in how A is measured. It can be the maximum values within an ROI, which is denoted by $\mathrm{SUV_{MAX}}$, or the average in a 1 cc volume, $\mathrm{SUV_{PEAK}}$. Despite nearly endless debate, most common is $\mathrm{SUV_{MAX}}$ as this is less sensitive to variations in how the ROI is drawn, which can be quite variable. There are also alternatives to using the patient's actual weight for w, as the uptake of tracer is not uniform for different tissue types, e.g., adipose tissue has little or no circulation for drug distribution. Pharmacokinetic-based corrections for 'lean-body-mass' are often used for correction of the biodistribution. There are different formulas for this based on height and weight, which are attempts to account for different tissue distribution caused by sex and other population-based phenotypic variations. In this case the SUV is typically denoted as SUL, i.e. L = lean body mass instead of the simple body weight w. A commonly used approach to estimating lean body mass in Western industrialized nations is the Janmahasatian method.

In the base case the overall units of an SUV measurement are:

$$\frac{Bq/ml}{Bq/g} = g/ml$$

We calculate SUVs using

$$\mathrm{SUV} = U \times s$$

where s is the SUV scaling factor described below, and U are the base pixel values with units specified in DICOM field Units (0054,1001), which is "BQML" (Bq/ml) for decay and attenuation corrected activity-concentration images. The activity-concentration pixel values U are calculated from the stored pixel values using

$$U = \mathrm{SV} \times m + b$$

where SV is the stored value for an image pixel, m is the value of Rescale Slope (0028,1053), and b is the value of Rescale Intercept (0028,1052). However, the Rescale Intercept *should* always be zero for PET images (but may not be in older images). The stored value (SV) for an image pixel is typically a two-byte integer in the data stream of the pixel values that comprise the Image in Pixel Data (7FE0,0010). The format can be unsigned or signed (two's-complement). Most PET images from modern systems do not have negative numbers, but small negative values did occur in in older systems for a few reasons, even though radiotracer concentration cannot be negative!

Why is rescaling used? In PET images the base pixel values U are floating point values that can vary over a wide range, depending on the patient and the acquisition protocol. Linear scaling of the pixel values using

$$\mathrm{SV} = (U - b)/m$$

allows use of the full dynamic range of the two-byte data representation to minimize quantization errors. The rescale slope value may be (but is not required to be) determined by matching the maximum image base pixel value to the maximum of the data representation format.

$$m = \max(U)/\max(\mathrm{range})$$

For example, using two-byte two's-complement representation, $\max(\mathrm{range}) = 32,767$ and if we inject 10 mCi (370 MBq) of 18F-FDG into a 70 kg patient and it is uniformly distributed. We assume the volume of distribution is 70 l and the average radioactivity concentration is 37,000,000/70,000 = 5,286 Bq/ml. After a typical 60 min uptake time, due to radioactive decay of the 18F with a half-life of 110 minutes, the average concentration has dropped to 68.5% of its original value based on exponential decay, where the fraction of the remaining activity at time t, $f(t)$, is given by:

$$f(t) = \frac{A(t)}{A(t=0)} = e^{-\left(\frac{t}{T_2/\ln(2)}\right)}$$, (or more simply $f(t) = 2^{-(t/T_2)}$)

where T_2 is the half-life

$$f = \exp(-60\,\mathrm{min}/(110\,\mathrm{min}/\ln(2))) = 0.685$$

or a value of 3,622 Bq/ml. If we assume there is a tumor that takes up 4 times the amount of 18F-FDG as normal tissue, then the maximum base pixel value is 14,488 Bq/ml and m = 14,488 / 32,767 = 0.4421. It is important to note that the DICOM standard allows the rescale slope values to vary on a slice-by-slice basis for a PET image series, or it can be fixed for the entire image volume formed from a 'stack' of slices, depending on the manufacturer's implementation.

Since PET images can be stored in DICOM format without corrections applied (e.g., to store non-attenuation corrected images), before attempting to compute SUV, the attributes that define a decay-corrected, attenuation-corrected suitable for SUV calculation need to be checked. In order to use DICOM elements to calculate SUVs, the following conditions need to be satisfied:

- Necessary corrections have been applied. The DICOM field (0028,0051) "Corrected Image" contains one or more values that indicate which, if any, corrections have been applied to the image. Needed for SUV calculation are:
    - ATTN (correction for attenuation is applied)
    - DECY (correction for radioactive decay is applied)
    - SCAT (correction for scattered coincidences is applied)
    - RAN or RANSNG (correction for random coincidences is applied)
- The Decay Correction (0054,1102) is START (images are decay corrected to the scan start time)
- The Units (0054,1001) are BQML (i.e. Bq/ml)
- Series Date (0008,0021) and Series Time (0008,0031) are not later than the Acquisition Date (0008,0022) and Acquisition Time (0008,0032). Otherwise this may be a post-processed image series and the Series Date and Time are of that series creation, which is arbitraryand not related to the physiology and pharmacology.

If these conditions are met (or a few other variations that are not covered here) then the SUV scale factor used to calculate SUV from the base pixel values, U, as described above is:

$$s = w \times 1000/d'$$

where the patient weight w is the value of Patient's Weight (0010,1030), which is encoded in kg, and needs to be converted to g in the above formula. Alternatively, the lean body mass can be computed from Patient's Weight (0010,1030) and Patient's Size (0010,1020) (height in meters) and used instead of body weight. The decay-corrected activity is determined by

$$d' = d \cdot 2^{-\left(\frac{(T_S - T_I)}{T_2}\right)}$$

where

d is the injected radioactivity in Bq from Radionuclide Total Dose (0018,1074)

T_2 is the half-life in seconds from Radionuclide Half Life (0018,1075)

T_S is the Series Time (0008,0031), i.e. the scan start time we are decay correcting to.

T_I is the Radiopharmaceutical Start Time (0018,1072), i.e. the injection time

To sum up:

$$\mathrm{SUV} = \left(\mathrm{SV} \cdot m + b\right) \cdot \left(\frac{1000w}{d \cdot 2^{-\left(\frac{(T_S - T_I)}{T_2}\right)}} \right)$$

Table 1. Variables and DICOM fields used in calculating SUVs.

Variable	description	Units	DICOM Tag	DICOM Attribute Name	Comments
SUV	standardized uptake value	g/ml	generally not encoded in image pixels, but see below	n/a	What we want to calculate

SV	stored value for an image pixel	as specified by Units (0054,1001)	(7FE0,0010)	Pixel Data	typically a two-byte integer
m	rescale slope	dimensionless	(0028,1053)	Rescale Slope	
b	rescale intercept	as specified by Units (0054,1001)	(0028,1052)	Rescale Intercept	*should* be zero
w	patient weight	kg	(0010,1030)	Patient's Weight	
d	injected radioactivity	Bq	(0018,1074)	Radionuclide Total Dose	
T_2	radioisotope half-life	s	(0018,1075)	Radionuclide Half Life	if absent, already known for specified nuclide
T_S	start of scan	absolute time	(0008,0031)	Series Time	the decay correction reference time
T_I	injection time	absolute time	(0018,1072)	Radiopharmaceutical Start Time	

Notes

1. This does not account for studies that span across midnight or more that one day for long-lived isotopes.

2. Series can use the radiopharmaceutical administration time as the reference time for decay correction, or not be decay corrected.

3. The stored values (SV) are assumed to be decay corrected to the scan start time, and this can be seen by observing the DICOM "Decay Factor" field (0054,1321) to be greater than 1.0, although this should be interpreted with caution.

4. PET image volumes are

5. The DICOM standard allows for storing a PET image as an 'SUV image' instead of the more standard approach of radioactivity concentration. The latter approach is much preferred as the image display software can switch between methods of SUV calculation as desired at the time of display. If the image is saved as SUVs rather than Bq/ml this is not possible in general, nor is estimation of the original radioactivity concentration, should that be needed. Nonetheless, if the image is in SUVs, the specific method of using weight in the SUV calculation *should* be indicated in SUV Type (0054,1006). If SUV Type is absent (which it may be, since this was added later, is optional and was not in the original standard), and the Units (0054,1001) are GML (i.e., g/ml), then the type of SUV normalization for volume of distribution is assumed to be BW (simple body weight).

6. Absolute times are in the local time zone or UTC but may be assumed to be in the same timezone for relative time calculations.

7. Radiopharmaceutical Start DateTime (0018,1078) may be present instead of Radiopharmaceutical Start Time (0018,1072)

PET imaging and the DICOM standard.

Details on the DICOM standard relevant for PET imaging are in section A.21 "Positron Emission Tomography Image IOD" of DICOM PS3.3 and its referenced Modules, which describe how to encode an image that has been reconstructed by a PET scanner from acquired data. DICOM is periodically standard, though in a backward compatible manner, so the current version should always be used.

Though SUV images can be encoded directly, more commonly SUV need to be computed from attenuation-corrected activity-concentration images. Important (M)andatory Modules for SUV calculations are:

PET Series: C.8.9.1, which describes the attribute common to all images in a series, including type, correction and units

PET Isotope C.8.9.2, which identifies the radioisotope and radiopharmaceutical used and specify activity and timing of administration

PET Image C.8.9.4, which describes acquisition timing and integer pixel value rescaling

Given the complexity and potential manufacturer-specific variations in the calculations of SUV from activity-concentration decay and attenuation corrected DICOM images, the QIBA PETSUV sub-group [ref] undertook a survey of vendors' approaches and reached consensus on an approach to computing SUV that is described in brief [ref] and in more detailed form [ref] as procedural pseudo-code.

Other items

1. Gated and dynamic studies

2. Methods and problems with LBM calculations

3. Vendor variants, including private attributes that need to be considered in SUV calculations

4. Scanner conformance statements

5. Uncertainties with 3rd party (and mfr) readers

6. Connection to RWVM to SUV images (Fedorov PeerJ 2016)

7. Bed position changes

8. Whether or not start and stop time of administration are both present