

Application note for listmode scanning

This application note explains what listmode acquisition is, how a listmode scan is done and how to process a listmode scan with SkyScan software.

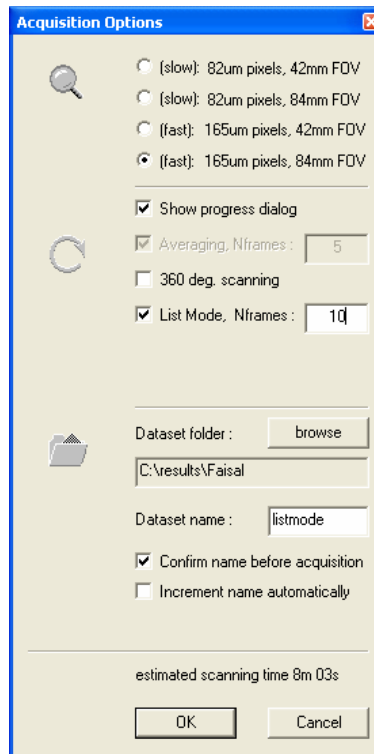
What is listmode?

Listmode refers to a special scanning mode in which each event and its precise time of occurrence is recorded sequentially, with selected properties, such as image captures at each rotation step and recorded time-points on the animal's breathing cycle. For example, if we consider the acquisition of one x-ray image as an event, the time of the acquisition, together with the times of physiological signals such as from breathing that are measured in the animal being scanned, can be recorded.

The SkyScan *in-vivo* scanners have listmode acquisition enabled together with a physiological monitoring system to allow users to acquire 4D images. Alternatively, one can use this mode to reduce motion artifacts (e.g. breathing artifacts). More specifically, at each view, or angular position, multiple projection images are acquired and the acquisition time of each image is recorded. These projection images at one angular position are called time frames. In the meantime, the time marks of a specified physiological signal, which may indicate breathing or heart beating or any periodic movement, are recorded separately by a physiological monitor over the duration of the scan.

How to acquire a listmode scan on SkyScan *in-vivo* scanners

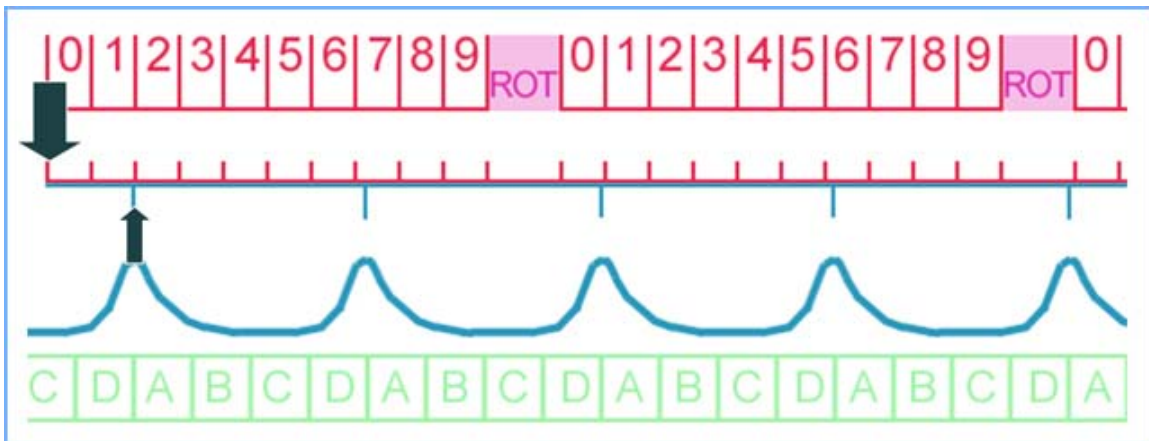
In the **Acquisition options** dialog as shown below, frame averaging will be disabled when *List Mode* is selected. Instead, multiple frames at one angular position will be acquired. All acquired frame images will be saved individually, and time marks corresponding to the exact acquisition time of each frame will be recorded in a separate text file. The number of frames per angular position can be given in the corresponding edit box (for example – 10).



During acquisition, 10 sequential images will be collected and saved directly into individual files without any averaging. The exact time marks of each image acquisition will be recorded in a separate text file as a list. The list of these time marks will be used later for sorting, together with time marks from physiological monitoring. The following graph illustrates the acquisition of a listmode scan: the red numbers indicate the sequential image frames obtained at each angular position, and the red marks on the time axis at the bottom are the corresponding time marks for the frames.



Physiological monitoring works independently from acquisition process. The physiological monitoring subsystem can record movements of the animal using a TV-camera mounted on the object bed, and breathing signals from an airflow sensor or heart beat through integrated ECG amplifier. One of these three signals can be selected to create synchronization pulses. In most cases, the breathing signals are used. The graph below illustrates the combination of a listmode scanning with monitoring on breathing (shown in blue curve). The exact time marks of each breathing cycle recorded by the physiological monitoring subsystem (blue marks) are also saved to a separate text file as a list.



At the end of a listmode acquisition, we will get a set of projections, and 2 text files with time marks. Please note that a slightly different name convention is used for listmode data. If a listmode scan is given the prefix *MyListModeData*, and there are in total 300 angular views and 10 time frames per view, the following items will form the complete dataset:

MyListmodeData.log the normal log file, which contains a few more entries related to the listmode acquisition

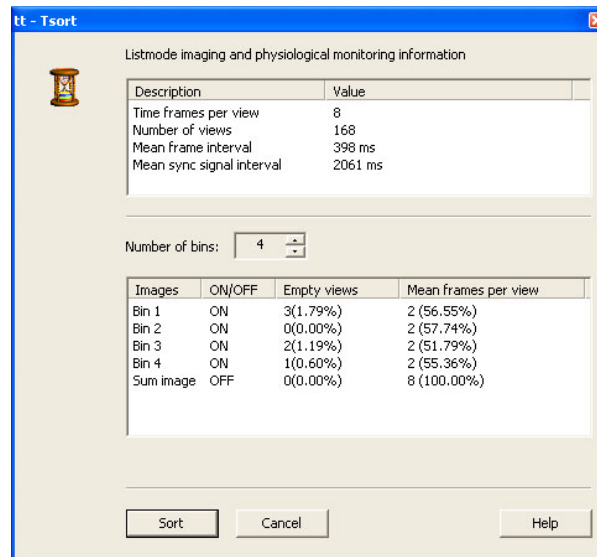
MyListmodeData_pm.lst contains a list of physiological time marks in ASCII format

MyListmodeData_aq.lst contains a list of acquisition time marks in ASCII format

MyListmodeData~dddd~ddd.tif the projection files: the first 4 digits (~dddd~) is the time frame index starting from 0; the last 4 digits (ddd) is the normal sequence number starting from 0. For example, *MyListmodeData~0008~0255.tif* is the 9-th frame at 256-th angular position. In total, there will be $300 \times 10 = 3000$ projection files.

How to sort list-mode data?

A listmode scan has to be sorted offline before any further processing. This can be done with Tsort, a standalone SkyScan program. For detailed and up-to-date information on how to use Tsort, please refer to online document coming with this program. The screenshot below shows that a raw listmode scan with 168 angular views and 8 time frames per view is loaded and is ready to be sorted into 4 time bins.



Tsort can be invoked by drag-and-drop, double-click or by other SkyScan programs. Multiple instances are allowed: care should be taken when one works on the same dataset with multiple instances of Tsort. The original projection image dataset will not be modified in any way by Tsort. The sorted datasets, or the bins, are stored in the same directory as the input listmode data. They are ready for reconstruction and further processing. These sorted datasets have a fixed name convention as well:

MyListModeData ~#dddd~dddd.tif, where the 4 digits in *~#dddd~* contains two numbers: the first 2-digit number is the bin index starting with 0, and the last 2-digit number is the total number of bins; the second 4 digits *dddd* is the view index as usual. For example, *MyListModeData~#0204~0255.tif* is the 256-th projection image in the 3rd time bin (00 is the first bin) out of 4 time bins in total.

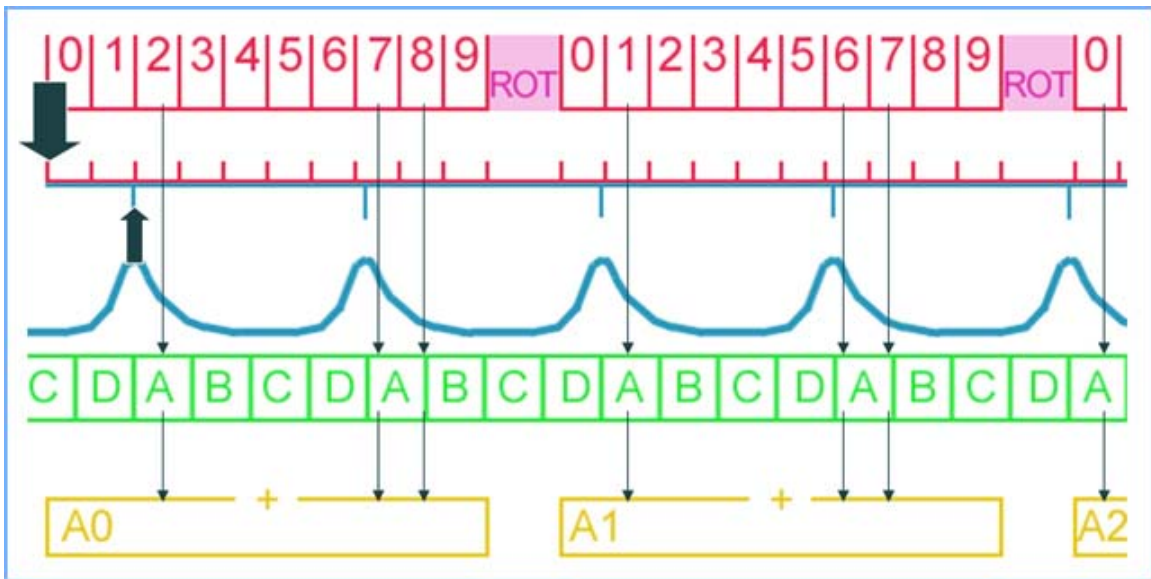
When opening a listmode dataset, time information is retrieved from the two *lst* files. On the main window, a table at the upper part shows a few relevant acquisition parameters: number of time frames, number of views, the average time interval between two time frames at one angular position, and the average synchronization signal interval. It is generally assumed that the mean sync. signal interval is the mean time period of a physiological signal, e.g., a breathing cycle, and should be at least a few times longer than the average time interval between two time frames.

Sorting consists of dividing a cycle evenly in time into a few segments (virtual division), also called time bins. This is performed for each angular position. Each bin is then filled with images obtained within the corresponding time interval. Irregularity of the physiological signals are tolerated, as each cycle is divided individually, and variation in number of images per bin is taken into account: a bin with multiple frame images is filled with the mean of the images, a bin with 0 frame image, also called a "hole", is replaced by its nearest neighbor.

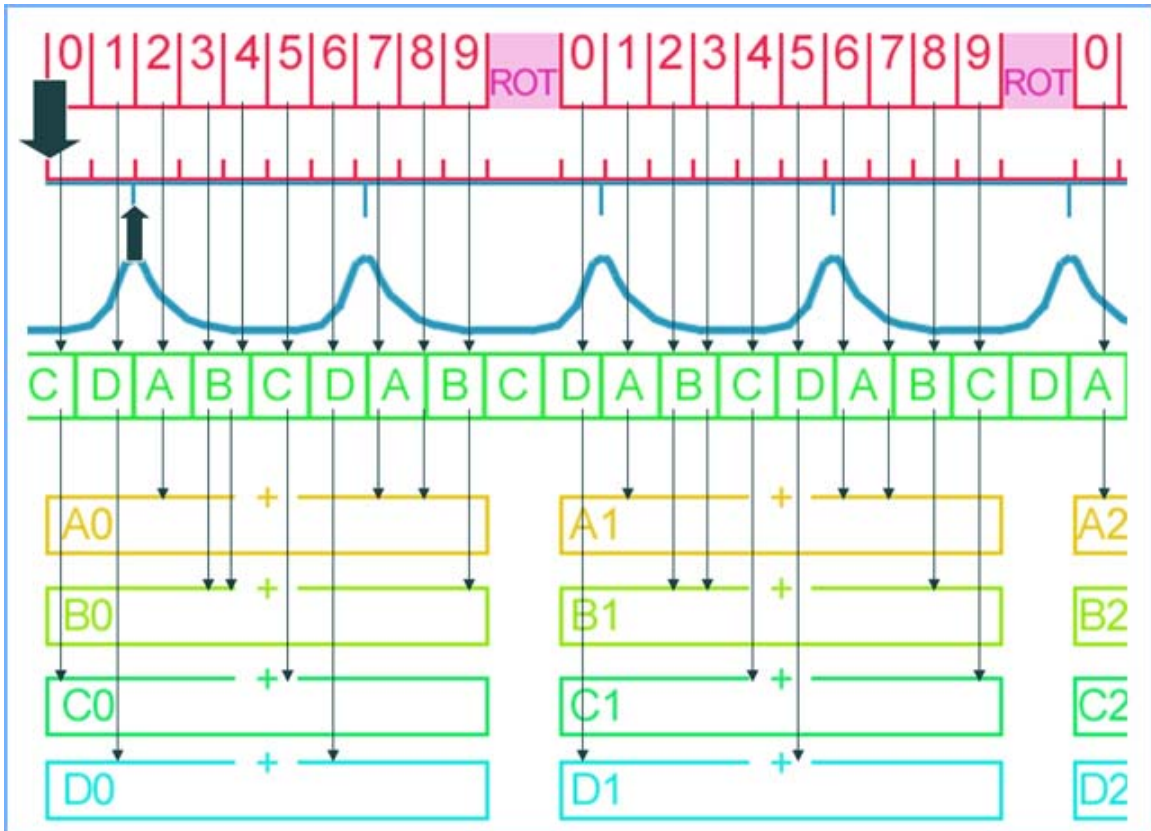
The number of bins can be given interactively. In Tsort, the bin number is limited to a maximum of 16. To minimize sorting error, it is not desirable to have more bins than the number of time frames per angular view. Whenever the number of bins per cycle is given, sorting statistics will be shown in a table at the lower part of Tsort window: the number of empty views and its percentage in the total number of views, and the number of time frames per view for the majority of views. Note that you may switch a bin on/off by double-click on the row. This is handy if you are only interested in a particular phase of the cycle, for example, only when the lung of the animal is at its fullest. You may sum up all the time frames at one angular position. This is equivalent to the situation when a normal scan is done with frame averaging.

How does sorting work?

To further illustrate how a listmode scan is sorted. Let's divide every breathing cycle into 4 time bins : A, B, C and D as depicted in the graph below. For time bin A at angular position 0, Tsort searches for all images acquired inside the time interval: frame 2, 7 and 8 are found , which are averaged to form the first projection image A0 in a new sorted projection dataset . This binning procedure is then performed for all angular positions to form A1, A2, Together with these new projection images, a log file is created based on the original one to form a complete scan which is ready for reconstruction.



Tsort performs the same procedure for all four time bins and finally creates four new sets of angular projections: A0,A1,A2,...; B0,B1,B2,...; C0,C1,C2,...; D0,D1,D2,... as shown in the following picture:



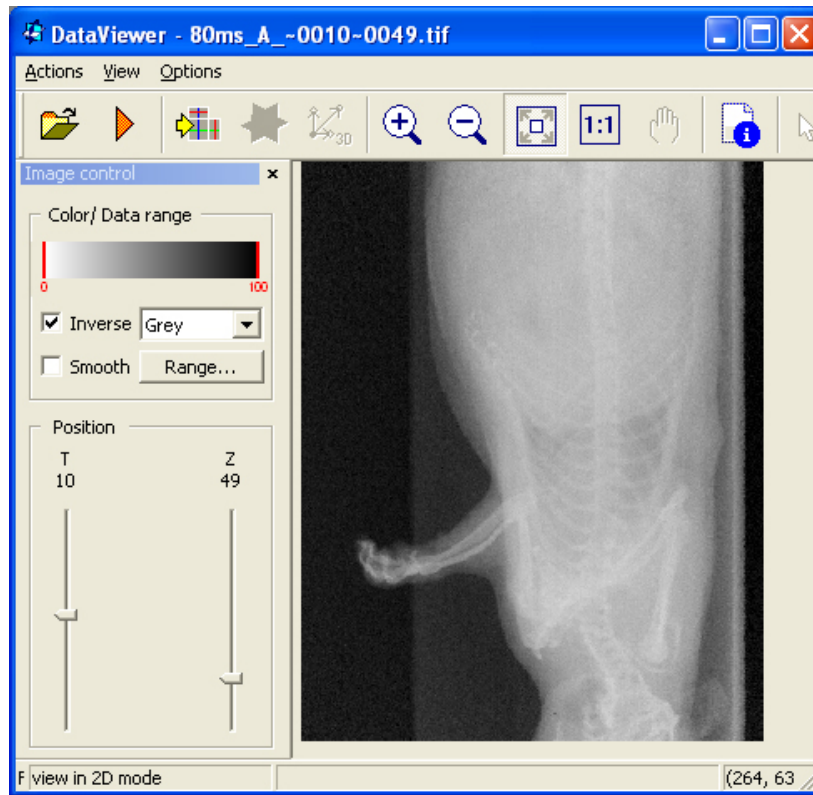
How to reconstruct sorted list-mode datasets?

The sorted listmode scans (time bins) can be reconstructed in the normal way in NRecon (use current version available from SkyScan website). For detailed and up-to-date information on how to use NRecon, please refer to the online document accompanying this program.

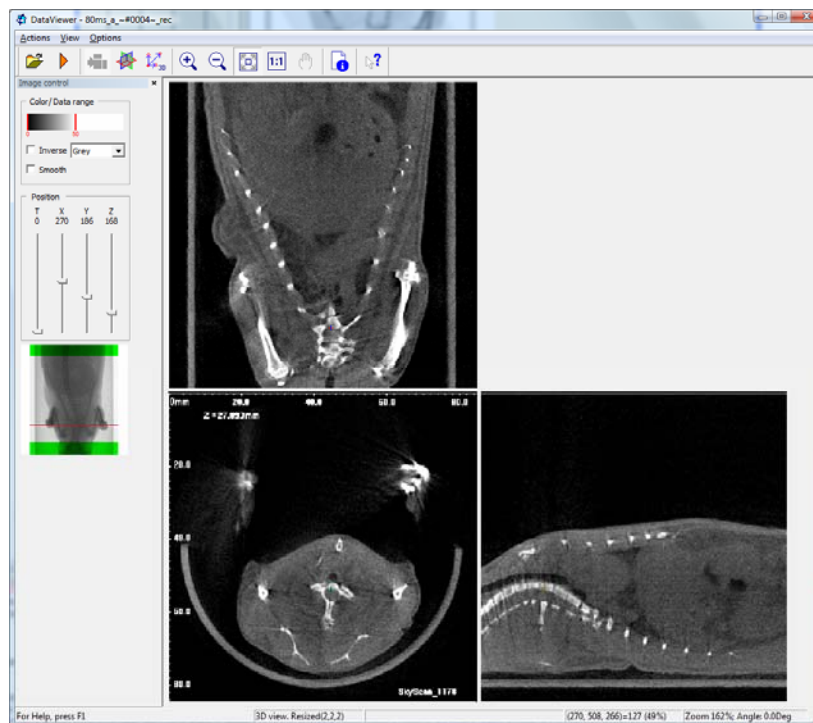
How to view list-mode images?

Raw listmode projection images, sorted listmode projection scans and reconstructed listmode scans can be viewed with DataViewer (use current version available from SkyScan website). For detailed and up-to-date information on how to use DataViewer, please refer to the online document accompanying this program.

All scans can be viewed either in 2D or 3D with the time axis (labelled "T" in dataviewer). An "animated" view can be obtained by either scrolling on the T-axis or using the animation button (select "Time" as the animation parameter in *Options->Preferences* at viewing). A few screenshots are shown below.



DataViewer screenshot: a raw listmode projection dataset is displayed in 2D mode.



DataViewer screenshot: a reconstructed sorted listmode dataset is displayed in 3D mode.