Optimized List-Mode Acquisition and Data Processing Procedures for ACS2 Based PET Systems

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Abstract

PET systems using the acquisition control system version 2 (ACS2), e.g. the ECAT Exact HR PET scanner series, offer a rather restricted list-mode functionality. For instance, typical transfers of acquisition data consume a considerable amount of time. This represents a severe obstacle to the utilization of potential advantages of list-mode acquisition. In our study, we have developed hardware and software solutions which do not only allow for the integration of list-mode into routine procedures, but also improve the overall runtime stability of the system. We show that our methods are able to speed up the transfer of the acquired data to the image reconstruction and processing workstations by a factor of up to 140. We discuss how this improvement allows for the integration of list-mode-based post-processing methods such as an event-driven movement correction into the data processing environment, and how list-mode is able to improve the overall flexibility of PET investigations in general. Furthermore, we show that our methods are also attractive for conventional histogram-mode acquisition, due to the improved stability of the ACS2 system.

Keywords: Dynamic data acquisition, list-mode, data processing, ACS2, ECAT Exact HR$^+$, positron emission tomography

Optimierte Listmode-Akquisition und Datenverarbeitung für ACS2-basierte PET-Systeme

Zusammenfassung

PET-Systeme, die wie der weit verbreitete ECAT Exact HR+ PET-Scanner das Acquisition Control System Version 2 (ACS2) nutzen, bieten eine eher begrenzte Listmode-Funktionalität, z.B. benötigt die Übertragung typischer Datensätze beträchtliche Zeit. Dies stellt eine schwerwiegende Hürde für die Ausnutzung potentieller Vorteile von Listmode-Messungen dar. In unserer Studie haben wir Hardware- und Softwarelösungen entwickelt, die nicht nur eine Integration von Listmode in die Routine erlauben, sondern auch die gesamte Stabilität des PET-Systems verbessern. Wir zeigen, dass unsere Methoden in der Lage sind, die Übertragung von akquirierten Daten um einen Faktor von bis zu 140 zu beschleunigen. Wir diskutieren wie diese Verbesserung eine Integration von Listmode-basierten Korrekturmethoden, z.B. einer Event-getriebenen Bewegungskorrektur, ermöglicht, und wie mit Listmode generell die Flexibilität von PET-Untersuchungen verbessert werden kann. Des Weiteren zeigen wir, dass durch die verbesserte Stabilität des ACS2-Systems unsere Methoden auch für konventionelle Histogramm-Akquisitionen attraktiv sind.

Schlüsselwörter: Dynamische Datenakquisition, Listmode, Datenverarbeitung, ACS2, ECAT Exact HR$^+$, Positronen-Emissions-Tomographie

1 Introduction

Modern positron emission tomography (PET) scanners usually acquire data in so-called *histogram-mode*, where all registered coincidences are sorted online into three dimensional histograms prior to the image reconstruction. This saves storage space and minimizes the required bandwidth, but it also represents a loss of information, because the temporal resolution is highly reduced and the raw information of several coincidences is combined into the same histogram bin. While this limitation is negligible during most clinical PET acquisition protocols, more advanced data processing methods such as an event-driven movement correction [1, 2], require the full unsorted information set. Therefore, PET scanners like the ECAT Exact HR$^+$ allow for the acquisition of data in a separate mode, called *list-mode*. During such a *list-mode* acquisition, every single coincidence information is preserved and encoded into a specific data file format.

The generated *list-mode* files consist of a continuous stream of 32-bit big-endian words called *event words* which contain the encoded coincidence information [3]. This stream of *event words* is periodically intermitted by a single *time word*. A *time word* represents the time that has passed since the beginning of the data acquisition, with a typical granularity of 1 millisecond (Fig. 1). Furthermore, the *time words* carry *gating* information bits set by PET systems that support external trigger input signals. In contrast, the data generated in *histogram-mode* is saved in a different data file format, called *sinogram file*. A sinogram corresponds to a three dimensional histogram containing all sorted coincidence information of a *list-mode* stream. Such a *sinogram file* is used during the image reconstruction phase and thus represents the typical data format for reconstructing an image with the native PET scanner environment.

Although *list-mode* files consist of 32-bit wide data words only, their total size can exceed several gigabyte during a typical *list-mode* acquisition. With such a very fine grained acquisition data set, methods aiming at the modification of the coincidence information can be applied prior to the image reconstruction. Especially for the increasingly important compensation of patient motion, *list-mode* is the preferred acquisition mode.

Several aspects of the scanner environment of an ECAT Exact HR$^+$ prevent the routine use of *list-mode* with this system. First, the missing feasibility to directly acquire *list-mode* data with the standard ECAT acquisition environment of the PET scanner. To acquire data in *list-mode*, it is necessary to work with third-party acquisition protocols using proprietary software which transfers the *list-mode* data from the underlying acquisition control system (ACS2) to another machine. This comprises the process of binning the raw coincidence information into a 3D histogram after having processed it accordingly. More importantly, the limited network capabilities of the control system, as well as hardware and software stability issues severely hinder the usability of *list-mode*. The limited network capabilities, due to the by now ≈ 10 years old hardware, lead to long time delays of up to several hours until the final image reconstruction can be applied. As a result, the image data is often available only the next day, thus representing an unacceptable delay for clinical PET.

To overcome these obstacles and to make *list-mode* usable for clinical PET, we have developed custom hardware and software methods. These methods do not only allow for the integration of *list-mode* in routine operation, they also improve the overall runtime stability of ACS2 based PET systems. In this paper, we present these methods as well as a software suite of *list-mode* aware applications. We show that a routine integration of *list-mode* is possible with such PET systems, and how event-driven post processing methods but also conventional *histogram-mode* acquisitions benefit from our hardware and software solutions. In addition and as a result of our research, we further suggest and emphasize the necessity of providing support for *list-mode* on future PET systems.

2 Methods

The sparse use of *list-mode* is caused by different means of limitations concerning both, hardware and software. Therefore, we have addressed these hardware and software issues separately with the goal to improve *list-mode* support in general. While our hardware solutions are specific to ACS2 based systems, our software solutions are of a more general nature and can also be adapted to other systems supporting *list-mode* acquisitions.

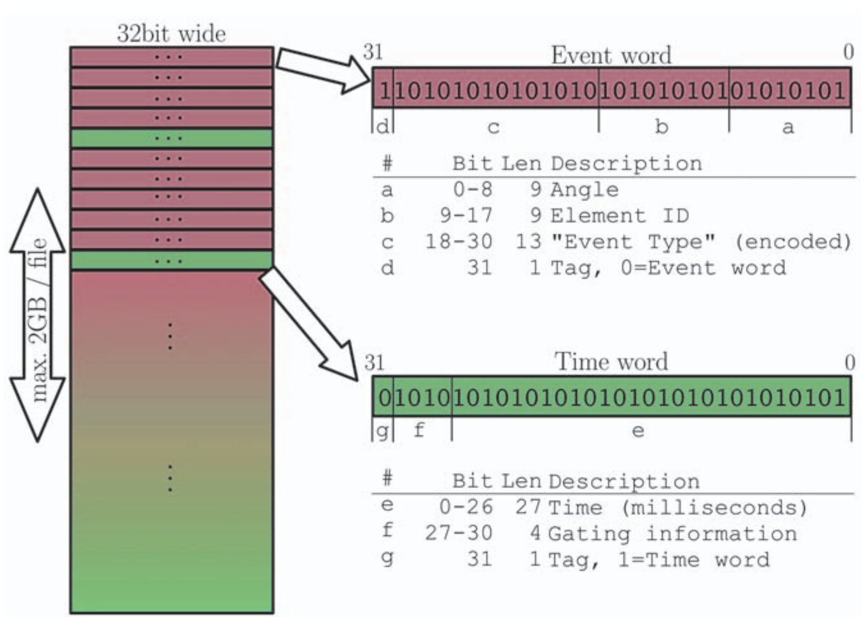

Figure 1 If running in list-mode, a PET scanner stores its raw data in so-called list-mode files. These files consist of 32-bit wide big-endian words, where the coincidence information itself is encoded in event words [3]. Furthermore, to introduce a time constraint, the PET scanner inserts periodic time information (time words) into the list-mode stream. By using this raw data format, data processing methods may employ the full information provided by a PET acquisition.

2.1 Optimized Hardware Based Acquisitions

One persistent and well-known issue with scanners like the ECAT Exact HR$^+$ are stability problems due to the underlying VxWorks based ACS2 control system. Although VxWorks is a *real-time operating system* (RTOS) known for its reliability [4], the implementation on the ACS2 runs very unstable, especially during *list-mode* processing. For example, parallel access to the ACS2 is not possible during a running data acquisition without compromising the stability of the entire data acquisition process. Failures vary from possible dropouts to a complete loss of the acquired data. While some causes related to software can be eliminated by disabling certain services, e.g. the *Network File System* (NFS) service, others can not be solved as easily and require other approaches.

One approach to relieve pressure from the ACS2 system is to move the data to the acquisition workstation immediately, before another process tries to access the same data on the ACS2. This in fact has recently been implemented by the manufacturer of the HR$^+$ with the ECAT 7.2.2r5 update. However, the problem of limited transfer bandwidth from the ACS2 system to other workstations remains. Especially for large *list-mode* data, a traditional transfer results in an unacceptable delay of several hours while blocking other parallel acquisition processes.

Because an upgrade of hardware components such as network components is not available, we primarily focused on analyzing the existing hardware constraints of the ACS2, and tried to find a way to reduce or even eliminate the aforementioned limitations.

2.1.1 Shared Storage Device Acquisition

The ACS2 usually stores the final acquisition data on an internal SCSI-2 hard disk. Although this standardized bus type supports a maximum theoretical throughput of 10 MB/s, the ACS2 does not allow for the transfer of data to other systems with rates higher than ≈0.5 MB/s (Fig. 2). Since SCSI is a well-known standard for data storage devices, commercial solutions exist that provide a parallel access of multiple systems to the same device. In addition, the communication protocol used by SCSI devices is backward compatible, enabling devices that comply to newer SCSI sub-standards, e.g. *Ultra160-SCSI*, to communicate with devices of an older SCSI version. This also applies to the SCSI host adapter of the ACS2 which complies to the SCSI-2 standard of 1994 [5]. Therefore, we replaced the internal hard disk of the ACS2 with a dual-channel *Ultra160-SCSI* RAID array supporting higher transfer bandwidths, and verified its operation under routine conditions. To arrange for a parallel access from another machine, we connected the second channel of the RAID device to a system using an *Ultra160-SCSI* host adapter, running Linux as its operating system (Fig. 3).

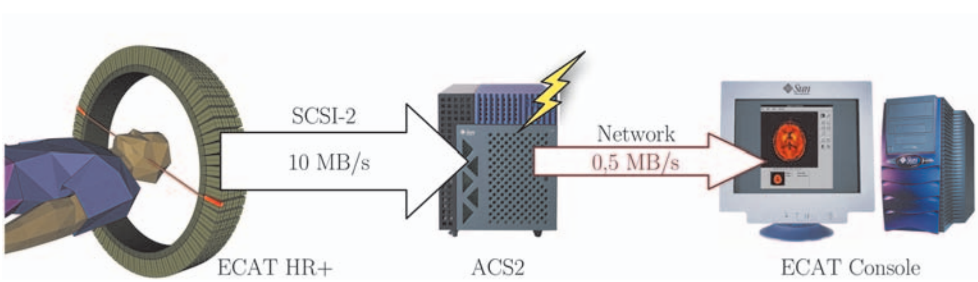

Figure 2 Because of hardware limitations of the ACS2, transfer of acquisition data to another system is limited to ≈0.5 MB/s. For large list-mode acquisitions, this leads to undesirable time delays. In addition, hardware and software stability issues severely limit the application of list-mode.

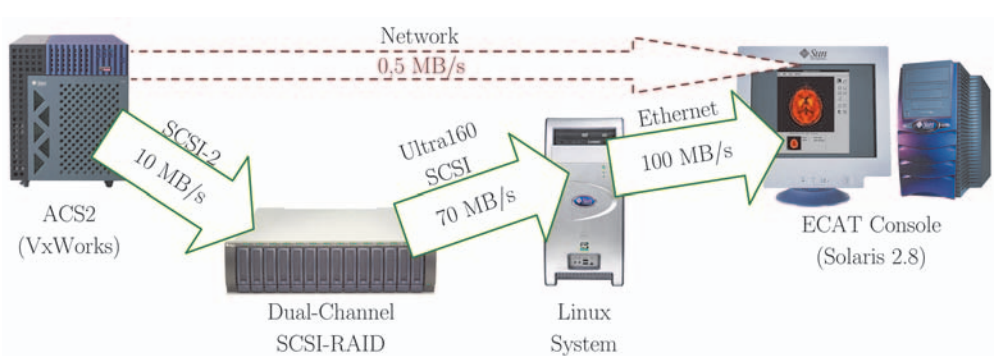

Figure 3 Using a dual-channel Ultra160-SCSI RAID storage device, it is possible to access the stored acquisition data from another system in parallel. The Linux system runs a custom implementation of the filesystem (VXEXT) used on the ACS2 system. This allows to read the list-mode or sinogram data with a maximum throughput of ≈70 MB/s.

To save the acquisition data on the storage device, the ACS2 uses a filesystem provided by its VxWorks operating system. This filesystem is a proprietary implementation of the FAT16 filesystem commonly used on many other operating systems [6]. However, in contrast to the original FAT16 filesystem specification, the VxWorks implementation supports the storage of files with a filename length of up to 40 characters. Furthermore, it allows to maintain more than 2 gigabyte of data on a single partition which is necessary for storing *list-mode* data. Consequently, these differences render the *VxWorks extended DOS filesystem* (*VXEXT*) incompatible to the *well defined* FAT16 filesystem standard. We therefore needed to reverse-engineer the filesystem structure of *VXEXT* and developed an implementation for the Linux operating system [7] using the C programming language. This implementation covers all systems based on the 2.6 version of the Linux kernel and can be either incorporated into the kernel, or loaded as a filesystem module at runtime. To achieve a direct incorporation of this new filesystem into future kernel versions of Linux, we released the source code under an open-source license (GPL) and submitted it to the official developer community of Linux [8].

Due to the data access management and the caching policies of a data storage process in general, a parallel write access of both the ACS2 and the Linux system is not possible. However, an explicit write access for the Linux system is not mandatory because the ACS2 can be remotely instructed to modify or delete data via ECAT command sequences, e.g. *rfaDelete* (Fig. 4). Concerning parallel read access, the data caching implied by the *VXEXT* filesystem requires that the Linux system refreshes the filesystem meta-information in regular time intervals. Otherwise it can not keep track of potentially modified data since the last access of another system and may return file system information which was already obsolete at the time of reading. Therefore, in order to synchronize the write operations of the ACS2 with the read operations of the Linux system, the hard disk has to be automatically remounted prior to every access by the Linux system. This is especially critical if the ACS2 has modified the data between different data acquisition sessions of the PET system. We implemented this *remounting facility* through the standard auto-mounter of Linux. It ensures that a partition is automatically unmounted if no further access is performed, and remounted for every new read access.

To achieve an integration into the ECAT acquisition environment, we use the discussed remounting and remote control facilities, and we also have developed own acquisition protocols. These protocols include proprietary shell scripts which move the acquisition data via the discussed RAID solution to the acquisition workstation before it is accessed for further processing or visualization. This relieves the ACS2 from the additional load of several processes accessing the same data. Furthermore, it considerably speeds up other common processes that try to access data stored on the ACS2, e.g. the *ECAT Sinogram Viewer* or similar tools that are part of the native ECAT environment.

2.1.2 External DAQ Based Acquisition

Although the discussed *Shared Storage Device* solution accesses data considerably faster, the PET system still has to be explicitly switched into another acquisition mode prior to each *list-mode* acquisition. This results not only in a delay, but represents another source for potential stability problems. Also it requires a manual change of patient database entries in the ECAT environment once the data has been successfully transfered. This, of course is not practical for clinical PET. Furthermore, no predefined *list-mode* acquisition protocols exist. To improve this situation, we carried out a more detailed analysis of the particular hardware components which are responsible for processing the raw coincidence data on the ACS2 until the data is saved on the storage device.

The hardware of the ACS2 is based on the *Versa Modular Eurocard* (VME) standard [9] and consists of several different VME modules. These modules are all internally connected and communicate through a standard *VMEbus*. In addition to the *VMEbus*, the ACS2 contains an additional proprietary data bus. This bus connects the main VME modules and routes the raw coincidence information from the scanner gantry through externally accessible data cables (Fig. 5). These cables have 32 data channels and carry digital signals based on the *Transitor-Transitor-Logic* (TTL) standard. Starting at the *fiberoptic module* (M1), the raw fiberoptic data from the PET gantry is converted into electrical TTL signals. In a next step, the data channels are routed until they pass a *rod converter module* (M2). From there, they are either routed to the *hardware coincidence sorter*, or to a separate *read/write module* (M3). If running in *histogram-mode*, the coincidence data is sorted online via the hardware sorter into

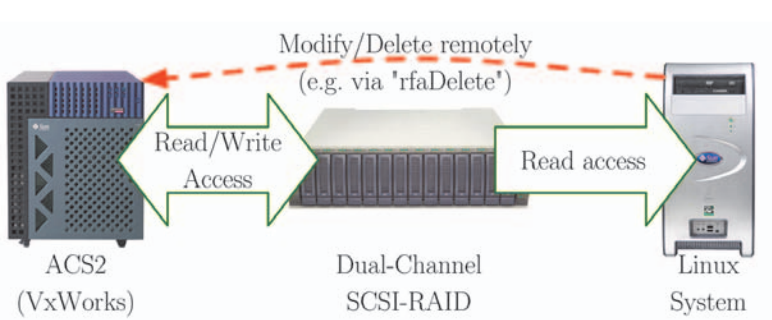

Figure 4 Because of caching policies of the filesystem a simultaneous write access to the shared storage device is not possible. However, access to the acquisition data can be provided through read-only access. Thus, after having transfered the data, the Linux system controls the ACS2 via remote control procedures, e.g. delete data via a network based remote control procedure.

a sinogram. Otherwise, if running in *list-mode*, the raw data is directly stored by the *read/write module* into *list-mode* compliant files [10].

We verified the routing of the raw coincidence data by sampling it using a digital oscilloscope, and we were able to identify the different existing events of a *list-mode* stream. During this verification process we also found that even if the PET scanner is running in standard *histogram-mode*, the external data cables carry a *list-mode* data stream.

To retrieve the coincidence data from the cables of the data bus without imposing any risk on the ACS2, we have developed a separate hardware adapter card in cooperation with *Seiler IT Services* [11]. This adapter uses optoelectronic couplers to isolate the ACS2's own circuits while routing the data signals to a separate passive connector.

In order to transfer the data from the adapter card to a computer system, we connected PCI based digital data acquisition cards (DAQ) installed in a Linux system to the passive end of the optoelectronic adapter (Fig. 6). This commercially available DAQ solution (two combined MI-7020 cards) supports the acquisition of 32 digital TTL signals in parallel, and the synchronization of the signals with an external clocking source [12]. The external clocking is required because the ACS2 itself uses an asymmetric clocking for transferring the coincidence data through the external data bus. On each positive clocking edge, the data of the 32 channels is obtained and corresponds to a 32-bit wide data word of an actual *list-mode* stream.

To permanently acquire *list-mode* data through the discussed DAQ solution, we have developed several software components. These components allow to access and to convert the obtained digital data into a *list-mode* stream. This permits to either use the standard binning methods to process the data and prepare it for image reconstruction instantly, or to apply post-processing methods to modify the data before image reconstruction, e.g. applying an event-driven *cardiac/respiration gating*.

The consistency of the externally acquired *list-mode* data was verified with different test acquisitions on the ECAT Exact HR^+. In three different *list-mode* acquisitions we stepwise increased the overall amount of local radioactivity until it reached the threshold where the PET system itself had to drop coincidences due to the high load. After having acquired the data from both the ACS2's own storage device and the DAQ solution, we compared the two data sets and found no relevant differences. In fact, because of the internals and hardware limitations of the used DAQ cards, a practically and statistically negligible amount of approximately 4 to 6 coincidences out of several hundred million per data acquisition were dropped.

As indicated earlier, the presented DAQ solution also enables us to obtain *list-mode* data if running in conventional *histogram-mode*. Unfortunately, while running in that mode, the ACS2 does not insert any timing information into the external data stream. To overcome this limitation, we modified our DAQ acquisition software to generate own *list-mode* compliant time words. Based on the fact that the used DAQ cards need a certain amount of time to fill their internal data buffers and on the current acquisition count rate, our software inserts generated time words in the data

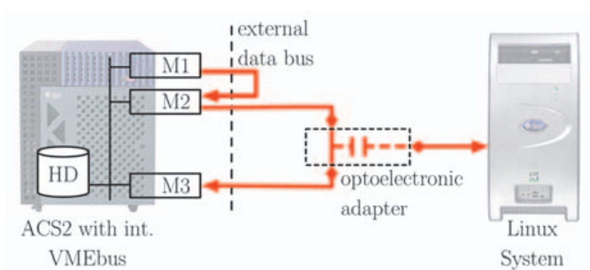

Figure 5 Schematic view of the ACS2 and its VME components. The raw coincidence data (continuous line) is routed through an external data bus through different VME modules (M1–M3) until is is saved to the internal hard disk (HD). By using an adapter with optoelectronic couplers, the data can be passively sampled and forwarded to another system directly from the bus, without interfering normal ACS2 operations.

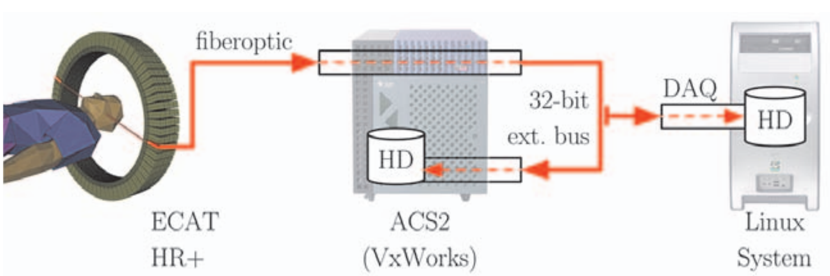

Figure 6 Data flow of the acquisition data. A digital acquisition card (DAQ) is used in a Linux system to acquire the raw data in parallel and to save it to a hard disk (HD) device. During histogram-mode or list-mode acquisition, this allows to obtain data in real-time from the 32-bit acquisition bus of the ACS2. Furthermore, it permits to permanently keep the PET system in histogram-mode and transparently acquire list-mode data through the DAQ solution.

stream. This, in turn, allows us to use the externally retrieved data in the same way as normal *list-mode* data; for example, binning it into standard sinograms with a multiple framing scheme.

2.2 Optimized Data Processing Procedures

A major obstacle for the integration of *list-mode* into clinical PET is the lack of native software tools to process the *list-mode* data. In addition to the aforementioned hardware limitations, this particular software limitation is one of the main reasons why the application of *list-mode* has been neglected in the past.

To improve the situation, we have developed data processing tools to initiate, process, and work on *list-mode* data, and to prepare it for the conventional sinogram based image reconstruction. Furthermore, in order to fully utilize *list-mode*, we have developed an optimized version of an event-driven movement correction method presented in [1]. These processing tools and methods are presented in this section to illustrate the potentials of *list-mode*, and to emphasize the necessity of the discussed hardware optimizations.

2.2.1 Acquisition Tools

On most PET systems, a direct *list-mode* acquisition can not be initiated from the native acquisition environment. For example, on an ECAT Exact HR$^+$ a *list-mode* acquisition is initiated by manually executing modified shell scripts instead of using the scanner's own acquisition environment. Therefore, we have developed a *Qt4* [13] based graphical software application that is automatically executed on the ECAT acquisition workstation. The application is invoked by a standard acquisition protocol block right after a processed transmission. It retrieves all patient relevant data from the transmission file and requests acquisition relevant data from the user. After user confirmation, the application executes all necessary steps to setup the PET scanner for *list-mode* acquisition. When the acquisition is finished, the application initiates the required binning of the *list-mode* data into a sinogram file. This sinogram is then used in the image producing reconstruction process of the PET system is achieved.

The process of initiating a *list-mode* acquisition and sorting its data afterwards is not only done semi-automatic, but also controlled via standard tools provided by the native acquisition environment.

2.2.2 List Mode Data Binning

In order to make use of an event-driven *list-mode* acquisition, it is necessary to be able to sort the encoded coincidence information into a sinogram file. This allows for the application of standard reconstruction algorithms shipped with the PET scanner. Thus a better integration into the whole acquisition process.

In previous studies [14] we have developed a method that decodes the coincidence information of the continuous *list-mode* stream and sorts it into conventional ECAT7 sinogram files. In contrast to the ACS2's own hardware coincidence sorter (VSB sorter), this software based method sorts *list-mode* data considerably faster. Moreover, the implemented *gating* support of the developed methods allows to take external trigger signals, e.g. from an electrocardiogram (ECG), into account.

According to this study we improved these methods and re-implemented the utilized sorting algorithms to take advantage of multiprocessor systems, resulting in a general speed-up for studies with a large number of dynamic frames. Furthermore, we have developed a graphical user interface and ported the application to all major platforms like Linux, MacOSX, Solaris etc. for an easier and more intuitive processing of the *list-mode* data on different operating systems. In addition and to support the discussed hardware based *list-mode* acquisition methods (DAQ solution), we also implemented procedures for the automatic sorting/binning of *list-mode* data right after the hardware acquisition took place.

2.2.3 Event-Driven Movement Correction

In previous studies [1] we have developed an event-driven movement correction method for the compensation of potential influences of patient motion during PET examinations. We showed that our *list-mode* based correction method is able to improve the image quality considerably due to a complete reorientation of every single *Line of Response* (LOR) in accordance to motion data provided by an external motion tracking device.

The presented method, however, had the drawback that for a complete reorientation of a typically one hour lasting PET acquisition, even modern computer systems required approximately 20 hours for applying the movement correction.

To improve this, we revised the involved movement correction algorithms and re-implemented them to utilize modern multiprocessor systems [15]. By analyzing the different dependencies of the algorithms, we were able to split the computations in independently executable sub computations. This enabled us to distribute the involved steps across all available processors of a computer system. For dynamic studies with a large number of frames, this results in a high speed-up. In practice, we were able to improve the processing time by an average factor of 9 to 20 for the reorientation of *list-mode* data that was created during an one hour lasting PET study (Table 1). In fact, in comparison to the old sequential implementation, this parallel re-implementation processes a *list-mode* based movement correction in about one hour.

Table 1 Optimized Movement Correction Procedures.

	Sequential	Parallel	Speed-up (∅)
Single frame study	≈27 h	≈3 h	9×
Multi frame study	≈20 h	≈1 h	20×

3 Results and Discussion

The presented methods facilitate *list-mode* acquisitions considerably. The hardware based acquisition methods overcome certain long-term hardware limitations of the acquisition control system (ACS2) of the ECAT Exact HR^+ PET Scanner series.

After having verified the operation of the *Shared Storage Device* solution under routine conditions, we were able to observe a high speed-up of the transfer of acquisition data to other computer systems. It allows to transfer stored data from the ACS2 to another system with a maximum throughput of ≈70 MB/s, a 140× speed-up in comparison to the ACS2's original capabilities. For *list-mode* acquisitions such a speed improvement means that a data transfer requires only ≈1 minute in contrast to the previously ≈2.5 hours for a typical amount of ≈4 GB of the acquired data (one hour ^{18}F-FDG @ ≈330 MBq). In addition, the immediate transfer of the acquired data also improves the general runtime stability of the ACS2. The possibility to immediately transfer all acquired data off the ACS2's storage device improves the stability of parallel accesses to the ACS2. Other processes accessing previously acquired data (e.g. visualization tools such as the *ECAT Volume Viewer*) also profit from the optimized access method. By having the acquired data available directly on the acquisition workstation right after the actual acquisition has terminated, enables these tools to access the data more quickly. Especially without having to wait for the data to be accessed through the slow network connection of the ACS2. Even for large acquisition data (e.g. sinograms with a large number of frames) this results in an instant access to the requested data, and thus is also attractive for conventional *histogram-mode* acquisitions.

Moreover, in combination with the presented *External DAQ Based Acquisition* solution, *list-mode* data can even be acquired and processed in real-time. That is because the ACS2 always transfers the raw coincidence data in the *list-mode* format over an external data bus. By using our DAQ solution, the ECAT Exact HR^+ can be operated in conventional *histogram-mode*, while a concurrently running Linux system reads out the raw *list-mode* stream in real-time. In addition to the instant access to the acquisition data, this has another positive impact on the runtime stability of the ACS2 due to the omission of the acquisition mode switching process. Furthermore, it allows us to use the default data processing environment of the PET system instead of having to use custom shell scripts to acquire the *list-mode* data. Although our DAQ solution requires a direct interaction with the ACS2 hardware, an interference with the ACS2's own operations is avoided. The hardware adapter works fully electrically isolated through optoelectronic components. This allows for the passive sampling and forwarding of the raw coincidence data from the external data bus of the ACS2 without imposing any risk to interfere with the standard hardware of the PET scanner. By being able to acquire a sinogram and *list-mode* file in parallel, a physician may base his first evaluation of the patient's data on the sinogram produced in conventional *histogram-mode*. Then, in a second step the physician may take the *list-mode* data into consideration, after having it modified with mentioned post processing methods. This represents an interesting new possibility for PET acquisitions. It also increases the examination flexibility of PET facilities because it provides both *list-mode* and *histogram-mode* acquisitions in parallel, without additional drawbacks.

In addition to the hardware based *list-mode* acquisition solutions, our developed data processing software illustrates the potential and the necessity of *list-mode* in general. Our *Qt4* application for initiating a *list-mode* acquisition out of the standard scanner environment allows us to deal with *list-mode* more intuitively than by having to execute all necessary acquisition steps manually. Furthermore, our optimized *list-mode* binning software, in addition to its multiprocessor capabilities, efficiently sorts the coincidence information into standard ECAT7 sinogram files. By using this approach, *list-mode* data is converted immediately into the PET scanner's native histogram format. This is required and allows to use conventional image reconstruction procedures of the scanner environment.

In combination with the presented hardware optimizations, our methods enable us to acquire, transfer, alter and finally sort *list-mode* data into standardized ECAT files. Our optimized event-driven movement correction procedures demonstrate the utilization of *list-mode* acquisitions in general. Being able to spatially re-orientate every single coincidence line within an acceptable time frame provides physicians with better images in spite of significant patient motion.

4 Conclusion

The improved stability, the data transfer speed-up due to our *Shared Disk Storage* solution, and the better integration of *list-mode* due to the *External DAQ Based Acquisition* solution solves important limiting issues of commonly used PET systems. In combination with our software solutions, the presented methods permit to use *list-mode* in clinical PET, especially with an ECAT Exact HR^+ PET scanner. This increases the overall flexibility and efficiency of PET facilities because integrating *list-mode*-based services provides physicians with a more accurate and flexible imaging process. In addition, our hardware and software optimizations also improve the stability and handling of standard *histogram-mode* acquisitions. Therefore, facilities using ACS2 based scanners may benefit from an implementation of the presented methods even if they are not using *list-mode*.

Although not part of this study, an adaptation of our methods to similar PET systems (e.g. ECAT Exact) may be an interesting enhancement and is principally possible if the system also uses the ACS2. As a consequence and experience of our study, PET scanner designs should provide more enhanced implementations of *list-mode* and their data access methods in future. Depending on the maximum count rate at which a PET system is able to acquire data, it must provide a sufficiently fast access method to the data. Otherwise the usability and benefits of *list-mode* on such systems are at risk.

As our study demonstrates, a seamless integration and processing of *list-mode* is desirable, possible, and not only available for forthcoming systems. Even for today's PET systems, such an integration is feasible, relatively inexpensive, and offers significant advantages.

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References

[1] Bühler, P., Just, U., Will, E., Kotzerke, J., van den Hoff, J.: An Accurate Method for Correction of Head Movement in PET. IEEE Trans Med Imag **23** (2004) 1176–1185

[2] Rahmim, A., Bloomfield, P., Houle, S., Lenox, M., Michel, C., Buckley, K., Ruth, T., Sossi, V.: Motion Compensation in Histogram-Mode and List-Mode EM Reconstructions: Beyond the Event-Driven Approach. IEEE Trans Nucl Science **51** (2004) 2588–2596

[3] Nichols, T., et al.: "HR$^+$ List Mode Format," 1998, technical note, unpublished

[4] The VxWorks 5.x Operating System, Wind River, Inc., 2005. [Online]. Available: http://www.windriver.com/

[5] SCSI-2 Standard Specification, ANSI Std. X3.131-1994, 1994

[6] FAT32 File System Specification, Microsoft, Inc., 2005. [Online]. Available: http://www.microsoft.com/whdc/system/platform/firmware/fatgen.mspx

[7] Langner, J., et al.: A reverse engineered implementation of the VxWorks 5.2+ extended DOS filesystem for Linux kernels 2.6+. 2005, [Online]. Available: http://www.jens-langner.de/vxext_fs/

[8] Langner, J.: Dateisysteme: FUSE, VXEXT und JFFS. Linux Magazin **06/05** (2005) 20, ISSN 1432-640X

[9] VME Standard Specification, IEEE Std. 1014-1987, IEC821, 1987

[10] ECAT EXACT HR$^+$ ACS2 Service Manual, Part Number 35 49 743 Rev. 01, Siemens Medical Systems, Inc., Knoxville, TN, 1996

[11] Specialized Hardware Developments, Seiler IT Services, Ungerstrasse 3, 30451 Hannover, Germany, 2005

[12] The MI-70xx Digital Acquisition Cards, Spectrum Mikroelektronik, GmbH, 2005. [Online]. Available: http://www.spec.de/

[13] Qt4 Application Framework, Trolltech AS, Norway, 2005. [Online]. Available: http://www.tolltech.com/

[14] Just, U., Will, E., Beuthien, B., Bühler, P., van den Hoff, J.: Nutzbarmachung der List-Mode Akquisition an der PET-Kamera ECAT EXACT HR. Nuklearmedizin **42** (2003) P42

[15] Langner, J.: Development of a Parallel Computing Optimized Head Movement Correction Method in Positron Emission Tomography. MSc. thesis, University of Applied Sciences Dresden and PET center Rossendorf, Dresden, Germany, Feb. 2004

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