A Relative Study on the Basic Approaches for MR based Attenuation Correction in Image Segmentation

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Abstract

To obtain quantitatively and qualitatively accurate PET images, the recorded emission data during a PET scan have to undergo different corrections. These corrections are normalization for different detector efficiencies, random and scattered coincidences, and dead time decay and tissue attenuation of the 511kev photons, which are emitted as pairs of opposing photons upon positron annihilation. There are different methods proposed so far for attenuation correction in image segmentation. The attenuation correction methods basically available are CT based Attenuation correction (CTAC), MR based Attenuation correction (MRAC), and the combination methods called Hybrid PET/CT, PET/MR, methods. In this paper MR based Attenuation Correction (AC) for PET/MR images have been taken for discussion. Various approaches has been developed based on Templates, Atlas information, Direct Segmentation of TI-Weighted MR images or Segmentation of images from special MR sequences, Transmission and Emission based methods. Each method has its own characteristics. This study is helpful for an appropriate use of existing AC methods and for improving their performance as well as for systematically designing new AC methods for reconstruction and evaluation of PET/MR images.

1. Introduction

The combination of Magnetic Resonance Imaging (MRI) and Positron Emission Tomography (PET) in hybrid systems has become a reality and such systems are currently being transformed from research prototypes into clinical systems. Hybrid PET/MR systems provide complementary multimodal information about perfusion, metabolism, receptor status, and function, together with excellent high-contrast soft tissue visualization without the need to expose the patient to additional radiation.

One of the most challenging issues of PET imaging in hybrid PET/MR systems is attenuation correction since the small bore inside MRI systems and the strong magnetic field do not allow PET transmission scans to be implemented with positron-emitting rod sources or additional computed tomography (CT)

The PET images (a)–(c) were first registered and fused (d)–(f) with the Corresponding MR images (g)–(i) that were segmented and classified into Different tissue types (j)–(l) to generate attenuation correction maps (m)–(o). devices. Thus, present solutions for PET- or CT-based transmission systems are not compatible with the MR environment. MR signal is not directly correlated to tissue density and these can't be converted by a simple transformation of intensity values .These present selection for PET or CT based transmission systems are not compatible with MR environment qualitative PET errors which could compromise diagnostic accuracy.

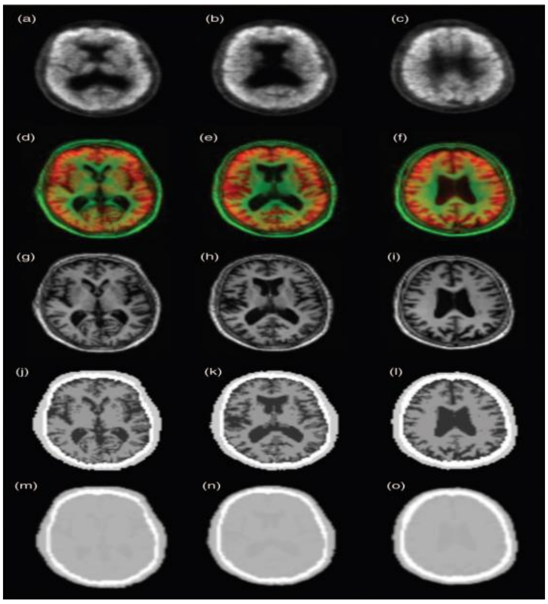

FIG. 1. Data flow for the generation of attenuation correction maps.

Attenuation correction can be performed in two different ways. One way is to pre-correct the measured emission data with the attenuation factors. These factors (attenuation correction factors (ACF)) can be derived from a transmission scan in PET-only scanners (nowadays practically obsolete, but still used in small animal PET) or by forward projecting the attenuation map (l-map), which represents the spatial distribution of the attenuation coefficient, into sinograms. The second method of correcting for tissue attenuation is to incorporate the knowledge on the l-map directly into the iterative reconstruction as, for example, the 3D attenuation-weighted ordered subset expectation maximization (OSEM) algorithm.

2. Challenges in attenuation correction for PET/MR

There are hardware constraints, which mainly apply to transmission-based or CT-based attenuation correction. Because these methods require an external acquisition system for the acquisition of the attenuation maps. Time constraints are an issue because one aims to use as little time as possible to acquire the attenuation map. Time may be an issue in transmission-based methods or in MR-based methods, which require the acquisition of specific MR images to determine the attenuation map.

An issue that is specific to MR-based methods is that there is no direct correlation between MR image intensity and electron density. Therefore, a direct conversion from an MR image to the attenuation map is difficult. An attenuation map should include not only the patient but also all of the other objects inside the PET scanner.

Thus, in PET/MR, the patient table and RF coils should also be included. The attenuation caused by the RF coils can be significant because the coils can be quite large and include metallic parts. This problem is often addressed by including a template of the coil in the attenuation map. Another issue may be caused by truncation of the attenuation map due to the limited field of view of CT and MR.

Another issue specific to MR-based attenuation correction is that a mismatch between PET and MR may cause an incorrect attenuation map and lead to incorrect attenuation correction.

A mismatch could be caused by geometric distortions of MR images. These distortions may result from static field in homogeneities or from dynamic field in homogeneities caused by gradient-field nonlinearities.

3. MR-based attenuation correction approaches

MR-based attenuation correction (AC) approaches consist of distinguishing the regions with different attenuation properties, assigning the correct linear attenuation coefficients to them and utilizing the resultant attenuation map to correct the PET emission data during reconstruction. MR-based approaches were first developed for multimodal PET/MR acquisitions of the brain.

The MR based four categories can be distinguished as: template based, atlas-based and direct segmentation approaches, and methods based on special bone-representing sequences.

3.1Template Based Approach:

This method is actually a solution to reduce the long acquisition time that is required for a transmission measurements in stand- alone brain PET image .Here a T_1weighted image which is used as a template instead of a non-corrected PET image. So that higher resolution of the MR image or template can be obtained. In this method an attenuation template is the formation of average image from available number of transmission scans. In this approach the advantage is high anatomical variability, pathologies and deformable organs or organ motion. So this approach is not mostly used for whole-body application.

3.2Voxel Based Approach:

In this approach the attenuation map can be formed from local information alone. In this approach there is a possibility of conversion of MR image intensities in to attenuation coefficient and direct correlation between MR image intensity and attenuation coefficient. Attenuation maps can be obtained directly based on histogram matching but with more artifacts. So, few approaches have been introduced as intermediate steps like image segmentation and tissue classification. The main drawback is the differentiation of tissue types and their intensities. In this approach the attenuation coefficient of a voxel in the MR image is formed from the information of the voxel using the image segmentation approach. The strength of this approach is its ability of the segmentation algorithm to differentiate the tissue types. The disadvantage is this approach is more sensitive to truncate some information in deriving the attenuation map by not considering the arms as this approach takes only the local information. This disadvantage can be overcome by using PET-pre reconstruction to extract the body surface as a mean of active contour methods.

3.3Transmission Based Approach:

This approach is helpful to find the attenuation coefficient of all the objects inside the FOV without any template or prior knowledge. Both the emission and transmission images are necessary to PET or MR to avoid the loss of acquisition time in deriving the attenuation map. The disadvantage is that this approach can be applicable to only simulation data and not in clinical practice another disadvantage is low statistical quality and resolution of the images.

3.4Emission Based Approach:

In this approach the attenuation map is formed directly from the emission or reconstructed data, so that it can be applicable to any PET/MR systems. Three techniques have been used in this approach

(1) In this approach the segmentation technique is used to form the cluster of voxels from the uncorrected emission images to an almost constant attenuation for which tissue dependent attenuation coefficient is assigned.

(2) Attenuation coefficient can also be obtained from the emission projections using the reconstruction of the activity and attenuation distributions at the same time.
(3) The third technique it derives the attenuation coefficient by using some consistency conditions.

The advantage in this approach is the stableness of the algorithm and accuracy of the connected regions obtained from the MR images. The disadvantage is the cross talk between the emission and attenuation that decreases the robustness. The problem can be overcome by using the prior knowledge in the form of connected regions from the MR images.

3.5Atlas Based Approach:

This approach uses the prior global anatomical knowledge and regional information as a combination to derive the attenuation map. It uses the T_1 weighted MR image and available number of reference MR-CT data set as the atlas .In order to overcome the local imperfections raised because of registration facilities and combined atlas-classification based method is used. The disadvantage is the computation time is long in whole-body imaging and attenuation values are taken on a continuous scale. But the advantage is the truncation artifacts can be removed.

3.6 Segmentation Based Approach:

In this approach the same attenuation coefficients for a particular tissue of all patients is assigned. So classification error may be possible to occur. This method is used to discriminate air, lung, soft tissues, spongious bone and cortical bone. The direct segmentation based approach works directly on T_1 weighted images. The disadvantage is no segmentation method will account for inter patient variability of the lung tissue attenuation coefficient. The important aspect of this approach is differentiating bone tissue from air-filled cavities as they have same intensity range and is the most demand in the clinical routine. Ignorance of cortical bone will lead to a quantification error. So the Ultra Sound Echo Time (UTE) is introduced.

3.7 Sequence Based Approach:

3.7.1Dixon Sequence for water (fat) Separation:

This technique depends on the frequency difference between protons in water and fat molecules to achieve water and fat images frame set of MR images acquired at different echo times. The difference in bone and soft tissue attenuation coefficient is fully omitted in this method. Advantage of this approach is that it uses the standard MR images can be acquired quickly for the whole body within few minutes.

3.7.2UTE-MR Sequence:

UTE also named as Dual Echo Sequences and is designed to visualize tissues with minimum relaxation times. UTE -MR image the other method is called Gaussian mixture regression model, which is used as a substitute CT for 3 different MR sequences. Advantage of this method is no segmentation is performed, so an attenuation map with continuous values and a whole – body attenuation map in the absence of prior knowledge can be obtained. To overcome this problem in Dixon sequences the discrimination of air, lung and cortical bone based on the image intensity of a single voxel is considered. Disadvantage of the UTE is the acquisition time of current UTE sequence is too long within a reasonable time frame.

4. Methods to Evaluate, Assess and Compare MR-based AC methods:

(1) The MR based attenuation map and or the segmented MR image should be compared to a gold standard image and local errors should be examined.

(2) The resultant attenuation corrected PET image should be compared to a reference attenuation corrected PET image. Sample size is the major problem in evaluating MR based images. To overcome this trimodality system can be used.

In this paper a brief description of these approaches are given as a literature survey below as the **previous work done.**

LITERATURE SURVEY

[1] The author J. Teuho1, J. Tuisku1, J. Linden1, 2 and M. Teräs3, 4, et.al (2018) proposed a MR-based attenuation correction method to improve the accuracy of attenuation maps and the assessment of regional PET quantification. **[2]**The author J. Teuho*, J. Tuisku, A. Karlsson, J. Linden and M. Teräs, et.al (2017) proposed a method to evaluate the effect of brain tissue and implemented continues template based skull for MR based attenuation coefficient (MRAC). **[3]** Thorsten Heußer, Christopher M. Rank, Martin T. Freitag, Antonia Dimitrakopoulou-Strauss, Heinz-Peter Schlemmer, Thomas Beyer, and Marc Kachelrieß (2016) et.al proposed an algorithm for attenuation correction which reconstructs activity and attenuation distribution from PET emission data using available MR images as anatomical prior information. **[4]** Elena Rota Kops, Hubertus Hautzel, Hans Herzog, *Member*, IEEE, Gerald Antoch, and N. Jon Shah (2015) et.al, proposed a method to compare the basic difference between template and CT based AC methods and their influence on reconstructed PET images. **[5]** Abolfazl Mehranian, *Student Member*, *IEEE*, and Habib Zaidi*, Senior Member, IEEE (2015), et.al proposed an algorithm MLAA for emission based attenuation correction method in whole – body PET/MR imaging. **[6]** J. Teuho, J. Linden, J. Johansson, J. Tuisku, T. Tuokkola, and M. Teräs, Member, IEEE,(2015) et.al Proposed a Tissue probability based attenuation correction method which employs the commonly available neurological toolbox SPM8, to derive a subject – specific µ - map by segmentation of t1 weighted MR images. **[7]** Ahmadreza Rezaei*, Michel Defrise, and Johan Nuyts (2014) et.al, proposed a maximum likelihood reconstruction algorithm that jointly estimates the activity image together with the sonogram of the attenuation factors**.** **[8]** Ninon Burgos*, M. Jorge Cardoso, Kris Thielemans, Marc Modat, Stefano Pedemonte, John Dickson, Anna Barnes, Rebekah Ahmed, Colin J. Mahoney, Jonathan M. Schott, John S. Duncan, David Atkinson, Simon R. Arridge, Brian F. Hutton, and Sébastien Ourselin (2014) et.al proposed a method to improve attenuation correction for PET/MR scanners by generating synthetic CTs and attenuation maps**.** **[9]** Jinsong Ouyang, *Senior Member*, *IEEE*, Se Young Chun, *Member*, *IEEE*, Yoann Petibon, Ali A. Bonab, Nathaniel Alpert, and Georges El Fakhri, Senior Member, IEEE (2013) et.al, proposed a method voxel-wise PET accuracy and precision using tissue segmentation for attenuation correction. **[10]** S. D. Wollenweber, *Senior Member*, *IEEE*, S. Ambwani, A. H. R. Lonn, D. D. Shanbhag, S. Thiruvenkadam,S. Kaushik, R. Mullick, H. Qian, G. Delso, and F. Wiesinger (2013)et.al, proposed a method with continuous variation in attenuation correction factor (ACF) between fat and water. **[11]** Ahmadreza Rezaei*, Michel Defrise, Girish Bal, Christian Michel, Maurizio Conti, Charles Watson, and Johan Nuyts (2012) et.al, proposed a maximum –a- posterior reconstruction algorithm for jointly estimating the attenuation and activity distribution from TOF PET data. **[12]**Pieter Mollet*, Vincent Keereman, Enrico Clementel, and Stefaan Vandenberghe (2012) et.al, proposed a method to derive the attenuation map and the emission data from a simultaneous scan without prior knowledge about the anatomy or the attenuation coefficients of the tissues. **[13]** Sangeetha Somayajula, Christos Panagiotou, Anand Rangarajan, Quanzheng Li, Simon R. Arridge, and Richard M. Leahy*(2011) et.al proposed a method a scale space based framework for incorporating anatomical information into PET image reconstruction using information theoretic priors. **[14]** André Salomon*, Andreas Goedicke, Bernd Schweizer, Til Aach, *Senior Member*, *IEEE*, and Volkmar Schulz (2011)et.al, proposed a generic iterative reconstruction approach to simultaneously estimate the local tracer concentration and the attenuation distribution using the segmented MR image as anatomical reference. **[15]** Mert R. Sabuncu*, B. T.

Thomas Yeo, Koen Van Leemput, Bruce Fischl, and Polina Golland (2010)et.al, proposed a probabilistic modeling frame work to develop automatic segmentation tools that delineate anatomical regions of interest in a novel medical image scan. **[16]** John M. M. Anderson, *Senior Member*, *IEEE*, Yoon-Chul Kim, and John R. Votaw(2009) et.al, proposed a concurrent segmentation and estimation algorithm for in corporating accurate attenuation coefficients. **[17]** Chuanyong Bai, *Member*, *IEEE*, Ling Shao, *Member, IEEE*, Angela J. Da Silva, and Zuo Zhao (2003) et.al, proposed a general model for the conversion from CT numbers to linear attenuation coefficients then use the water- A-assumption for the composition of biological tissues that is similar to simplify the model. **[18]** Andrzej Krol*, James E. Bowsher, Stephen H. Manglos, David H. Feiglin, Martin P. Tornai, and F. Deaver Thomas (2001) et.al, proposed a EM-INTRA SPECT for simultaneously estimating single photon emission computed tomography emission and attenuation parameters for emission data alone **[19]** Andrew Bromiley, Andrew Welch, Felice Chilcott, Smruti Waikar, Stephen McCallum, Maurice Dodd, Stuart Craib, Lutz Schweiger, and Peter Sharp (2001)et.al, proposed a template correction method to produce a useful attenuation correction in situations where either it is impractical to acquire transmission data or there is significant misregistration between the transmission and emission data. **[20]** Andrei V. Bronnikov (2000) et.al, proposed a method based on discrete consistency conditions, which can easily be applied in various scanning configurations, including fully 3-D data acquisition protocols.

Overview of the categories of attenuation correction methods which were discussed in this paper, with their respective advantages and drawbacks is given in the table

SI.No	PAPER	METHOD	PARAMETER	ADVANTAGES	DISADVANTAGES
1	Effect of sinus attenuation in MR-based attenuation correction in 18F-FDG brain PET/MR(2018)	MR-based attenuation correction method(MRAC)	To improve attenuation maps	MRAC can be conducted for without a specific tissue class for the sinuses.	---
2	Effect of brain tissue and continuous template-based in MR–based attenuation correction for brain PET/MR(2017)	MR–based attenuation correction(MRAC) for discrete & continuous skull methods	Attenuation co-efficient for Brain	Quantitative evaluation of PET images by VOI analysis, no large difference was seen between the discrete skull & continuous skull methods	Only the variation of the bone density of the skull is taken into account while individual is neglected which reduces the benefit of having continues attenuation –co – efficient. Continuous bone value is limited due to poorer correspondence of individual anatomy.
3	MR _Consistent Simultaneous Reconstruction of Attenuation and Activity for Non _TOF PET/MR (2016)	MR-based Maximum – Likelihood Reconstruction of Attenuation and Activity(MR-MLAA)	Reconstruction activity & attenuation correction	Predefined attenuation values for air, bone and soft tissues to occur in the reconstruction attenuation map to reduce the cross talk between attenuation & activity. Achieves almost complete detection of bone attenuation information, in contrast to standard MRAC images are used, so no additional acquisition time is necessary.	Optimality is very much application dependent and therefore need to involve humans that analyze the images. So results must be carefully interpreted. Simulation technique used limits the physical accuracy of the simulated emission data.
4	Comparison of Template-Based Versus CT-Based Attenuation Correction For Hybrid MR/PET Scanners.(2015)	Transmission template –based method for attenuation correction method.	Dice coefficients of bone and soft tissue.	Higher resolution CT-Based Attenuation Map with respect to dice coefficients in classification of bone and soft tissues.	---

5	Joint Estimation of Activity and Attenuation in Whole-Body TOF PET/MR Using Constrained Gaussian Mixture Models.(2015)	Maximum Likelihood Reconstruction of Attenuation and Activity (MLAA) algorithm for Emission –Based Attenuation Correction method.	Attenuation Coefficient	Cross talk is suppressed and scaling problem of activity and attenuation is reduced, thus improving quantitative accuracy.	---
6	Tissue Probability – Based Attenuation Correction for Brain PET/MR BY Using SPM8(2015)	Tissue Probability – Based Attenuation Correction (TPB-AC)	Visual quality & quantitative accuracy of mean & standard derivation	An individual attenuation map can be created, solely from a single MR sequence. This method is simple, modifiable and computationally efficient.	Deformed anatomy generally poses a problem with template based method. TPB-AC is not entirely comparable due to the differences in deriving the final µ-map. TPB-AC is less robust when anatomy is deformed or when MRI images have areas of void signal due to metal implants.
7	ML-Reconstruction for TOF-PET With Simultaneous Estimation of the Attenuation Factors(2014)	Maximum Likelihood Algorithm (MLACF) algorithm for emission – based attenuation correction method.	Estimate the activity image and attenuation factors.	It avoids the reconstruction of the attenuation image and thus requires some a prior knowledge about the activity or the attenuation factors to be quantitatively accurate. Very robust against variations in detector pair sensitivities. In 3-D simulation MLAA iteration computation time is 2.5 times longer than MLACF.	MLACF is noisier than MLAA algorithm. It does not impose consistency to the estimate attenuation factors.
8	Attenuation Correction Synthesis for Hybrid PET-MR Scanners : Application to Brain Studies(2014)	Multi-Atlas Information Propagation Scheme for attenuation correction method	To improve Attenuation correction, Average, Standard deviation.	Significant improvement in CT synthesis and PET reconstruction accuracy when compared to segmentation method using an ultrasound –echo-time-MRI sequence and to simplified Atlas-Based methods. This method relies on the morphological similarity rather than the assumption of one-to-one intensity mapping between MRI and CT. Does not require any segmentation of MRI images and thus allows the synthesis of a continuous valued attenuation map and avoids large misclassifications	Due to limited anatomical information of CT and T1-Weighted MRI images
9	Bias Atlases for Segmentation – Based PET Attenuation Correction Using PET-CT and MR(2013)	Tissue Segmentation based attenuation correction method.	Mean and Standard Deviation	Inter and Intra- patient lung density variations contribute almost equally to the overall standard deviation of bias within the lungs.	_
10	Comparison of 4-Class and	MR-Based attenuation	Mean standard uptake values	Improves overall quantitation accuracy of	The use of a tri-modality setup for comparison of

	Continuous Fat/Water Methods for Whole – body , MR-Based PET Attenuation Correction(2013)	correction 4-class method		MR-AC.	AC methods was the difficulty in characterizing differences in patient registration and respiration state between the CT and MR imaging. Difficult to predict in patients how AC errors may manifest, emphasizing the need to simply have as accurate an attenuation estimation as possible when using an MR-based AC method.
11	Simultaneous Reconstruction of Activity and Attenuation in Time –of-Flight PET(2012)	Maximum-a-Posteriori reconstruction algorithm for attenuation correction method	Attenuation image is estimated	The utilization of Time-of-Flight in simultaneous reconstruction eliminates the problem of activity and attenuation cross talk. It also increases the time resolution and convergence and it is robust to noise.	The limited prior knowledge is required because the solution is only determined up to a constant.
12	Simultaneous MR-Compatible Emission and Transmission Imaging for PET Using Time-of-Flight Information(2012)	Emission –based attenuation correction method to derive attenuation map for transmission scan.	Attenuation coefficients	The random and scatter will increase the noise and decrease contrast yielding less accurate attenuation coefficients. This is reduced by estimating random using delayed window method	–
13	PET Image Reconstruction Using Information Theoretic Anatomical Priors(2011)	Space based theory that provides the frame work for analysis of the image	Computing the priors and their derivatives to reduce the complexity	Improved the behavior of the information theoretic priors and gave better overall quantitative accuracy. The scale – space based approach is the solution to the non-spatial nature of the theoretic measures as priors in PET reconstruction.	The scale – space based information are non-convexity of the priors and tendency to unpredictable solutions for high values of hyper parameters.
14	Simultaneous Reconstruction of Activity for PET/MR(2011)	Generic Iterative Reconstruction method	Absolute Mean Difference	Implementation of this method does not require any calibration of the PET facilities. The method can be improved or adapted to any 3D image modality whom the data to be segmented are in hyper signal. Partial volume errors are partially compensated by the attenuation values estimated instead of being strengthened as in tabular methods which tend to generate high local derivatives in the attenuation coefficient near tissue boundaries,	Some details could not be reconstructed correctly such as the attenuation of the ribs due to the respiratory motion during the PET scan. The attenuation estimate in the cranial bone contained inaccurate values caused by slight misalignments between the PET and MR scan of the head.
15	A Generative Model for Image Segmentation Based on Label Fusion(2010)	Generative Non parametric probabilistic model for automatic segmentation	Accuracy of the segmentation	Across subject anatomical variability is better captured than in a single atlas method. Multiple registrations improve robustness against occasional registration facilities	Computational burden introduced by the multiple registrations and information fusion from the entire training data.

16	Concurrent Segmentation and Estimation of Transmission Images for Attenuation Correction in Positron emission Tomography(2009)	Concurrent Segmentation and Estimation algorithm for segmentation based Attenuation correction method	Accurate attenuation coefficient	Estimates the proportion of each class, is more accurate than existing segmentation based attenuation correction methods because the manner by which partial volume effects are addressed is theoretically justified. It provides the correction for attenuation is that it is more consistent with the emission data than existing methods.	_
17	A Generalized Model for the Conversion CT Numbers to Linear Attenuation coefficients(2003)	Generalized Model for accurate conversion	Accurate attenuation coefficient	Requires a simple CT scan at each operational kv_p of a CT system therefore it is easy and convenient. It can also be used to characterize a CT system by obtaining the effective CT energy for each kv_p , so that the CT system can be used for absolute attenuation measurement.	
18	An EM Algorithm for Estimating SPECT Emission And Transmission Parameters from Emission Data Only(2001)	Maximum likelihood expectation maximization algorithm for attenuation correction method	Attenuation coefficient	The EM intra SPECT reconstructed attenuation images are easily distinguished and correct shapes and sizes are provided. It provides more uniform estimates of cardiac activity in the physical phantom study and in simulation study.	_
19	Attenuation Correction in PET Using Consistency Conditions and a Three Dimensional Template(2001)	Uniform template correction method	Accurate attenuation correction	Transforming a 3D template automatically prevents large variations in the object from slice to slice. There is a reduction in processing overheads since only one search need to be done, instead of one for each slice. More useful in removing m is registration errors between emission and transmission scans.	The algorithm is too unstable to allow for accurate attenuation correction without any transmission measurement.
20	Reconstruction of Attenuation Map Using Discrete Consistency Conditions(2000)	Attenuation correction method for discrete consistency conditions.	Accuracy , SVD	It provides a stable numerical implementation allowing avoiding the cross talk between the attenuation map and the source function.	

Conclusion

In this paper, an overview was provided for the challenges in attenuation correction PET/MR images and the different methods that have been proposed to overcome these challenges. MR-based methods and methods based on transmission or emission data, segmentation based methods, sequence based methods, were discussed. Although much progress has been made in the last few years, no method is currently capable for solving all of the issues. For a method to become widely accepted in clinical practice it should be completely automated and not require any intervention from the user.

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