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Image fusion in neuroradiology: Three clinical examples including MRI of Parkinson disease

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Abstract

Image data fusion has been developed over the last decade as an important additional visual diagnostic tool to integrate the growing amount of imaging data obtained from different medical imaging modalities. The overwhelming amount of digital information calls for data consolidation to improve clinical treatment strategies based upon anatomical and physiological imaging. Three different low level image data fusion techniques are described and their characteristics are illustrated with some rare yet key examples. We used MR images to show neurodegeneration in the cerebral peduncle of the midbrain and found that image data fusion using colors can be a valuable tool to visually assess and quantify the loss of neural cells in the Substantia Nigra pars compacta in Parkinson's disease.

Keywords: Image data fusion; Data consolidation; Color data fusion; Parkinson disease; MRI; SIRRIM

1. Introduction

Combinations of radiological imaging modalities are nowadays standard add-on procedures to confirm or rule out pathologies in medical diagnosis and outline treatment strategies. Though the number of publications concerning image data fusion topics has been growing exponentially over the last 10 years, its real clinical value remains somewhat elusive. A myriad of intriguing techniques makes it worthwhile to take a closer look without being biased towards one method in particular and therefore favoring one technique over another. Most medical imaging modalities are complementary which makes them suitable for data consolidation also coined as image data fusion. Nobody would argue that image data fusion can potentially assist medical diagnosis through visual enhancement of the imaging data. However, it is unclear to what extent this is really true since many methods are still in a validation process.

Radiological imaging offers the possibility to generate image fusion using the images of the same or several distinct modalities. Different imaging modalities barely ever generate redundant information. CT data for example complements MRI data which excels in distinguishing subtle variations in soft tissues while essentially not revealing any bone information. Physiological information is commonly obtained with SPECT or PET imaging which lacks anatomical details.

Data fusion can be thought of as a multimodal and multiparametric integration of data as well as longitudinal integration of single modality data. The required accurate anatomical landmarks required to perform data fusion can be obtained, e.g. using MR imaging which excels in anatomical details. Multimodal data fusion can be performed as anatomical–anatomical image fusion for example an MRI study with the corresponding T1, T2 and PD images, longitudinal studies such as MRI–MRI, CT–CT, MRI–CT and in anatomical–physiological data fusion such as MRI–SPECT, MRI–PET, CT–PET, CT–SPECT and MRI–fMRI. Some MRI studies using T1, T2 and PD images

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and MRI–SPECT data fusion cases have been reported over 10 years ago [1–4].

Data fusion cannot be carried out as long as three-dimensional data co-registration has not been performed. Intrinsic and extrinsic co-registration techniques have been extensively reported in the literature [5–16]. Data co-registration is not within the scope of the present paper. Nevertheless we are aware that co-registration of imaging data is the primary real challenge before thinking in image data fusion. Maintz and Viergever [12] have discussed extensively nine classification criteria with their respective subdivisions citing over 280 references related to the subject. Many software packages that perform co-registration are available, *inter alia* the freeware Spamalize, a software package used at the Keck Laboratory (University of Wisconsin) for *Functional Brain Imaging to Analyze and Display Image Data* [17]. Once registration between different imaging modalities or the same modality has been performed, data fusion becomes a fairly easy task dictated by anatomical and physiological considerations and some creative techniques which reflect to some extent imagination combined with a well-defined goal in mind. Image data fusion has the great advantage of not suffering of any particular restrictions, leaving therefore the end user as the judge of the results of a particular fusion technique.

Image data fusion is a rather generic terminology describing a process which can be implemented at different levels described by pixel, feature and decision level fusions [18–21]. Data fusion has been implemented using a large variety of simple and sophisticated techniques which are by no means restricted to medical imaging. Whatever one wishes to achieve, data fusion represents an intriguing add-on to medical imaging with some real practical value. In the low level image data fusion technique used herein, we deal with arithmetic integration of image data on a pixel by pixel base. Though black and white data fusion is reported [22], medical applications generally involve the use of colors in any chosen technique [19,22]. There are many approaches to combine inter- and intra-modality imaging data. All these techniques have their merits and eventual pitfalls or no gain at all. The choice of some particular fusion approach is mainly dictated by the imaging modalities themselves and *a fortiori* by the achieved quality of the fused images. In general, there is consensus that different fusion techniques can yield objective diagnostic information eventually combined with some subjective pleasant image features due to the enhancement properties of the data fusion process itself.

Our main objective is by no means to present a complete review of data fusion techniques yet rather apply some comprehensive fusion techniques to three selected neurological pathologies and discuss their respective contribution and potential importance with special emphasis on the difficult use of colors. We applied image data fusion techniques to a rare case of tuberous sclerosis (MRI and SPECT), epilepsy (MRI and SPECT) and finally to images of the cerebral peduncle (MRI) in Parkinson's disease. In particular, we will focus on some image data fusion in MR imaging of sporadic Parkinson's disease pointing out the natural difficulties encountered in the use of different color spaces. The neurodegeneration observed in the Substantia Nigra pars compacta (SN_C) in sporadic Parkinson's disease was imaged using two different inversion recovery sequences which allowed image data fusion revealing dramatically the neural cell loss by means of the achieved visual enhancement. In this last monomodality example (MR imaging of the mesencephalon) no registration was necessary since sequential imaging was performed with the immobilized patient using two different inversion recovery imaging sequences applied to the same slices.

2. Patients and methods

2.1. Patients

We have applied three different standard low level fusion techniques to three different pathologies to demonstrate the clinical potential of such image manipulations: Our first case shows a patient diagnosed with a rare genetic disease known as Bourneville's disease or tuberous sclerosis. It has been observed at any age with an incidence of 1 in 6000 to 10,000. Tuberous sclerosis appears on MRI as tumors or tuberosities. Although the multiple tumors are benign, they can develop as astrocytic tumors leading to mental retardation and spread to other organs leading to serious systemic disorders. In the present interesting case one of the tuberous sclerosis tumors lead to the development of an epileptogenic focus which appears hyperperfused in the corresponding SPECT study. EEG confirmed the localized seizure site.

Our second case illustrates image data fusion between SPECT and MR images acquired from a 17-year-old patient with partial complex epilepsy which underwent right temporal lobotomy at the age of 15 due to refractory epileptic seizures [23]. Thereafter, the patient remained stable during the following year and a half. Epilepsy relapsed at this time. Ictal SPECT images showed clearly hyperperfusion at the epileptogenic focus on the right superior temporal lobe of the brain. The MR image did not reveal anything but accurate normal morphological information.

Our third case of neurological disorders shows image data fusion of white and gray matter suppressed MR inversion recovery images of the cerebral peduncle used to visualize morphological changes observed as neural cell loss in the Substantia Nigra pars compacta (SN_C) in sporadic Parkinson's disease [24–27]. The Parkinson's patients were compared to age-matched control subjects and a disease control subject. This was the first reported direct evidence of eventual apoptotic cell loss using MR imaging in Parkinson's disease.

2.2. Methodology

Three fusion methods are presented, applied and discussed in this paper:

(a) *Color spaces*, as commonly known, true color images can be thought of as a fusion of three monochrome channels commonly labeled as RGB (red, green, blue). For whatever reason, RGB images can be transformed to any other useful color spaces for enhancement purposes, e.g. HSV, YIQ, Lab, Luv, etc. [28–30]. A more appealing non linear color system

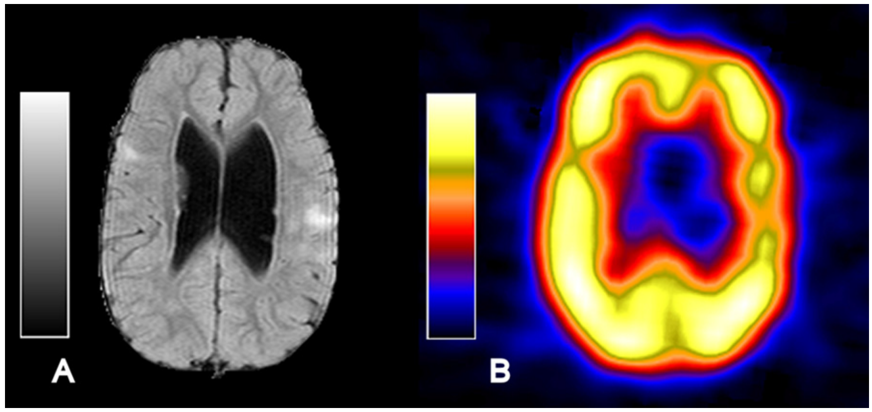

Fig. 1. MR image (A) and corregistered SPECT image (B) of a patient with tuberous sclerosis. Standard black and white (256 gray levels) is used for the MR image while the "SD GAMMA-11" color palette is used for the SPECT Tc-99m ECD (ethyl cysteinate dimer or Neurolite®) image. Co-registration was performed with proprietary ADAC® software (Image Fusion and Review v4.2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

which we have also used is known as the HSV where the hue (H) describes the wavelength enabling to distinguish one color from another, the saturation (S) describes the purity of the color and the value (V) describes the brightness of the color [28].

Images from different modalities can be inserted into any of the three R, G or B channels [22]. We have first used a simple RGB representation where the SPECT image of Fig. 1B was put into the red and blue channels while the MR image (Fig. 1A) of the same patient was loaded into the

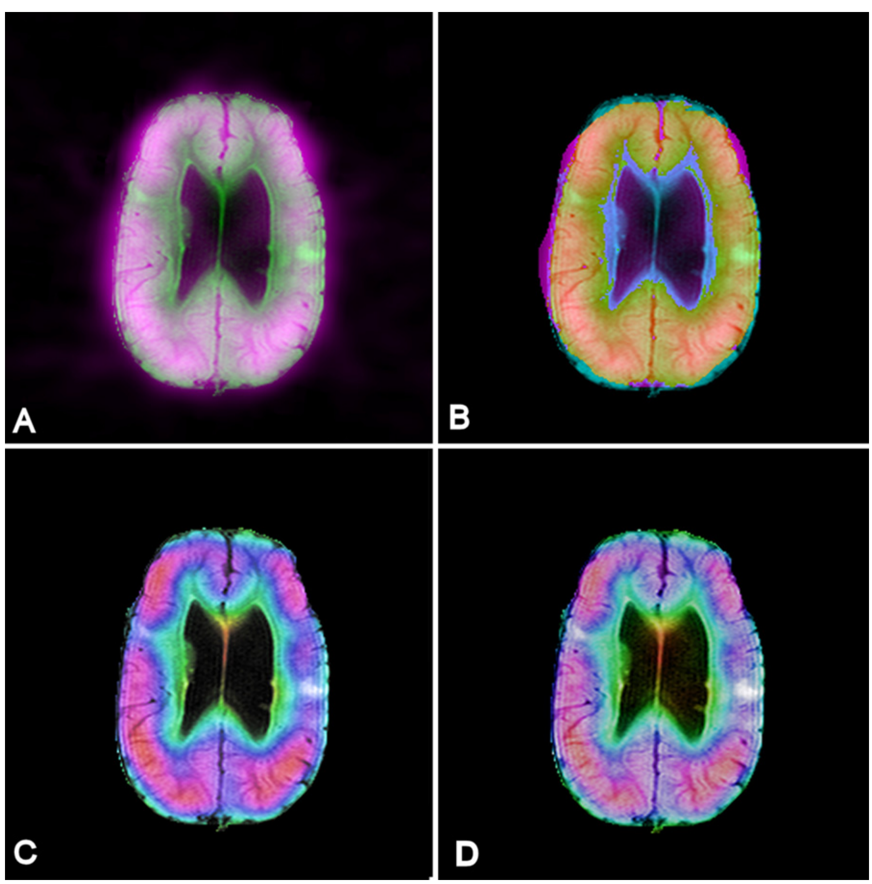

Fig. 2. (A) "RGB" data fusion with the SPECT image in the red and blue channels and the MR image in the green channel. (B) SPECT image in the red channel, MR image in the green channel and the sum of MR and SPECT images in the blue channel. The public domain software ImageJ® v1.34k from Wayne Rasband, National Institute of Health, USA was used to generate the image. (C) HSL image data fusion: SPECT image in the hue channel, MR image in the saturation channel and lightness channels. (D) HSL image data fusion with SPECT image in the hue channel, the negative of the MR image in the saturation channel and the MR image in the lightness channel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

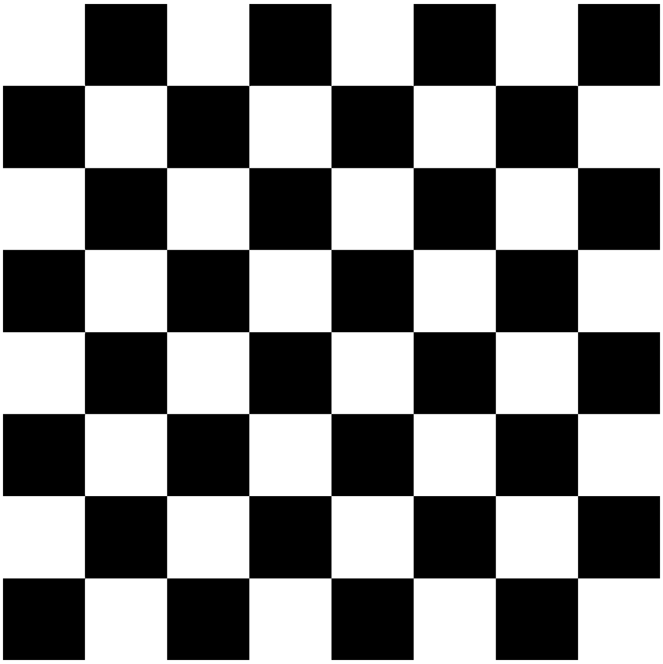

Fig. 3. Chessboard template used to generate chessboard fusion with two images.

green channel. Something similar can be performed in any other meaningful color space if desired. The second RGB representation contains the SPECT image in the red channel, the MR image in the green channel and moves the sum of SPECT and MR byte format images into the blue channel. This late sum was then treated as a single byte mode image generating the interesting enhanced image seen in Fig. 2B. In Fig. 2C the SPECT and MR images of the patient shown in Fig. 1 are combined into an HSV format where the SPECT image was put into the hue channel while the MR image was loaded into the saturation and value (lightness) channels.

(b) *The chessboard technique or alternate pixel display technique* [22]. Data fusion is accomplished by alternating MRI black and white pixels (or groups of pixels) with SPECT colored pixels to visualize perfusion defects (hypo- and hyperperfusion) at their corresponding anatomical location obtained with MR imaging. Fig. 3 shows a simple chessboard where white squares can correspond to MRI pixels and the black squares correspond usually to the SPECT pixels. Instead of using single pixels (1 × 1) groups of 2 × 2, 4 × 4 and 8 × 8 could be used as displayed in Fig. 4.

(c) *The transparency* (*matte*) *or alfa channel technique* [31–33]. The technique uses four channels which can be written as (R, G, B, α) or (R, G, B, A) where R, G and B refer to the red, green and blue components of the SPECT color image

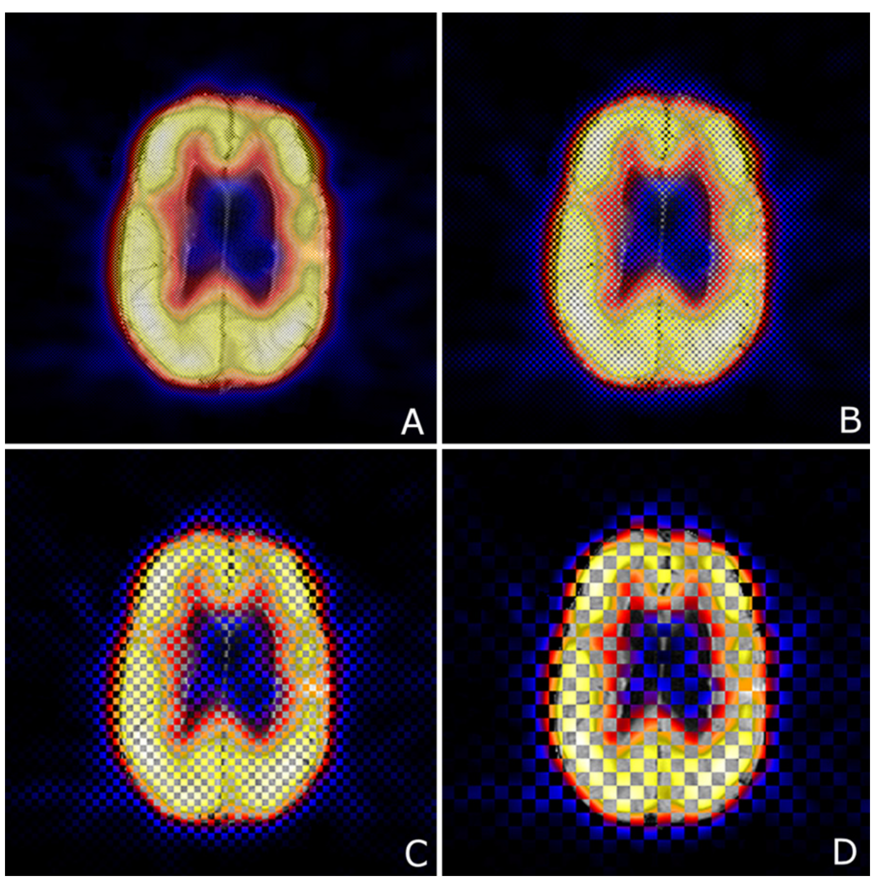

Fig. 4. Chessboard fusion of tuberous sclerosis case using blocks of 1 pixel × 1 pixel, 2 pixel × 2 pixel, 4 pixel × 4 pixel, and 8 pixel × 8 pixel, respectively. The same color palettes as shown in Fig. 1 are used in the present figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

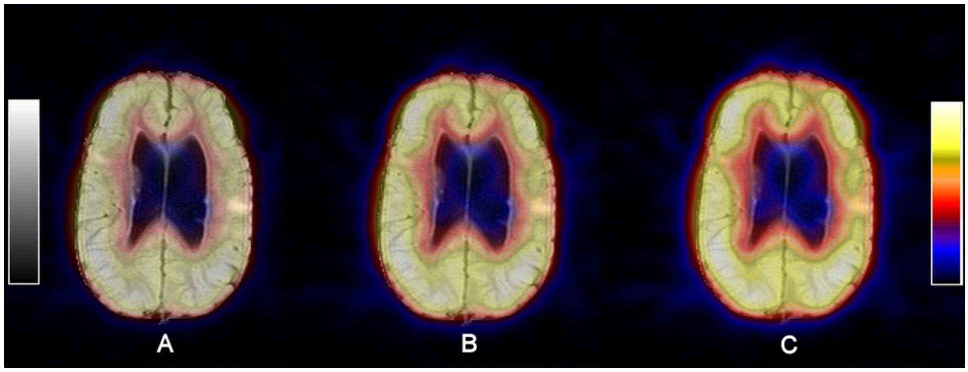

Fig. 5. Data fusion of same slices shown in Figs. 2 and 4 using the transparency model (matte channel). From left to right the alfa (transparency) factor is equal to (A) 60, (B) 90, and (C) 120, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

of Fig. 1 while the matte channel α reflects the transparency, i.e. the intensity attenuation in R, G and B which allows to look through a foreground image and detect the MR background image of the patient. Transparency described with the a channel, is applied only to the foreground image which then corresponds to a linear interpolation according to [34]:

$$I = \alpha F + (1 - \alpha)B \tag{1}$$

Eq. (1) is then applied to the three color channels (RGB) yielding a "true" color image with a fourth (matte) channel where the opacity factor α can be interactively varied from 0 to 255 or normalized from 0% to 100%. This means that each final fusion result is naturally described by four channels (RGBA). In Fig. 5 we have successively applied three different transparency (α) factors to the SPECT image and opacity $(1-\alpha)$ factors to the MR image. Transparencies of 23.5% (60 in the range of [0, 255]), 35.3% and 47% were applied in (A), (B) and (C), respectively.

Fig. 9 uses the interactive alfa data fusion technique of Eq. (1) with $\alpha = 0.5$ (transparency of foreground image = opacity of background image) applied to images of the cerebral peduncle in Parkinson patients and normal subjects (Fig. 8). The hue, saturation and lightness of the fused images (50% transparency and hence 50% opacity) was modified to hue = 2, saturation = 20 and lightness = 30, respectively. All parameters were fixed.

All computations were performed with the use of the development software IDL 6.0.1 from Research Systems Inc., Boulder, CO, USA—now a "Kodak Company", Rochester, NY, USA.

3. Results

Together with its standard black and white palette, Fig. 1A shows the MRI slice of the tuberous sclerosis case while Fig. 1B shows the corresponding corregistered SPECT image with a common nuclear medicine color palette. The tuberous sclerotic tumors appear as bright localized areas on the right temporal and left parietal side of the brain. Accordingly, the SPECT image shows clear hypoperfused areas which corresponds to the tumors. Fig. 2 shows from left to right the RGB data fusion according to the method described above. Due to the artificial byte truncation and the use of colors, additional anatomical details of the MRI image are enhancing the location of the tumors seen in light green as in Fig. 2A. The Fig. 2C shows the result of the fusion in the HSV color space as mentioned above. Exquisite details are revealed with the tumors visualized as white spots.

Fig. 4 shows the results of the checkerboard fusion process. The results are displayed from left to right and top to bottom using alternating SPECT and MR 1 pixel × 1 pixel, 2 pixel × 2 pixel, 4 pixel × 4 pixel, and 8 pixel × 8 pixel blocks to generate the data fusion. Anatomical information is obtained through visual integration of the whole fusion pattern obtained.

Fig. 5 shows the results of applying opacity to the MR background image and transparency to the SPECT foreground image of the tuberous sclerosis case shown in Fig. 1 with their respective color palettes on the left (background) and right (foreground). Depending on the value of α the MR information is rapidly lost partially due to the decreasing transparency of the SPECT image.

Fig. 6 shows the results of the epilepsy case. Two different slices are presented. On the left hand side are the SPECT interictal (far left) and ictal (second from left) results with a standard color palette used in this particular software package. The right hand side shows the MR images first without data fusion and finally with the MRI–SPECT image data fusion. MR images are normal and are only used to localize the epileptogenic focus anatomically as pointed out with arrows.

Fig. 7 shows the results of data fusion in the very interesting case of the patient with tuberous sclerosis however using a different slice. The Osiris Medical Imaging Software® was used to demonstrate the fusion of SPECT and MRI images. Fig. 7A and B show the MRI and SPECT slices with arrows indicating the location of a tuberous tumor where the tumor is identified by its high signal while hypoperfusion is detected in the SPECT image. The SPECT image is displayed in a common nuclear medicine color palette. In this very interesting and rare case, the tuberous sclerosis generated an epileptogenic focus adjacent to the tumor itself. Fig. 7C shows the checkerboard fusion of the MR and SPECT images. An arrow indicates the epileptogenic

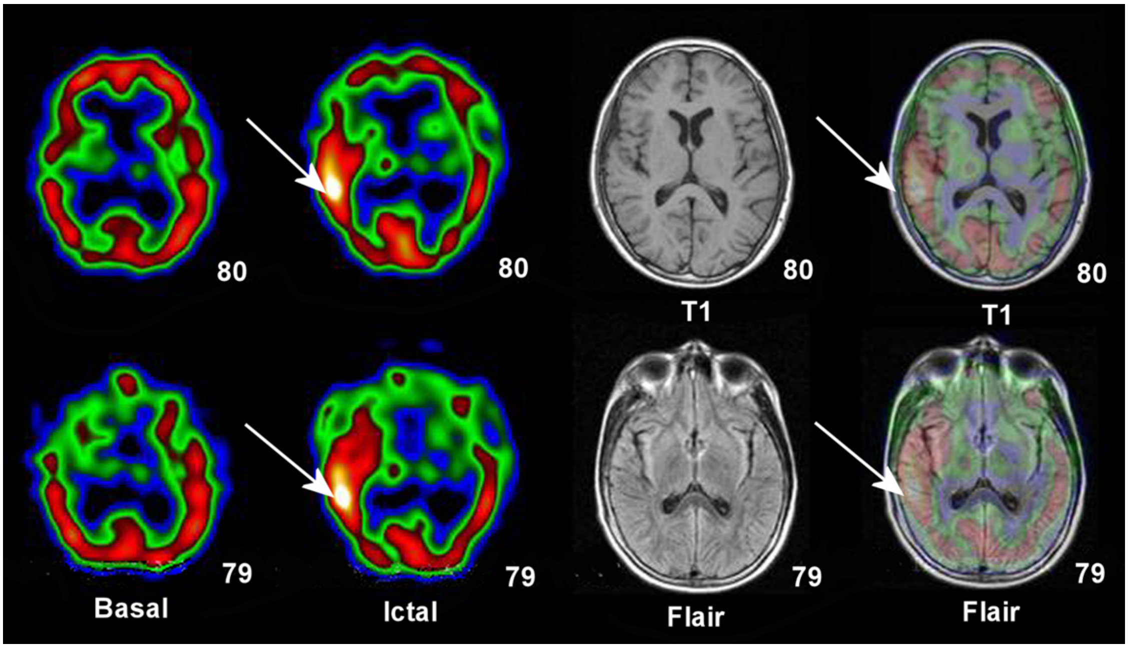

Fig. 6. Epileptogenic focus visualized with ictal SPECT Tc-99m ECD scanning. The focus of two contiguous slices is indicated with the white arrows. The right hand side shows the data fusion of MR imaging of the same patient with coregistered SPECT images (transparency factor, alfa = 50%). The right hand side (slice 80 in upper row) shows a T1 weighted MR slice while the lower is a FLAIR MR image of the same patient. Co-registration and fusion were performed with proprietary ADAC® software (Image Fusion and Review v4.2).

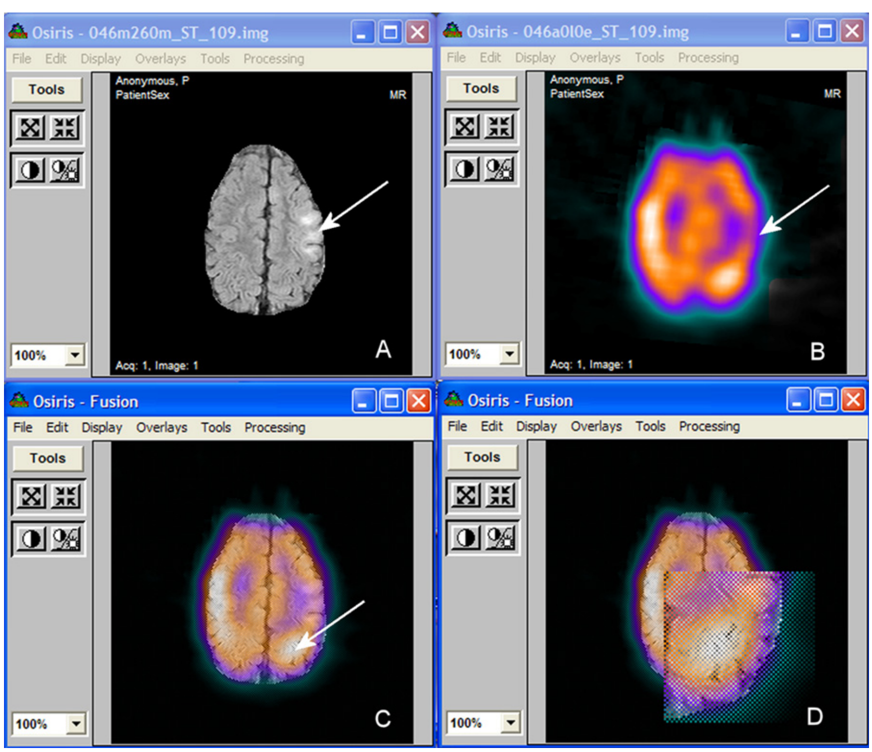

Fig. 7. Public domain application software (Osiris, Medical Imaging Software, version 4.19, University Hospital of Geneva, URL: http://www.expasy.ch/UIN) which allows to perform image data fusion which is shown for the same patient as in Fig. 4 using the checkerboard technique. (A) MRI of tuberous sclerosis case where the tumor is indicated with the white arrow on the left side of the patient's image. (B) Corresponding coregistered SPECT Tc-99m ECD with hypo perfusion indicating the location of the tumor. (C) MRI–SPECT image fusion using the GE-COLOR palette of the Osiris software. The arrow indicates the adjacent epileptogenic focus due to the tuberous sclerotic tumor showing hyperperfusion in the SPECT slice. (D) Zoom of epileptogenic focus displaying the checkerboard technique over the zone of interest.

focus on the left occipital side of the brain. Fig. 7D displays the use of a magnifying glass which can be interactively roamed over the image to appreciate the details of the region pointed out with an arrow in Fig. 7C.

Fig. 8 shows the images used to perform image fusion of the white matter suppressed (WMS) and gray matter suppressed (GMS) images of the cerebral peduncles of three sporadic Parkinson patients and three age matched control subjects. Fig. 9 shows these data fusion results using the transparency (opacity) alfa technique defined by Eq. (1) where the WMS peduncular image is chosen as the background (left color palette) and the GMS peduncular image is used as the foreground image (right color palette). Normal subjects showed clearly red-orange arches indicating the Substantia Nigra pars compacta (Fig. 9A). The bottom row shows the typical loss of neural cells from lateral to medial sections of the cerebral peduncles as well a thinning of the Substantia Nigra as reported elsewhere [24,25]. Loss of neural cells is indicated with arrows.

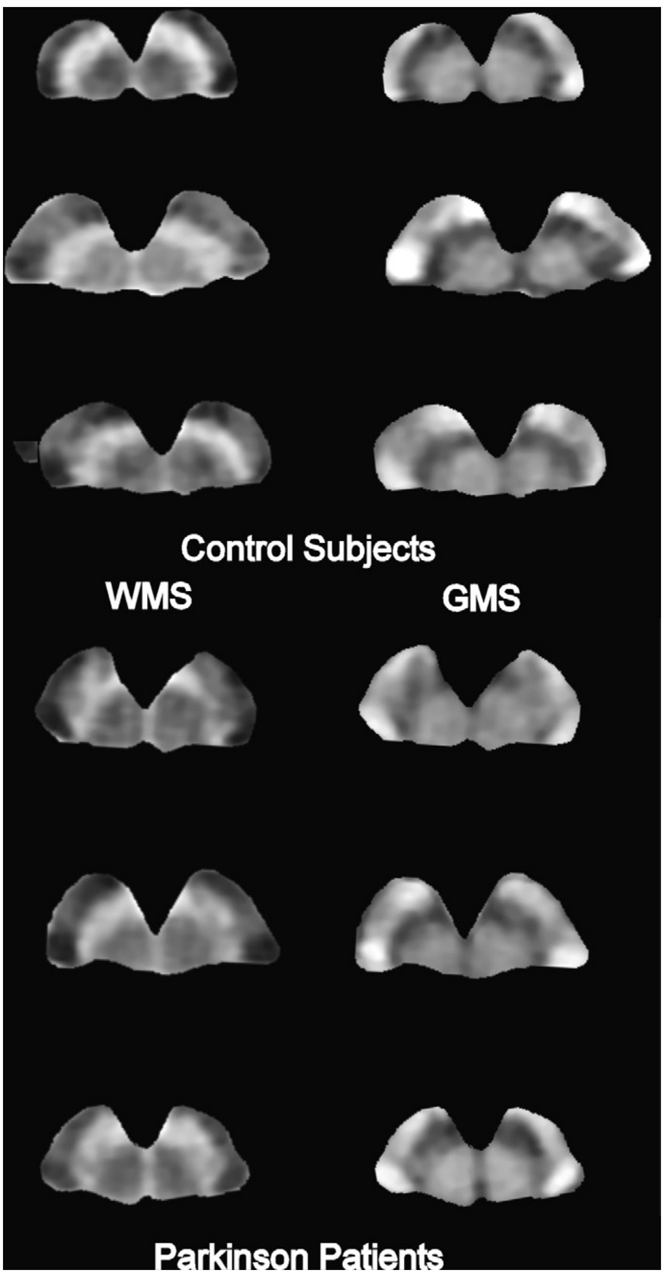

Fig. 8. The cerebral peduncles of three patients with sporadic Parkinson disease (bottom) and three age matched normal subjects (top) extracted from the midbrain of two MR inversion recovery imaging sequences. The left side shows the white matter suppressed (WMS) peduncles and the right column the gray matter suppressed (GMS) images respectively. The Substantia Nigra pars compacta (SN_C) responsible for idiopathic Parkinson disease is clearly visualized as an arch across the peduncle from the lateral to the medial sides of it. The SN_C shows up bright in the WMS image and dark in the GMS image.

Fig. 10 shows the results of the alfa fusion technique ($\alpha = 0.5$) using the same MR WMS and GMS images of the cerebral peduncle of a Parkinson patient in (A) and (B), swapping however in Fig. 10B foreground and background images, i.e. in Fig. 10B the background was chosen as the GMS image (left color palette) while the WMS image was used as foreground (right color palette). It becomes quite clear that the results are not matching and that the image (B) cannot be used to visualize neurodegeneration in the cerebral peduncle. The loss of neural cells in the Substantia Nigra is pointed out with arrows.

Fig. 11 shows the potential application of complex color palettes in the alfa (matte channel) fusion technique of Eq. (1) applied to one of the images displayed in Fig. 9. The fusion of background image (left color palette) with foreground image (right color palette) using $\alpha = 0.5$ yields the colorful result displayed in Fig. 11 revealing exquisite details of the peduncular anatomy of this particular Parkinson patient. The dark red-orange areas (arrow a) indicate the corticospinal tracts. Arrow (b) points out the red nucleus. Arrow (d) points to well preserved gray matter in the medial section of the SN_C. Arrows (e) and (c) indicate blue and blue-green areas respectively of the SN_C where arrow (c) corresponds to severe neural cell loss. The light blue area (arrow f) corresponds to the Substantia Nigra pars reticulata.

4. Discussion

Inter- and intra-modality image data fusion has been increasingly applied in the visual assessment of anatomy and pathology in radiology. Our goal was to choose three unusual yet illustrative examples taken from neuroradiology to explore the potential and practicality of three different image data fusion approaches. Image data fusion is almost always accomplished through the combination of a gray scale image with a pseudo-color image. One exception we found was the use of the checkerboard method where a PET image is overlaid with the corresponding MR image using two black and white palettes [22].

No one would argue that the use of colors in diagnostic radiology is an extremely complex issue. The contribution of color to radiological imaging remains questionable since color is not providing any objective information with exception of some enhancement capable of generating visually pleasant images. Nevertheless, the use of colors is appealing and has been slowly accepted in selective physiological and functional imaging scenarios. The underlying psycho visual paradigms of color perception are not well understood if at all, and hence the use of colors calls for a cautious and justified manipulation of them.

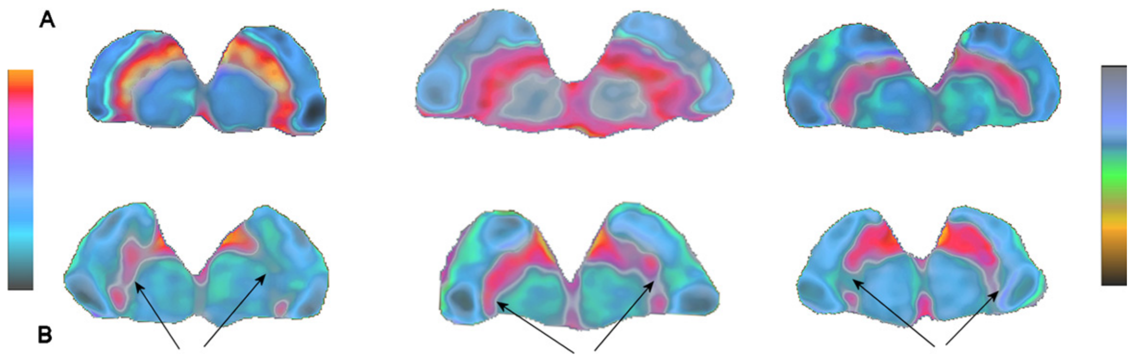

Fig. 9. Fusion of the WMS and GMS cerebral peduncle images (see Fig. 8) of three Parkinson' patients (B) and three age-matched control subjects (A) are displayed using the left color bar for the background image (WMS) and the right color bar for the foreground image (GMS). The transparency factor alfa (matte channel) was chosen as 50%. An adjustment using the hue, saturation and lightness values was performed leaving the hue H unchanged, the saturation value S was chosen as $S = +20\%$ (within a range of -100% to 100%) and the lightness value was fixed at $L = +30\%$ (within a range [-100%, 100%]). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

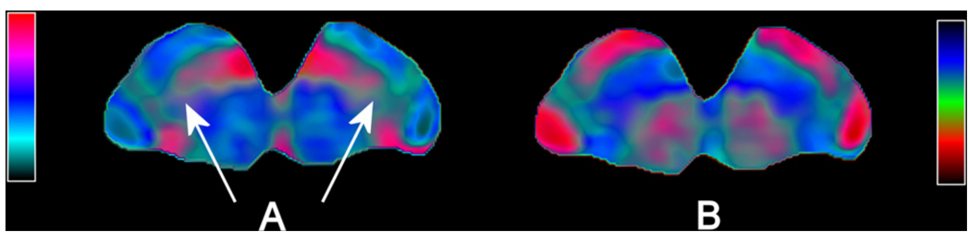

Fig. 10. The result of interchanging background and foreground images is displayed using the cerebral peduncle image of a Parkinson patient. Left side: color palette of background and image (A) WMS used as background image while the GMS image corresponds to the foreground image. Neurodegeneration of the SN_C pointed out with an arrow is clearly visible. In image (B) background and foreground images have been swapped while maintaining the respective color palettes as indicated.

The used RGB data fusion in our first example is simple and straightforward to implement. The difficulties encountered are elsewhere: given a certain RGB color (used to display color images on CRT), it remains difficult to determine the exact amount of each primary color and hence the RGB color system does not match our visual perception adding complexity when used in the context of data fusion. In spite of that, the advantage of it remains its simplicity to generate true color and pseudo color pictures. Due to these inherent difficulties, some pseudo color palettes became standard such as the one used in SPECT imaging of this rare case of tuberous sclerosis in Fig. 1. It seems debatable how much information is gained by performing RGB data fusion shown in Fig. 2A and B. This approach shows the fused SPECT and MR images with little information, merely showing the tumors of this case in light green.

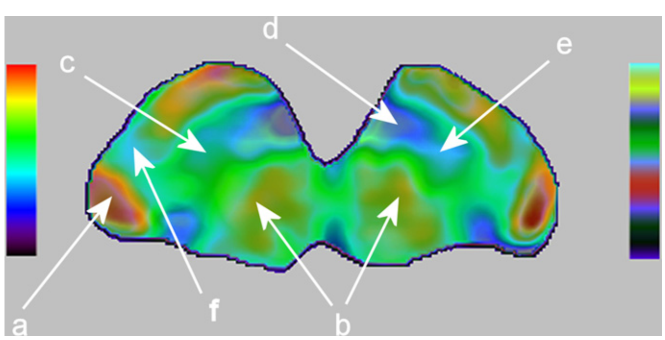

Fig. 11. Data fusion technique using two different color palettes for background (left, rainbow palette, IDL, Research Systems, CO) and foreground (right, ocean wave palette, IDL, Research Systems, CO). Notice that the foreground palette (right side) has subtle complex variations in the blue and green colors which make it possible to enhance the anatomy of the cerebral peduncle used to illustrate a rare application of alfa color fusion technique to a neurodegenerative disorder. The transparency of the matte channel was chosen as 50%. The various arrows depict the following: (a) corticospinal tracts, (b) red nucleus, (c) the green gray area pointed out is defined by RGB values approximately equal to $R = 15$, $G = 180$, and $B = 130$ and belongs to the SN_C with severe neurodegeneration, (d) the dark blue area ($R = 70$, $G = 120$, and $B = 190$ approximately) corresponds to preserved neural tissue of the SN_C and (e) the light blue area of the SN_C with approximate values $R = 50$, $G = 180$, and $B = 250$ correspond to some preserved neural tissue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

The use of the HSV color space yielded an improved composite image where the information from the SPECT image is enhanced while the tumors are displayed white since the MR image is loaded into the value channel of the HSV color space which provided a more precise and easier visual appreciation of the tumor location. In this case the tumor appears white since the lesion is white in the MR image. The HSV image Fig. 2D shows subtle improvement over Fig. 2C since it reveals more anatomical details from the MR image without losing the perfusion information of the corresponding SPECT image. These manipulations reveal great potential in the use of colors which has still to be explored and validated. Image data fusion performed at the low level on a pixel by pixel base is easy to perform and does not involve any complex image processing steps which can be considered a major advantage. These simple operations utilizing pseudo colors allow applying a wide spectrum of "colorful" combinations of inter- and intra-imaging modalities improving visual perception of integrated data.

Fig. 4 shows the results of the checkerboard fusion method where alternating pixels (Fig. 4A) allow barely discerning the tuberous sclerotic tumors due to poor contrast and little information from the MR image. Indeed, the MR information is gradually lost when increasing the size of the pixel blocks up to a point where it seems useless. With gradually larger alternating pixel blocks the underlying MR image is practically lost (Fig. 4B–D). We conclude that the technique might be quite useful as quality control of co-registration of inter-modality imaging. In addition perfusion and anatomy cannot be visualized simultaneously due to the alternating pixel blocks, showing only local adjacent image information and might be considered a drawback of this technique regarding the aim of image data fusion.

The alfa data fusion technique has a definite advantage since it is able to interactively show simultaneous details of both images to the desired degree appealing to the user. In addition any color palettes enhancing the visualization can be interactively selected to improve the final results of the fusion process. Fig. 5A reveals quite well the anatomy due to the high transparency of the alfa channel used for the SPECT image. Fig. 5C which used a higher opacity factor for the SPECT image shows hyper and hypo perfusion areas at the cost of disappearing information of the structures of the MR background image and therefore seems to lack any clinical contribution. Fig. 5B seems to yield the most reasonable fusion result regarding an accurate assessment of the location of the tuberous sclerotic tumors.

Fig. 6 displays the interesting case of a patient with epilepsy. The image fusion process of (inter-ictal) MR images with the ictal SPECT images demonstrated exquisitely the anatomical location of the epileptogenic focus. Though the SPECT images reveal important information per se, the fusion process adds invaluable information and illustrates in our opinion a novel approach invaluable for further treatment.

Fig. 7 shows how readily available software (freeware) can be used to perform image data fusion. The Osiris Medical Imaging Software® used in the collage of Fig. 7 demonstrates nicely how fusion of previously corregistered data can be displayed. The included tools of checkerboard fusion and interactive magnifying glass over this rare case of an epileptogenic focus observed as a consequence of tuberous sclerosis is well localized in Fig. 7C and D. Arrows point out the epileptogenic focus underneath the tuberous sclerotic tumor in the occipital region of the left side of the brain. This demonstrates that image data fusion can be easily implemented and used for several purposes such as quality of co-registration, accurate location of morphological changes in anatomy and metabolic changes and visual corroboration of radiological diagnosis.

Fig. 9 shows a novel data fusion process used to illustrate neurodegeneration in sporadic Parkinson's disease using the WMS and GMNS suppressed images of Fig. 8. The fused peduncular color images displayed in Fig. 9A and B, show the potential of image data fusion in Parkinson's disease. The peduncular images displayed in Fig. 9A correspond to normal age-matched subjects displaying a slice through the Substantia Nigra pars compacta which reaches all across the peduncle from the lateral to the medial sections appearing as an arch. The lower row dramatically displays the neurodegeneration (pointed out with arrows) observed in Parkinson patients which begins on the lateral section of the SN_C and progressively reaches the medial section of the SN_C in advanced cases. The somewhat lurid colors were intentionally chosen to generate maximum enhancement, though we are aware of the interpretation difficulties generated by such approach. In spite of the fact that, we are conscious of the danger in using colors in radiological imaging, yet believe that image data fusion justifies the judicious use of color palettes in selected cases.

Fig. 10 shows the color fusion result of a WMS and a GMS slice through the cerebral peduncle showing neurodegeneration in the Substantia Nigra pars compacta of a Parkinson patient similar to the one displayed in Fig. 9 using however the color palette on the left for the background and the one of the right for the foreground. In Fig. 10A, the background image was chosen as the WMS image and the foreground image was the corresponding GMS image. Neurodegeneration is clearly visible from the lateral to medial sections of the SN_C. Fig. 10B demonstrates the importance of the choice made in Fig. 10A where the loss of neural cells is pointed out with an arrow. Swapping background and foreground images makes the result looks normal and the image data fusion process becomes meaningless. This indicates that data fusion cannot be performed arbitrarily.

Image data fusion is an image processing tool which has gained interest due to its undeniable visible enhancement of pathology with inter- and intra-modality imaging techniques. Since color is an essential part of the fusion process, the final product can cover an unlimited myriad of potential representations of fused images. Fig. 11, which uses the alfa blending technique, shows the results of data fusion of WMS (background) and GMS (foreground) images of the peduncle in a Parkinson patient. The choice of color palettes enhanced the information to a very subtle level showing several degrees of neurodegeneration in the SN_C ranging from severe to preserved neural tissue. This particular example illustrates the power of image data fusion in a particular situation and only the imagination might be the limit of how to obtain a meaningful representation of fused data. By no means are we claiming that this technique can be generalized to all types of images. Despite the fact that the alfa blending technique seems to be the most powerful one, we must keep in mind that the dynamic range of both fused images is reduced to half the value of the original ones which seems the major limitation of this technique.

5. Summary

Image data fusion developed over the last decade, uses different sources of information to improve and integrate the performance of radiological imaging due to combination of complementary information. Image data fusion is primarily a visual technique based on enhancement of the available information and is therefore not quantitative per se. Quantitative analysis can be performed afterwards. Image fusion in radiology can be useful for several reasons such as lesion identification, tracking of pathology in longitudinal studies, accurate location for surgical interventions and decision making in general. The image fusion process is usually divided in three categories labeled as low level, intermediate and high level fusion respectively. In the present paper we will use low level image fusion also coined as data fusion and shall use this terminology indistinguishably in our context. Typically, radiological image processing deals with images generated by different modalities such as CT, MR, SPECT, PET and conventional radiography. Each imaging modality can be interpreted as a spectral band providing different information which then can be examined separately. Ultimately the goal is to use a single image where various bands are fused together. In the applied low level image fusion precise registration of images is required. Once co-registration has been performed, fusion on a pixel to pixel base can be performed to highlight relevant information. MRI in particular is an attractive imaging modality since many different channels (T1, T2, PD, FLAIR) are available for data fusion without previous complex co-registration.

We have examined three different image fusion techniques and applied them to images from neuroradiology. Two of the three techniques are quite simple and very efficient. The first ubiquitous technique capable of sometimes revealing interesting and subtle details, uses data fusion as found in color image processing, i.e. three color channels contain different corregistered images on a pixel to pixel base. This can be done, e.g. in an RGB or HSL color space with two or three different channels. The second technique is known as chessboard or checkerboard technique and uses pixel blocks of varying size (1×1, 2×2, 4×4) which are alternating in the final display of two fused images. We found that it is an excellent co-registration quality control method with little impact on detailed integrated information. The third technique uses four channels labeled as (RGBA) where A represents the alfa or matte channel. Two images are fused together with different degrees of transparency or vive versa opacity. The major advantages are the use of two different color palettes and the interactive fusion process.

We have chosen a rare yet quite intriguing case of tuberous sclerosis which developed an epileptogenic focus as a consequence of his disease (MRI and SPECT), an epilepsy case with ictal SPECT imaging allowing accurate location of the epileptogenic focus with the corregistered MR image and finally, using the interactive alfa technique, we have performed image fusion of the cerebral peduncle in Parkinson disease and age-matched control subjects to show neurodegeneration of the Substantia Nigra pars compacta.

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