The weighted-peak method in time and frequency domain: an operative application to the analysis on MRI gradient signals

R. Pinto[1] , N. Zoppetti[2], C. Merla[1], R. Lodato[1], R. Falsaperla[3], V. Lopresto[1], G. Contessa[3], D. Andreuccetti[2]

[1]ENEA, Rome, Italy,
[2]IFAC, Institute for Applied Physics "N. Carrara", CNR, Florence, Italy
[3]INAIL, Italian Workers' Compensation Authority Rome, Italy,

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Summary

- Scenario
- Measurement set up and protocol
- Weighted peak method for exposure assessment
- Results
- Discussion

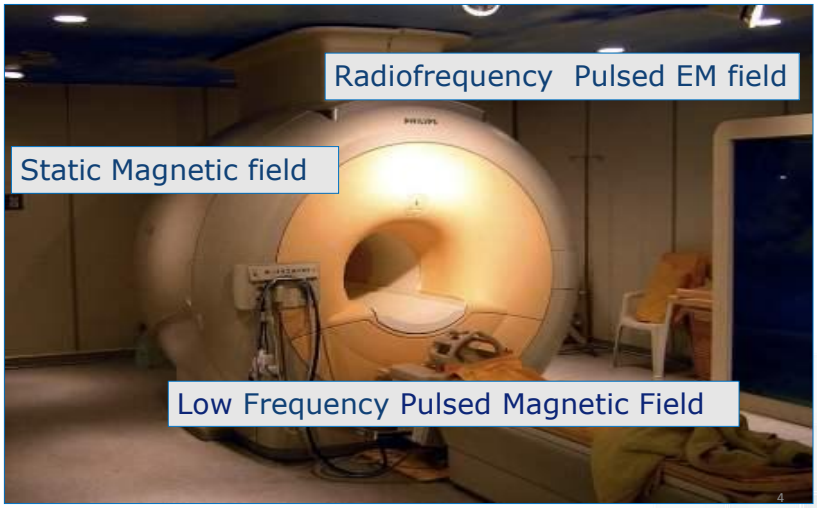
MRI Applications

MRI in research

Occupational exposure assessment for health staff working in MRI facilities

Interventional MRI

Exposure Scenario



Gradient Magnetic Field

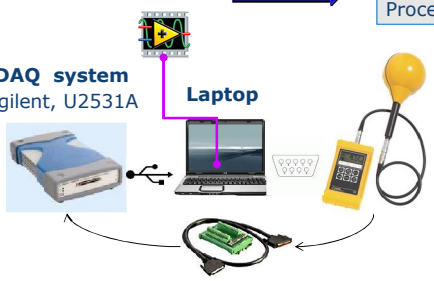
Gradient coils are used to spatially encode the positions of protons by varying the magnetic field linearly across the imaging volume.

Generally pulsed signals having spectral components up to few kHz

Measurement set up

Software Procedure
National Instruments, Labview 2009

Setting instrumentations
Managing acquisition
Processing the signals



DAQ system
Agilent, U2531A

Laptop

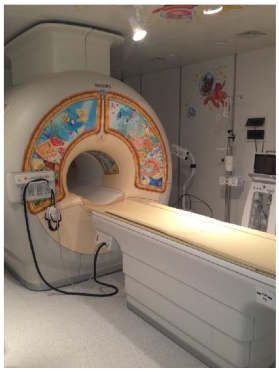
Magnetic field meter
Narda,ELT400
bandwidth [1Hz-400kHz]

SCSI-II 68 pin connector
Agilent, U2902A

High speed USB 2.0 DAQ
4 differential input channels
14 bits resolution
sampling rate up to 2MSa/s/ch.

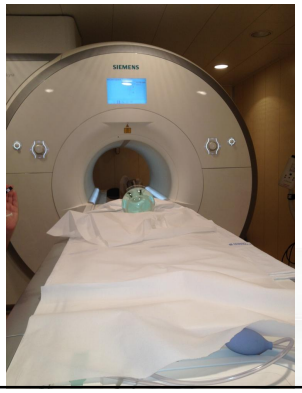
Settable low cut off frequencies
RMS, peak detector
ICNIRP 98 Occupational
analog outputs, RS232 port

Exposure facilities



1.5 T Philips Achieva
whole-body scanner

3 T Siemens Magnetom Skyra
whole-body scanner



In the paediatric MRI use, the staff can be present during the examinations to take care of the children

Measurement protocol

Measurement points considered both for 1.5 T and 3 T scanners

Position	Distance from the gantry [cm]	Distance from the centre of the couch [cm]	Height from the ground [cm]
P1	Inside the bore		
P2	**50**	**67**	**70**
P3	**50**	**67**	**120**
P4	**50**	**67**	**170**
P5	100	67	120
P6	150	67	120

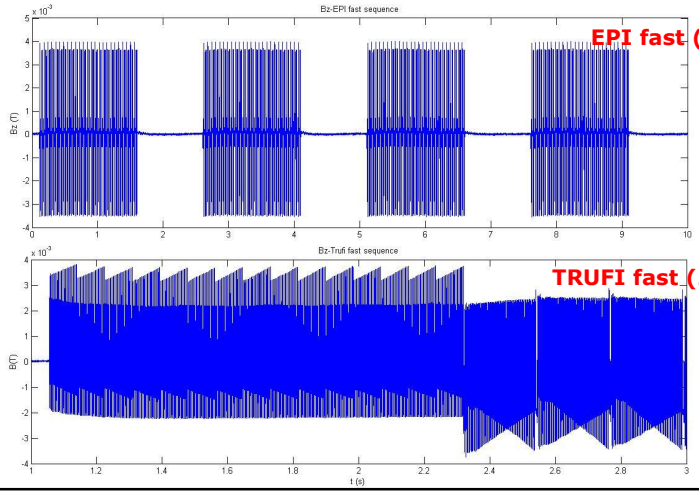
Medical staff position

Acquisition time: 10 s
Sampling rate: 50 ks/s

Eight additional measurements points for 3T scanner

Measurement protocol: signals

1.5 T scanner: four different echo-planar imaging (EPI) sequences investigated in each measurement point.
3 T scanner: four different signals, two EPI and two fast imaging with steady precession (TRUFI) investigated.



EPI fast (270 μs)

TRUFI fast (250 μs)

Weighted peak method

- Parameters like peak or RMS values are poorly descriptive with complex waveforms: ICNIRP reference levels vary with frequency.
- ICNIRP is recommending the "**weighted-peak**" approach, for assessing compliance of non-sinusoidal low frequency fields.
- The waveform frequency contents must be weighted taking both the frequency behavior of the reference levels and the relative phases of the spectral components into account.

$$WPI\ (t) = \left| \sum_k \frac{B_k}{BL_k} \cos(\ 2\pi f_k t + \vartheta_k + \varphi_k\ ) \right| \leq 1$$

This method is indicated by new EU Directive to assess the compliance for complex signals (Annex 2)

ICNIRP 2010 LIMITS

Basic restrictions for occupational exposure

Exposure characteristic	Frequency Range	Internal electric field [V/m]
CNS tissue of the head	1-10 Hz	0.5/f
	10HZ-25Hz	0.05
	25Hz-400Hz	$2x10^{-3}f$
	400 Hz-3kHz	0.8
	2kHz-10 MHz	$2.7x10^{-4}f$
All tissue of head and body	1Hz-3kHz	0.8
	3kHz-10MHz	$2.7x10^{-4}f$

Reference levels for occupational exposure

Frequency Range	E-field [V/m]	H-field [A/m]	B-field [T]
1Hz-8Hz	20	$1.63x10^5/f^2$	$0.2/f^2$
8Hz-25Hz	20	$2x10^4/f$	$2.5x10^{-2}/f$
25Hz-300Hz	$5x10^2f$	$8x10^2$	$1x10^{-3}$
300Hz-3kHz	$5x10^2f$	$2.4x10^5/f$	0.3/f
3kHz-10MHz	$1.7x10^{-1}$	80	$1x10^{-4}$

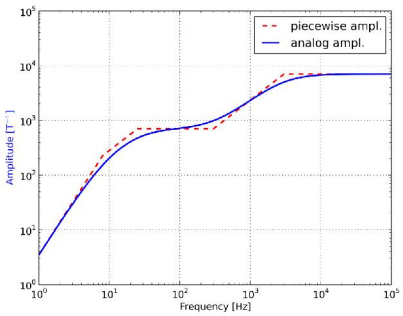
Frequency domain implementation

- Computing the spectrum of the waveform under analysis for each component.
- Computing the WPI index in FD applying directly the WPI formula: the piecewise behavior of the transfer function is strictly maintained
- The index of each measured component of the B-field is computed back in the TD
- The sum-root square is evaluated to obtain WPI(t)
- Its maximum value is the WPI index

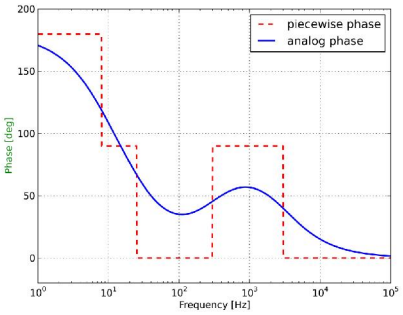
Time domain implementation

- Process the measured samples of each component of B with digital filters representing the inverse of ICNIRP reference levels
- Filters implemented as a series of analogue RC filters, whose digital IIR version was obtained using the so called 'pole-zero matching' technique
- Output of the filters represents WP index for each Cartesian component of the field
- The sum-root square is evaluated to obtain WPI(t)
- Its maximum value is the WPI index

Filters Bode's diagrams



Piecewise pattern used in FD, analog ones used in TD



ICNIRP requirements: variation from the exact piecewise responses of no more than 3 dB for the amplitude and of no more than 90°for the phase.

Results: MRI exposure compliance

Position	1.5 T WPIocc FD EPI 200 μs	3 T WPIocc FD EPI 270 μs	3T WPIocc TD EPI 270 μs
P1	10.31	16.75	16.35
P2	0.11	0.11	0.09
P3	0.14	0.14	0.12
P4	0.07	0.11	0.09
P5	0.04	0.05	0.04
P6	0.02	0.02	0.02

- WPI for **1.5 T scanner:** the gradient B fields measured for **all the acquired sequences (EPI norm and fast) are compliant with occupational reference levels**
- WPI for **3 T scanner:** the gradient B field measured in the same points **are compliant with occupational reference levels for all measured sequences**

Results: MRI exposure compliance

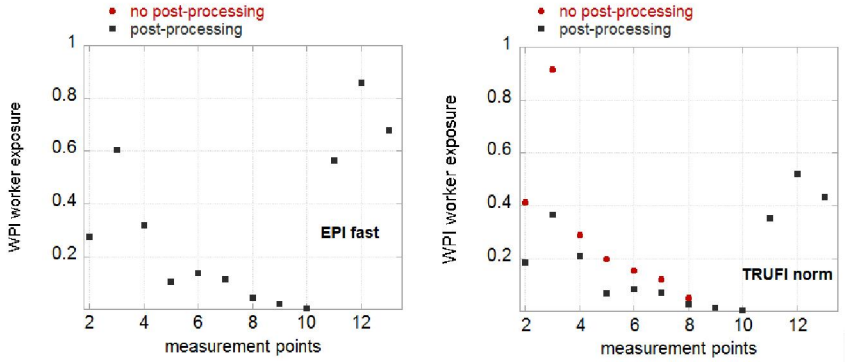
Other points measured nearby 3 T scanner: in some case exposure resulted **not compliant**

Distance from the gantry [cm]	Distance from the centre of the couch [cm]	Height from the ground [cm]	MRI sequence
0	67	70	**TRUFI fast depending on WPI computational method; EPI fast**
0	67	120	**All**
0	67	170	**TRUFI fast; EPI fast**
0	117	70	**All**
0	117	120	**All**
0	117	170	**All**
0	17	120	**All**

Points in proximity of the bore where medical staff can be present!

Results: FD WPI, the role of the signal postprocessing (i.e. include or not boundary samples)

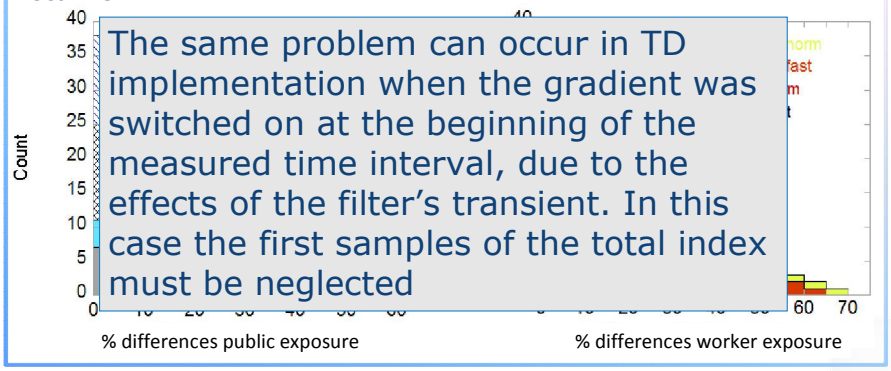
WPIs evaluated for EPI fast and Trufi norm nearby 3 T scanner



- Negligible influence of FFT windowing algorithm on periodic sequences (e.g. EPI)
- Attention should be paid to chose an appropriate post processing on anti-transformed waveforms when non periodic sequences have to be taken into account (e.g. TRUFI)

Results: FD WPI, the role of the signal postprocessing

% differences of WPI evaluated for 4 gradient signals nearby 3 T scanner

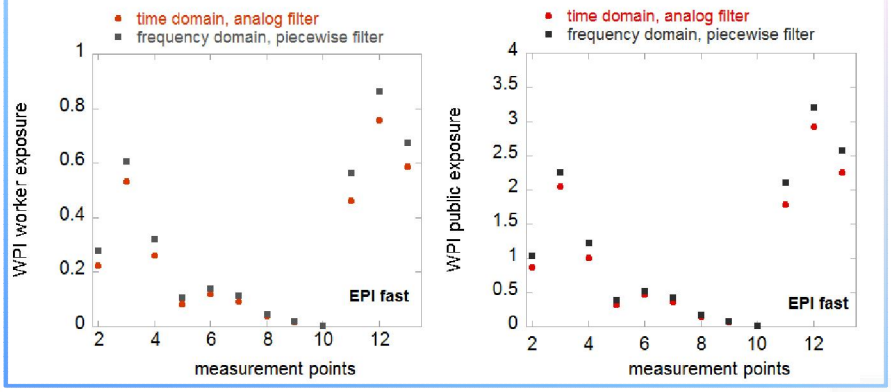


The same problem can occur in TD implementation when the gradient was switched on at the beginning of the measured time interval, due to the effects of the filter's transient. In this case the first samples of the total index must be neglected

max % differences are around **5% for EPI NORM** sequences and **30 % for EPI fast** sequences while for **TRUFI (norm and fast) sequences max differences are over 50%** both for public and worker exposures

Results: comparing TD vs FD WPI

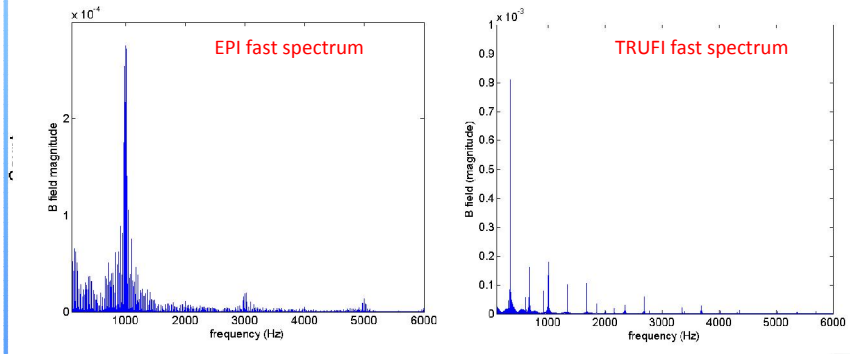
WPIs evaluated for EPI fast nearby 3 T scanner



- WPI for workers are compliant with the limits, higher WPI values are obtained for the population
- Variations are due to the different method employed for WPI calculation: FD vs TD
- Two filter types are used (analog/piecewise) always in agreement with the ICNIRP 2010 guidelines

% difference: comparing TD vs FD WPI

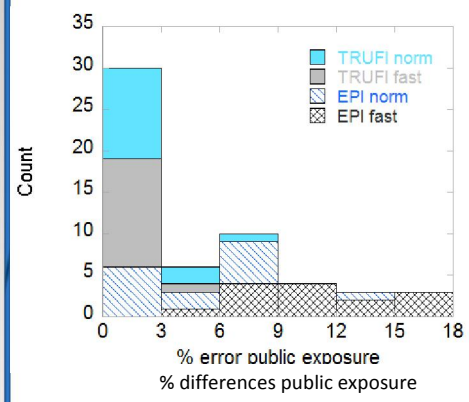
% differences of WPI evaluated for 4 gradient signals nearby 3 T scanner (analog vs piecewise)

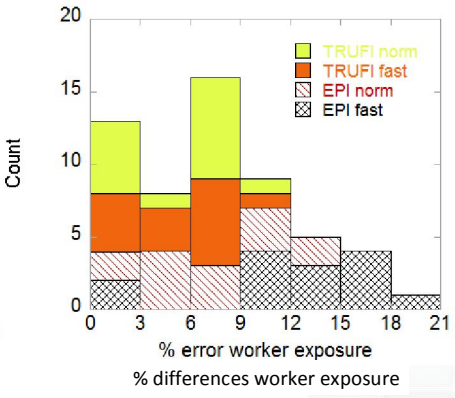


% differences are higher for the EPI sequences (fast and norm) due to their wide frequency content; **this makes more evident the differences when analog (TD) versus piecewise filter (FD) is used.**

Results: comparing analog vs PW FD WPI

Are differences between the TD and the FD approach only due to the different filter types used for the WPI calculations?





Same trend for population and worker exposures (EPI sequences are the worst cases) as previously observed comparing FD and TD approach for WPI calculation

Conclusions

- Two measurement surveys were performed nearby a 1.5 and a 3 T total body MRI, different gradient signals were measured
- The WPIs were evaluated in agreement with the ICNIRP guidelines in TD and FD
- In the positions normally occupied by the medical staff the WPIs do not overcome the occupational reference levels for both scanners
- Some variability among data occurred due to the different adopted filters, both satisfying the ICNIRP requirements for the implementation of WP method
- Obtained results revealed the need of a critical analysis on the guidelines' exposure assessment criteria