RF Exposure and Resulting Temperature in the Foetus during MRI

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RECOMMENDED TEMPERATURE LIMITS

Mode	Increase in temperature deg C	Spatially localised temperature limits		
		Head	Torso	Extremities
Normal	0.5	38	39	40
1st controlled	1.0	38	39	40
2nd controlled	> 1.0	> 38	> 39	> 40
HPA 2008:	2.0	39	40	41

ICNIRP (2004) “It seems reasonable to assume that adverse developmental effects will be avoided with a margin of safety if the body temperature of pregnant women does not rise by more than 0.5°C and the temperature of the foetus is less than 38°C”.

THERMAL MODEL

Heat loss by the foetus to the mother is achieved via two major routes:

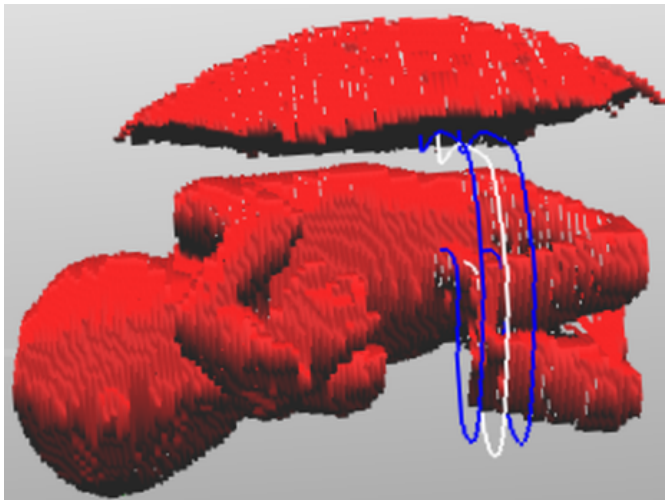
- heat transfer across the foetal skin/amniotic fluid and amniotic fluid/ uterine wall boundaries.

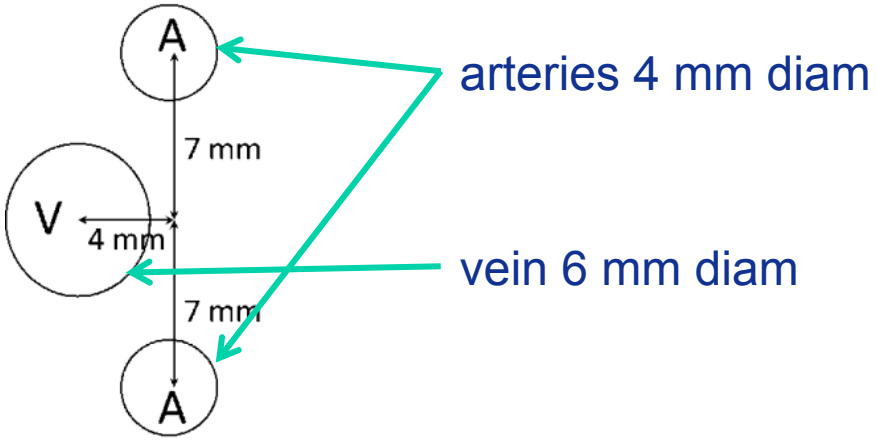
- heat transfer from foetal to maternal blood in the placenta

Accounts for ~ 80% of total foetal/maternal heat transfer

THERMAL MODEL

Umbilical vein and arteries were modelled as discrete vessels





Vessels centred on splines following an arbitrary path from the umbilicus, around the foetal limbs, to the placenta. Length was 30 cm.

	Umbilical vein	Umbilical arteries
Volumetric flow ($m^3\ s^{-1}$)	2×10^{-6}	1×10^{-6}
Entry temperature (^oC)	37	37.5

THERMAL MODEL

This initial model:

- ignores the coiled nature of the umbilical cord.
- assumes the dielectric properties of Wharton's jelley within the umbilical cord to be the same as those for amniotic fluid
  - high water content
  - similar conductivity to amniotic fluid
- ignores sheath around the 3 umbilical cord vessels.

THERMAL MODEL

Thermal solver within SEMCAD X v14 uses:

Pennes' "bioheat" equation

$$c_{tissue}\rho_{tissue}\frac{\partial T}{\partial t} = \nabla.\left(k_{tissue}\nabla T\right) + \sigma_{tissue}\left|E\right|^2 + M - wc_{blood}\left(T - T_{blood}\right)$$

DIscrete **VA**sculature thermal model

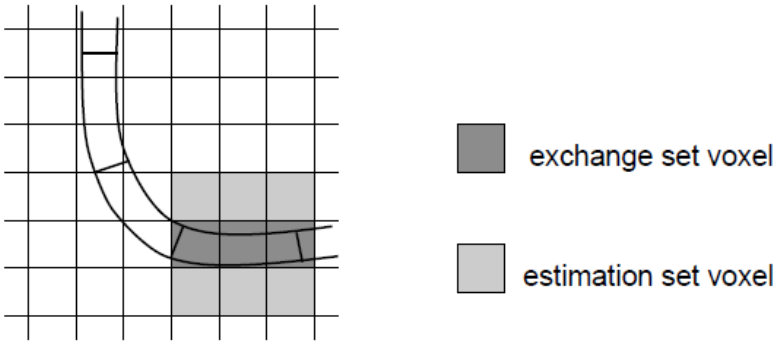
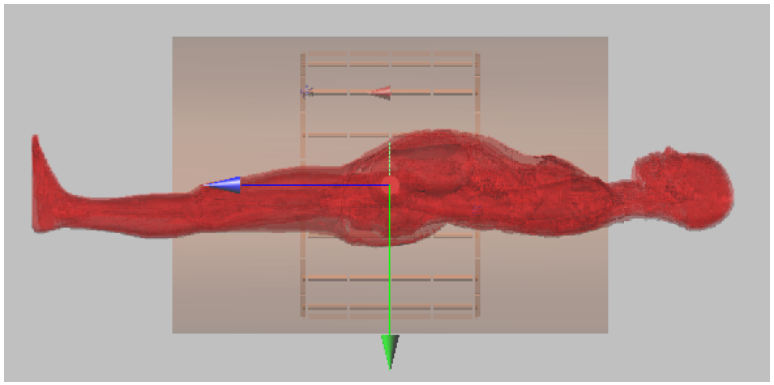


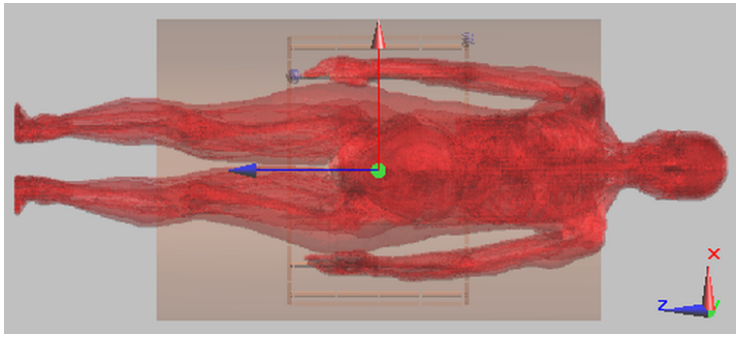
Figure 1. Part of a vessel segment projected on to the grid. Three buckets are indicated. For one bucket the two sets needed for the heat exchange between bucket and tissue are shown.

Kotte A *et al* 1996 A description of discrete vessel segments in thermal modelling of tissues *Phys Med Biol* **41** 865-884.

E-M Model

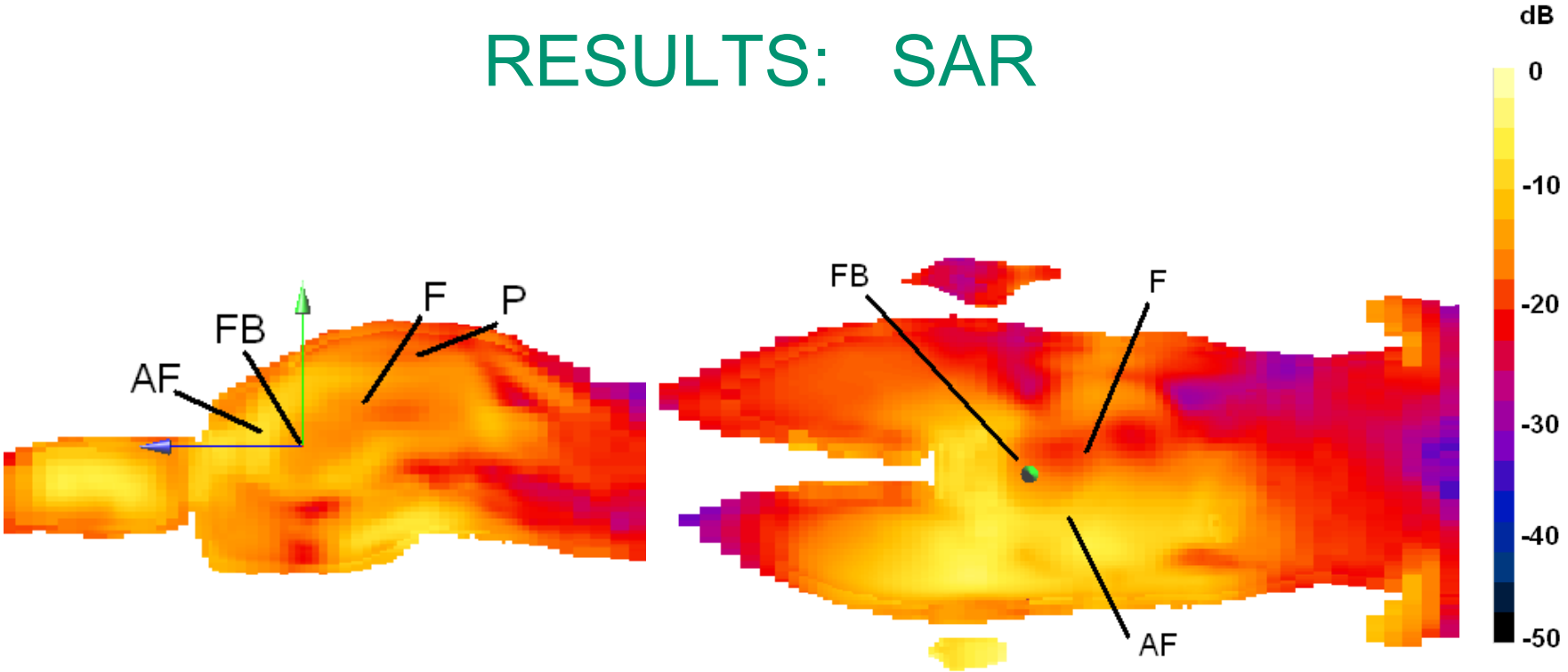
- generic low-pass, 16-rung, shielded circular birdcage coil
- diameter = 600 mm, end rings centre-centre spacing = 400 mm
- driven in quadrature by voltage sources in 2 rungs
- tuned to 64 MHz
- patient model positioned such that foetal brain was at isocentre





- FDTD solver SEMCAD X v14.0 (Schmid & Partner Engineering AG, Zurich)
- *E*-, *H*-, and SAR_{10g}, SAR_{MWB}, & SAR averaged over specified tissue types
- PCs with 4 Intel Xeon 3.2 GHz CPUs, 8 GB RAM, and an aXware FDTD HW accelerator card (v3.0 500)

RESULTS: SAR



Maternal whole body SAR: 2 W/kg

	Tissue				
	Foetus	Foetal brain	Amniotic fluid	Placenta	Uterine wall
Tissue averaged SAR W/kg	1.2	1.7	3.4	0.6	2.6
Max SAR_{10g} W/kg	5.5	3.0	12.0	2.5	15.0

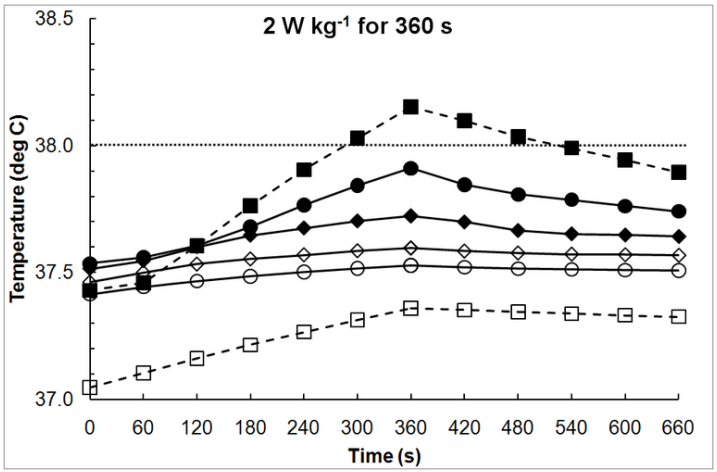
RESULTS: Temperature

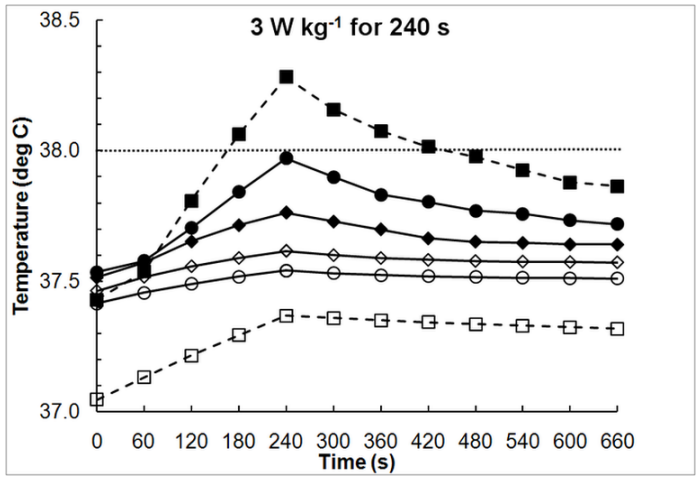
Maternal whole body SAR: 2 W/kg

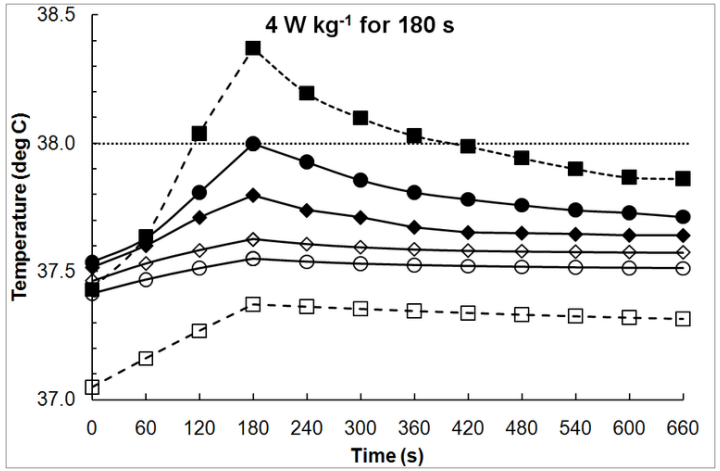
TISSUE/ RF EXPOSURE	Mean T °C	Δ_{meanT} °C	Max T °C	Δ_{maxT} °C
Foetus				
600 s	37.6	0.15	38.2	0.7
1800 s	37.7	0.24	38.9	1.4
Foetal brain				
600 s	37.6	0.16	37.8	0.3
1800 s	37.6	0.19	38.0	0.5
Amniotic fluid				
600 s	37.5	0.47	38.7	1.2
1800 s	38.0	0.95	40.1	2.6
Uterine wall				
600 s	37.3	0.23	38.7	1.4
1800 s	37.4	0.32	39.0	1.7
Placenta				
600 s	37.0	0.02	37.1	0.02
1800 s	37.0	0.03	37.2	0.07

RESULTS: Temperature

Maternal whole body SAR: 2 W/kg averaged over 6 minutes







Mean Max

○ ● foetus

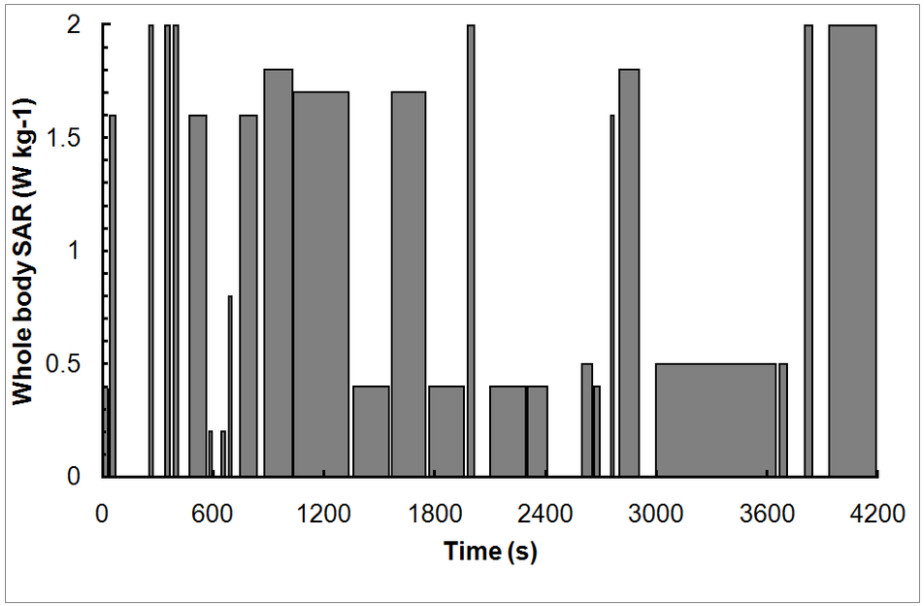
◇ ◆ foetal brain

□ ■ amniotic fluid

RESULTS: Temperature

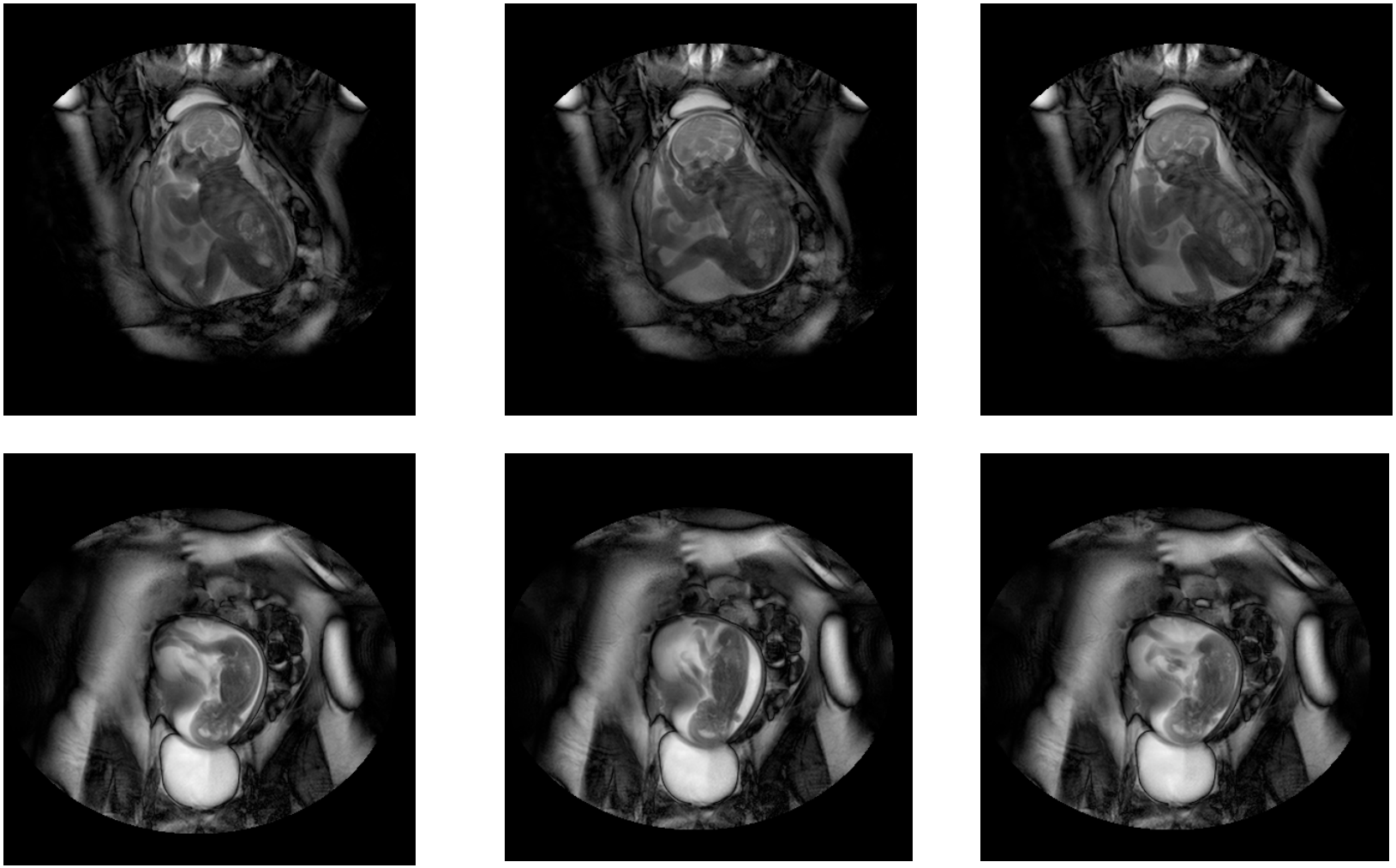
Maternal whole body SAR versus time from a clinical examination

Mean sequence SAR: 1.17 W/kg Mean exam SAR: 0.75 W/kg



TISSUE	Mean T °C	Max T °C
Foetus	37.6	37.9
Foetal brain	37.6	37.7

Foetal Movement



SUMMARY

Results suggest that

- for MRI procedures carried out under IEC normal mode conditions (SAR_{MWB} = 2 W kg^{-1}), foetal whole body SAR and foetal average temperature are compliant with recommended limits
- long, continuous exposure at SAR_{MWB} = 2 W kg^{-1} could result in maximum foetal temperature > 38 ^{o}C

  However

  - maximum temperature difficult to interpret because of foetal movement
  - for exposures of clinically realistic duration, maximum temperature does not exceed 38 ^{o}C.

Further work required to investigate:

- different body models, different positions in coil, different coils
- effect of foetal movement on foetal SAR and temperature

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