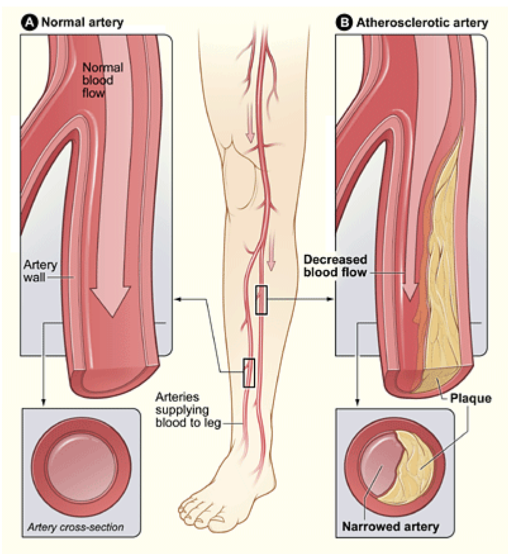
Development of a hybrid microwave-optical tissue oxygenation monitor

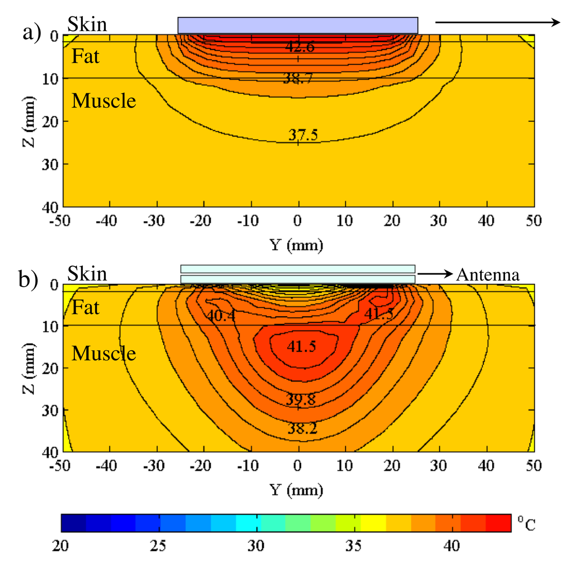
Allann Al-Armaghany[1], Dr. Kenneth Tong[1], Dr. Terence Leung[2]

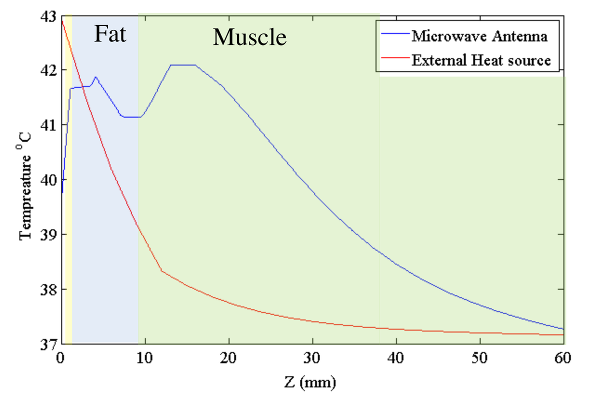
[1]Department of Electronic & Electrical Engineering - University College London - Torrington Place - London WC1E 7JE
[2]Department of Medical Physics and Bioengineering - University College London

1. Introduction

- The development of a new type of non-invasive microwave antenna for deep tissue warming is presented. It consists of a specially designed microstrip patch antenna operating at around 2450 MHz and a superstrate as a coupling interface.
- The electromagnetic wave radiated from the antenna is capable of raising the temperature in the muscle by a few degrees Celsius while sustain low temperature in the superficial layers.
- The induced heat causes vasodilation and therefore an increase in blood flow and volume. To measure the thermal response in the form of oxy- and dexoy-heamoglobin concentrations changes, an optical emitter and detector pair has been integrated with the antenna,
- These thermal responses allow investigations into the thermoregulation in deep tissue and can provide diagnostic information particularly useful in the study of vascular diseases including Atherosclerotic.


Normal artery and atherosclerotic restricted artery


Thermal Distribution in three layer tissue model, a) with external heat source, b) microwave antenna


Peak temperature inside the modelled tissue

2. EM Interaction In Biological Tissue

- Dielectric constant and the electrical conductivity of biological tissue have a unique dependence on frequency due to the composition of cells and water.
- Microwave energy propagating in biological tissue is absorbed and this is known by the Specific Absorption Rate (SAR), which is commonly used to model deposited EM energy in the tissue:

$$SAR(x,y,z)=\frac{\sigma}{2\rho}\left|E(x,y,z)\right|^2$$

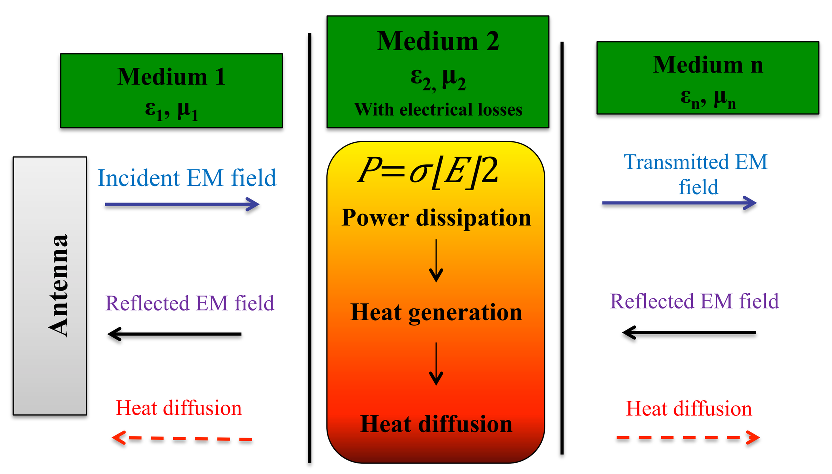
σ = Electrical conductivity,, ρ=Volume density E = Field component

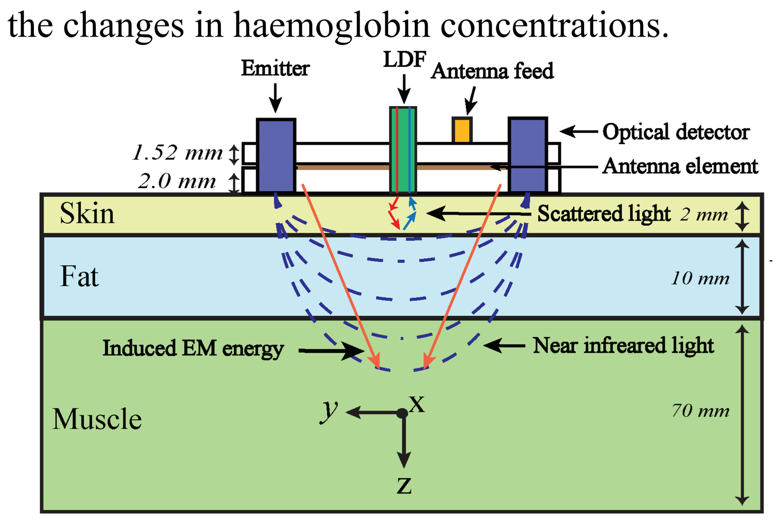
- The Absorbed EM energy causes inner molecular vibration and produces joule heating. The induced heat is modelled with biological heat equation which considers the human thermoregulations.

$$\rho c\frac{\partial T}{\partial t}=k\nabla^2 T+\rho(SAR)+Q_m-Q_b\left(T-T_b\right)$$

c = Heat capacity,, k = Thermal conductivity Q_b =Blood perfusion,, Q_m = Metabolic rate.

- The human thermoregulation reacts to the induced heat, causing blood vessels to dilate and thus increasing oxygen transport to the tissue to transport the excess of heat away. Optical sensors based on Near Infra-red Spectroscopy is integrated with the applicator to monitor the changes in haemoglobin concentrations.


Heat generation concept in lossy biological medium

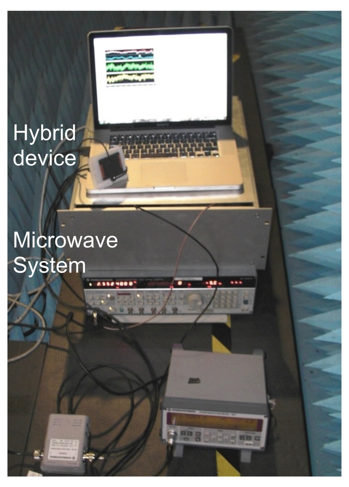

Applicator operation concept

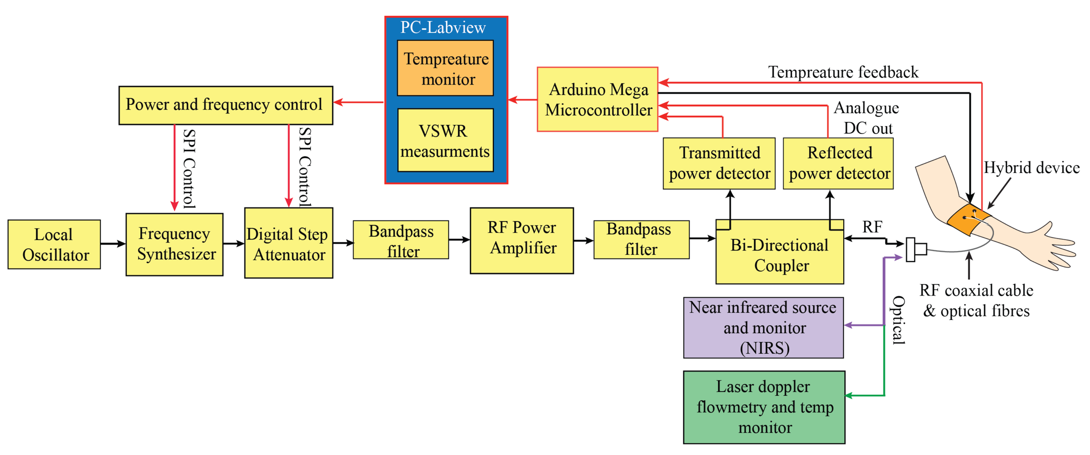
3. Hybrid System

The applicator is placed either on thigh or arms of the patient, therefore the design must be compact. The Hybrid device running on three different systems including RF to induce EM field, NIRS to monitor changes in human physiology and Laser Doppler Flowmetry (LDF) to monitor changes of blood flow in the skin.


LDF monitor

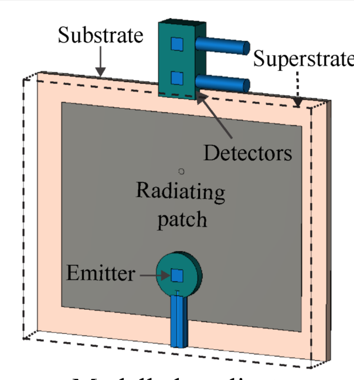

Optical Source & detector (NIRS)

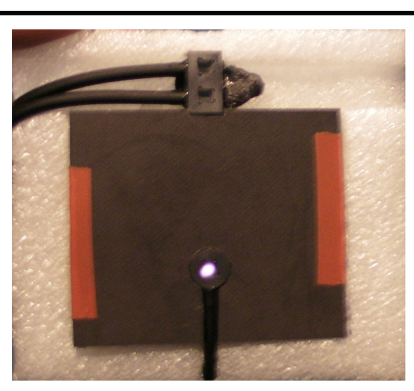

RF system

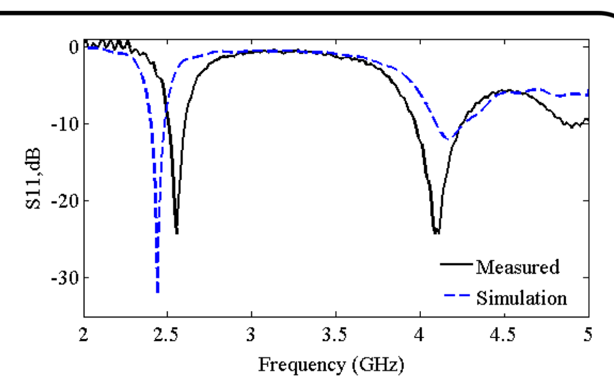

General system outline

4. Applicator Design

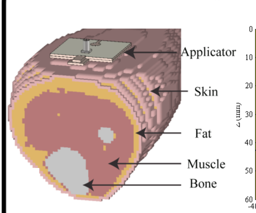
Antenna is modelled with CST Microwave Studio, the operating frequency is 2450 MHz, the measured and simulated frequency are different due to fabrication accuracies and variation in tissue dielectric.

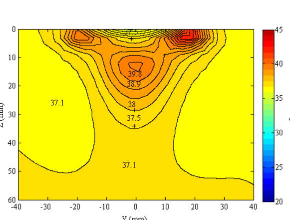

Modelled applicator


Designed applicator


Simulated and measured S-parameter

Modelling and Simulation


Human Calf model


Thermal Simulation

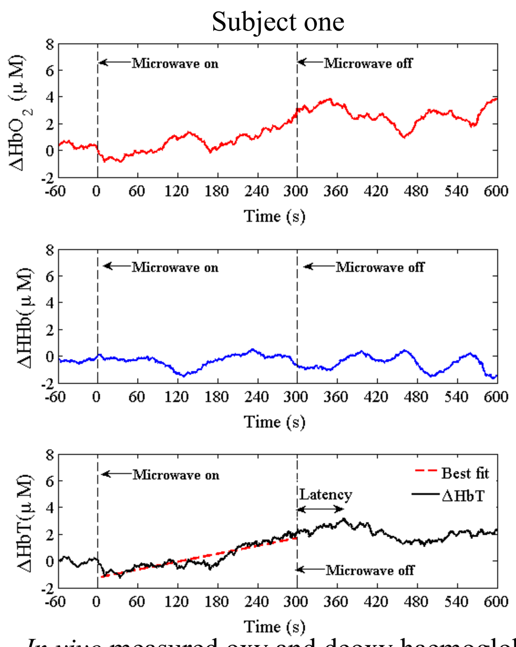
Experiments


In vitro Phantom / chicken breast

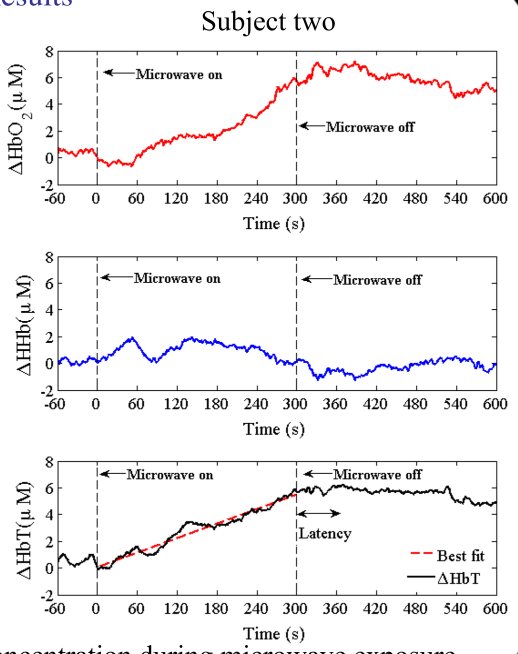

In Vivo Human calf

In vivo Results

Subject one



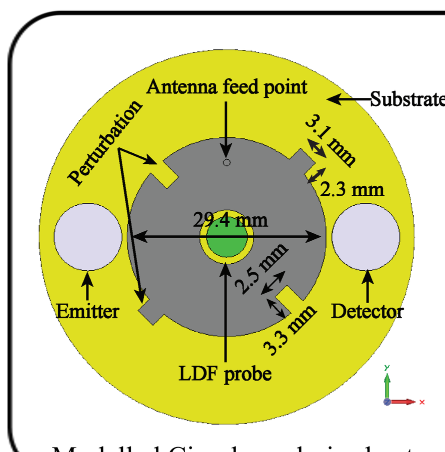
Subject two

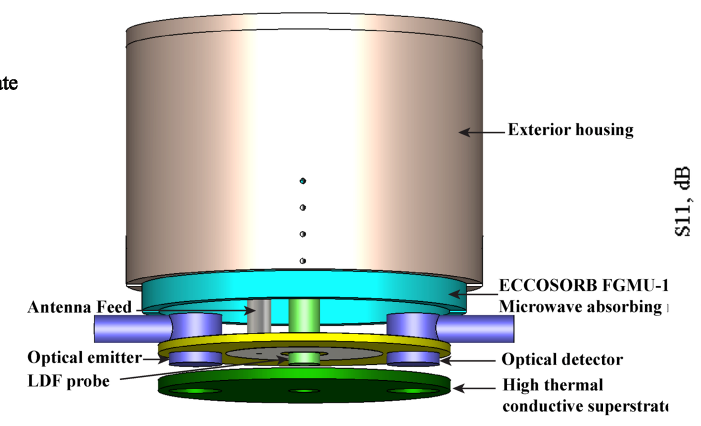


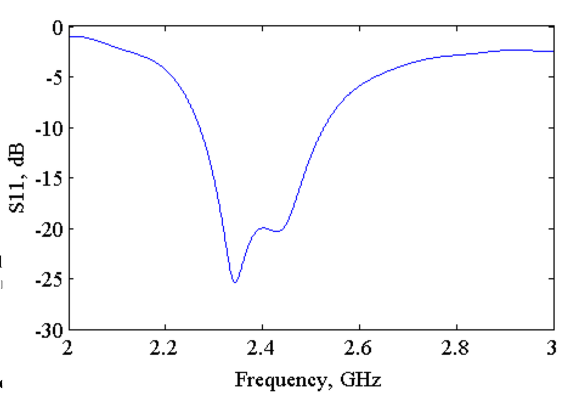
In vivo measured oxy and deoxy haemoglobin concentration during microwave exposure

5. Improvements

- The contribution of skin heating to the measured thermal response during in vivo trial was unknown.
- A second optical monitor based on Laser Doppler technique is included in the applicator to measure the changes in skin blood flow, which is used to validate the results obtained by the NIRS.
- Previously antenna operates on linear polarisation, and typically the induced EM field is maximum at the radiating edges, producing a concentrated peak stray radiation on each radiating edge.
- To mitigate the peak stationary E-field components, we investigate circularly polarised antenna, where the electric field components varies in time and space, thus induced field is spatially distributed.

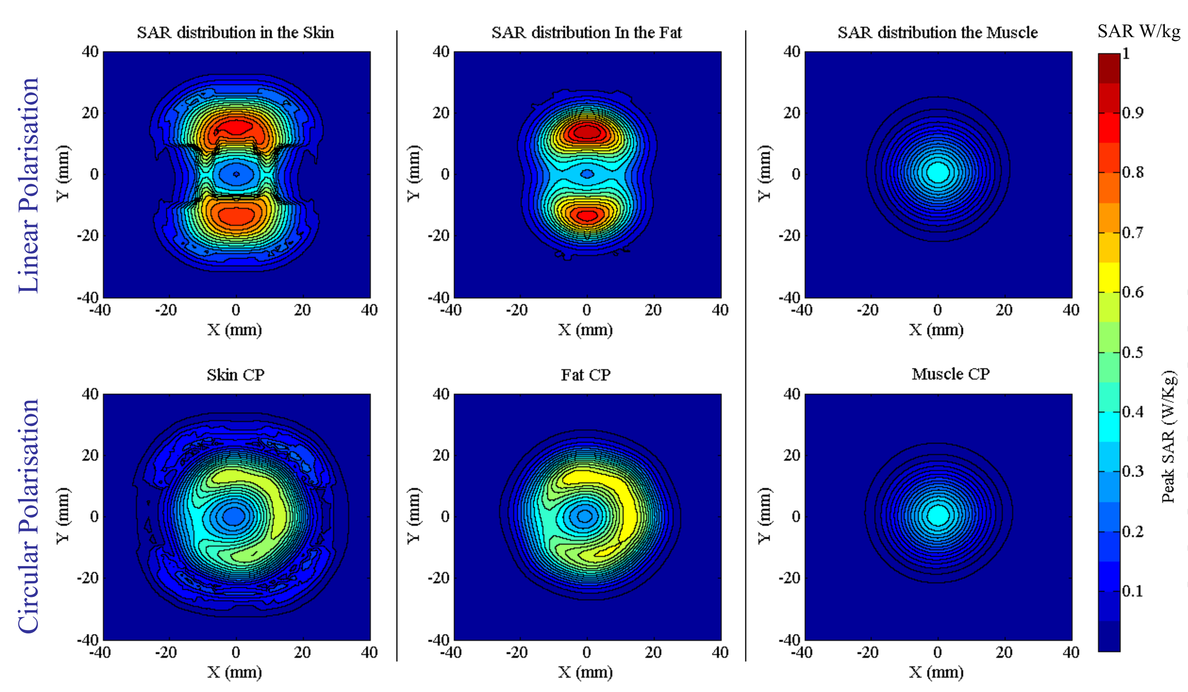

Modelled Circular polarised antenna

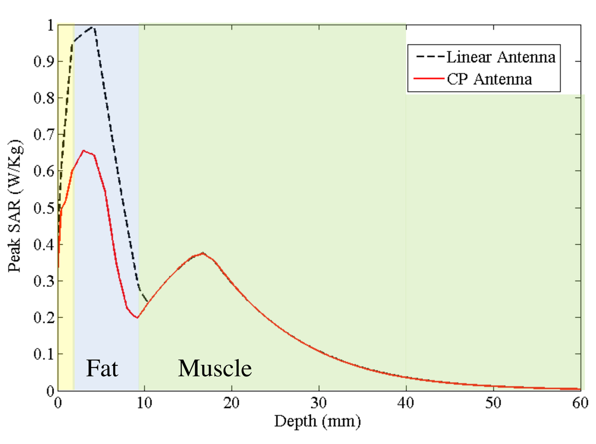

Applicator housing


Simulated S-parameter

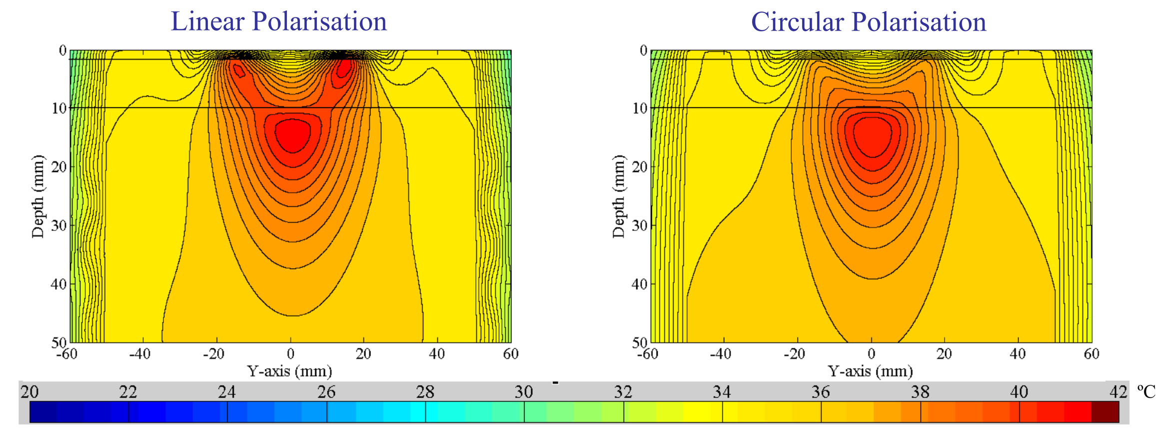
6. SAR Reduction

- Based on the SAR equation, the distribution of the deposited EM energy is used to estimate the performance of the applicator. The SAR is normalised to 1 W/kg inside each layer of tissue corresponding to skin, fat and muscle across *yx*-plane
- The results are comparison between linear and circular polarisation, and it can be seen with circular polarisation the deposited energy is distributed and therefore decreases the peak SAR in the skin and fat.


Simulated SAR distribution between linear and circular polarised antenna


Peak SAR in the tissue at different polarisation

- Simulation of thermal distribution based on the bio-heat equation, for 10 minutes of microwave exposure across the *yz*-plane . The peak temperature for linear polarised antenna is located at the skin-fat interface agreeing with the SAR results.
- Thermal distribution of circular polarised antenna have a peak temperature in the muscle and reduced superficial heating caused distributed EM field. The new design uses a superstrate with high thermal conductivity which takes the excess of heat away from the skin.



Thermal Distribution after 10 minutes of microwave exposure

7. Conclusion

- First applicator was modelled and designed, however simulation results indicates skin heating will occur which effect the measured response of muscle.
- *In vivo* results demonstrates the increase in oxy-haemoglobin concentration during microwave exposure which causes arterial blood vessel to dilate in the muscle and possibly in the skin.
- RF system includes safety features and provides flexibility to the operating frequency.
- New applicator design includes an LDF sensor to monitor the amount of skin flow changes
- New applicator design based on circular polarisation, where in simulation it proves to reduces superficial heating.

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Email contact :
a.armaghany@ee.ucl.ac.uk