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Introduction to ionizing radiation acoustics: history, principles, and technologies

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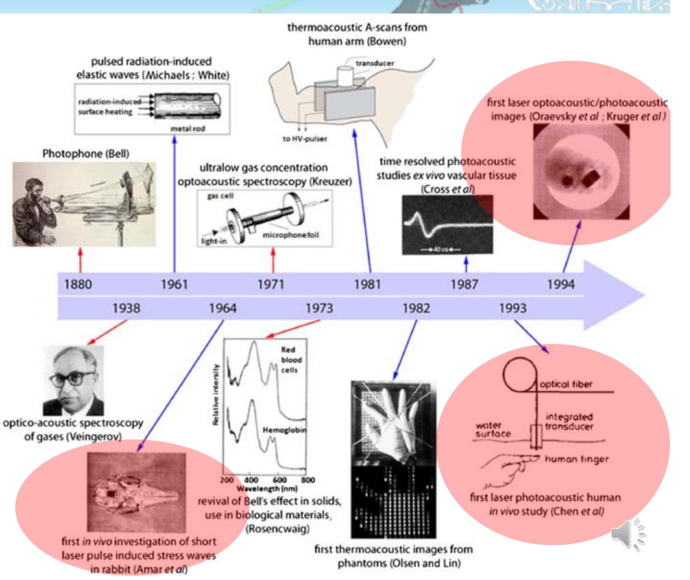
Introduction

In 1880, studying first optical-driven forms of communications (photophone), Bell realized that modulated light produces acoustic waves

"… sounds can be produced by the action of a variable light from substances of all kinds…".
Bell, Am. J. Sci. 118, 305 (1880)

This „radiophonic" found a new revival with the laser developments in the 1960s, leading to the widely established biomedical field of opto/photoacoustics

Manohar & Razansky, Adv. Opt. Phot. 8, 586 (2016)



The underlying principles of radiation acoustics

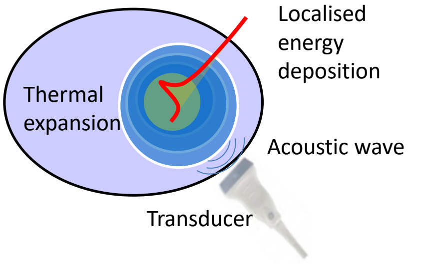
As historical “radiophonic” name suggests, acoustic emissions are not limited to light absorption

For ionizing radiation, the thermoacoustic emission can be linked to dose deposition

$$D = \frac{E}{m} = \frac{E_H}{(1 - k_{HD})m}$$

Heat energy

Heat defect ≈0…0.01



For E_H deposition on a shorter time scale than volume/density change, temperature rise is

$$\Delta T = \frac{H}{\rho_0 \cdot C_v}$$

Heat energy density (E_H/V)

Mass density

Specific heat capacity at constant volume

Hickling et al Med Phys 45, e707 (2018), Parodi and Assmann, Mod Phys Lett A 30, 1540025 (2015)

The underlying principles of radiation acoustics

Temperature increase ΔT is linked to pressure generation via thermodynamics equations

Isothermal compressibility

$$\mathbf{0 =}\ \Delta\rho = \rho_0 K_T \Delta p - \rho_0 \beta \Delta T$$

Differential pressure

Isobaric expansion coefficient

Speed of sound

$$v_s^2 = \frac{C_p}{K_T \rho_0 C_v}$$

Specific heat capacity at constant pressure

$$\Delta p = \frac{\beta v_s^2}{C_p} H$$

Dimensionless Grüneinsen coefficient Γ indicating conversion efficiency of deposited heat into pressure variation

Initial pressure distribution following a pulse of ionizing radiation at location **r** is

$$p_0(\mathbf{r}) = \Gamma(\mathbf{r}) \cdot D(\mathbf{r}) \cdot \rho(\mathbf{r}) \cdot (1 - k_{HD}(\mathbf{r}))$$

Hickling et al Med Phys 45, e707 (2018)

The underlying principles of radiation acoustics

Acoustic wave propagation after radiation pulse in elastic and inertial medium

$$\nabla^2 p(\mathbf{r},t) - \frac{1}{v_s^2}\frac{\partial^2}{\partial t^2}p(\mathbf{r},t) = -\frac{\beta}{C_p}\frac{\partial}{\partial t}H(\mathbf{r},t)$$

Where the heat energy deposition can be assumed instantaneous if heating pulse width τ_H satisfies

Thermal confinement:

$\tau_H < \tau_{therm}$ (thermal relaxation time >> 100 ms)

$$p_\delta(\mathbf{r},t) = \frac{1}{4\pi v_s^2}\frac{\partial}{\partial t}\left[\int d\mathbf{r}'\,\frac{p_0(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}\delta\left(t-\frac{|\mathbf{r}-\mathbf{r}'|}{v_s}\right)\right]$$

Stress confinement:

$\tau_H < \tau_{stress} = \frac{d}{v_s}$ (stress relaxation time, ≈ 0.7 μs for d = 1mm)

Otherwise
$$p(\mathbf{r},t) = \int_{-\infty}^{+\infty} dt'\,p_\delta(\mathbf{r},t-t')S(t')$$

with *S(t)* temporal profile of heating source (only possible for temporally varying sources!)

Hickling et al Med Phys 45, e707 (2018)

The first investigations of radiation acoustics

Beam diagnostics

EXPERIMENTAL STUDIES OF THE ACOUSTIC SIGNATURE OF PROTON BEAMS TRAVERSING FLUID MEDIA*

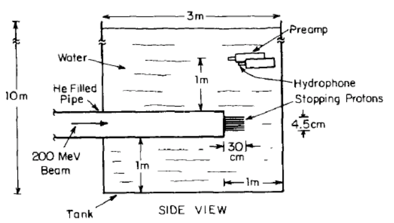


Fig. 3. Detector arrangement for the linac experiment.

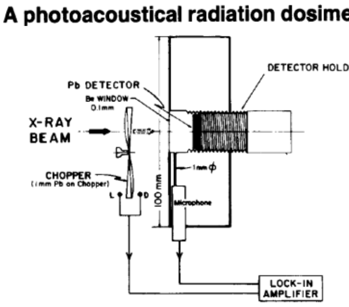
6. Conclusions

We have demonstrated that an observable acoustic signal is produced in a single transducer by charged particle depositions $\gtrsim 10^{14}$ eV in fluid media. The source of the signal is dominantly thermal expansion. Applications to beam monitoring, heavy ion experiments, high energy physics and cosmic ray physics are foreseeable.

Sulak et al, NIM 161 (1979)

Dosimetry

A photoacoustical radiation dosimeter



CONCLUSIONS

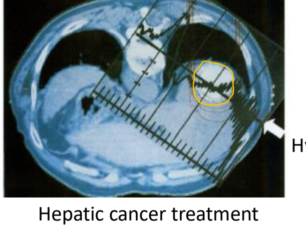
The photoacoustical radiation dosimeter has the following characteristics for diagnostic x-ray beams: (1) It has a linear response with radiation intensity at a fixed radiation quality. (2) It measures directly the energy fluence rate in the radiation beam when a totally absorbing detector is used. (3) It has an inverse frequency response for the case of an opaque thermally thin sample.

Mascarenhas et al, Med Phys 11 (1984)

In-vivo treatment monitoring

Acoustic Pulse Generated in a Patient During Treatment by Pulsed Proton Radiation Beam

Pulsed *p* beam



Hydrophone

Hepatic cancer treatment

DISCUSSION

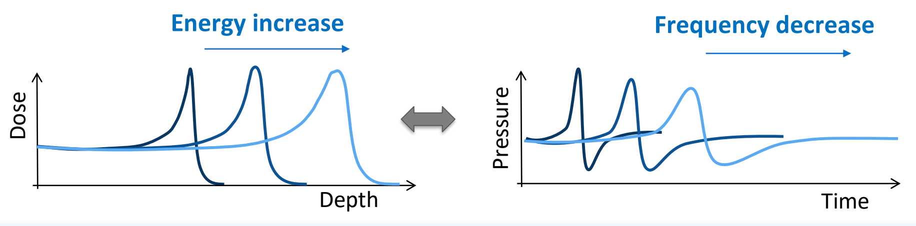
To utilize acoustic pulse generation for non-invasive monitoring of three-dimensional dose distributions in a patient's body, a two-dimensional array of hydrophones must be created [12]. This two-dimensional array of hydrophones may be applied in the echo technique allowing the three-dimensional dose distributions to be superimposed on the anatomic structures.

Y. Hayakawa et al, Rad. Onc. Invest., 3, (1995)

The challenges of radiation acoustic detection

Ultrasonic detectors

- High sensitivity (e.g., in proton therapy ~mPa thermoacoustic pressure << ~100 kPa for US)
- Central frequency & bandwidth matched to application, depending on radiation quality and source temporal properties (e.g., for proton therapy at synchrocyclotrons ~10-50 kHz vs ~MHz for US)
- Space requirement / material budget



Courtesy J. Lascaud, LMU

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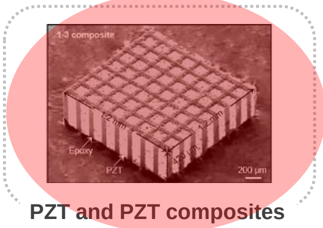
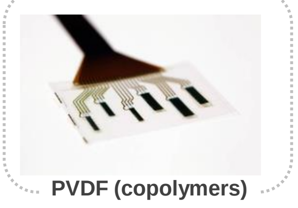
US transducer technologies

Piezoelectric based transducers

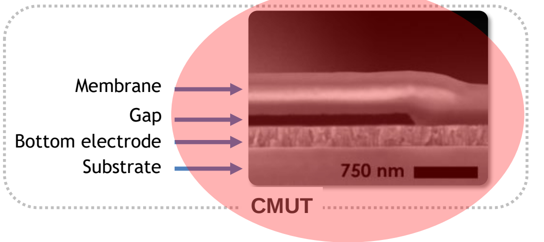




- Widely used in US imaging
- Bulk ceramic material or epoxy/PZT composites
- Narrow bandwidth

- Widely used as broadband receivers (hydrophones)
- Thin films (usually ~28 µm)
- Flexible
- Good sensitivity

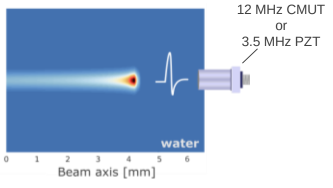
MicroElectroMechanical Systems (MEMS)

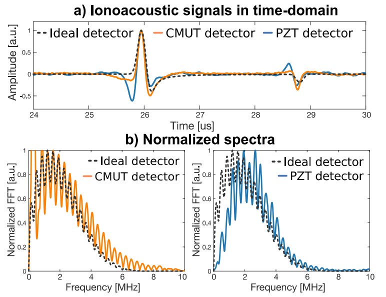


- Emerging technologies in US imaging
- 3D microstructures with suspended membrane sealed under vacuum
- Broad bandwidth
- Good sensitivity

PZT: Lead zirconate titanate – PVDF: Polyinylidene difluoride – CMUT: Capacitive Micromachined Ultrasonic Transducers

CMUT vs PZT for 20 MeV pulsed proton beams in water





Without ripple filter

And more technologies to be presented in next talks …

Larger bandwidth and better sensitivity of CMUT* vs PZT:

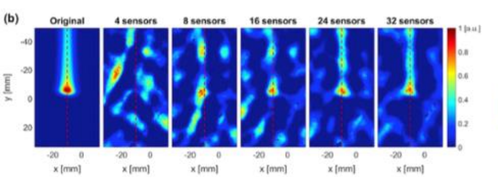
- Increased SNR
- Independent of beam energy and probe position
- Bi-modality imaging (US / Radiation acoustics)

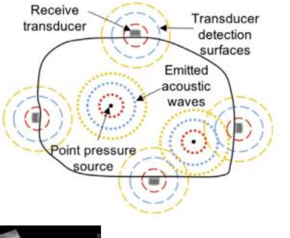
CMUT developed by Dr Savoia in Università Tre Rome, Italy** ***J. Lascaud …Parodi, IEEE IUS 2019; see also TU-A-TRACK 3-0

The workflow possibilities of radiation acoustics

Detection of radiation acoustics signal, ideally with multiple transducers enables

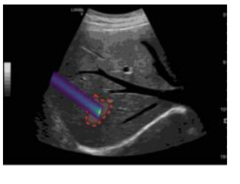
- Image / dose reconstruction
- Triangulation





Co-registration with US for

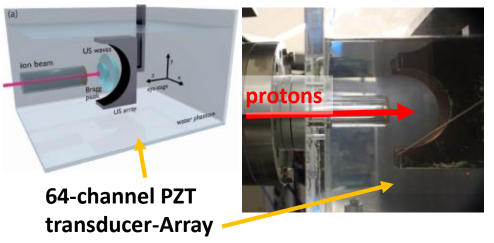
- Overlay with underlying anatomy
- Compensation of the speed of sound variations

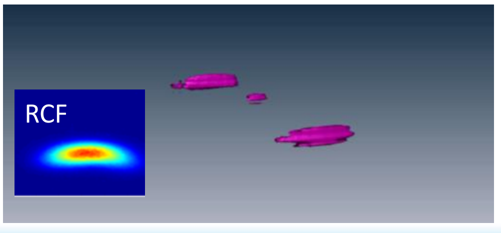


Yu et al. Med Phys 46(8), 3649-3662 (2019), Hickling et al Med Phys 45, e707 (2018)

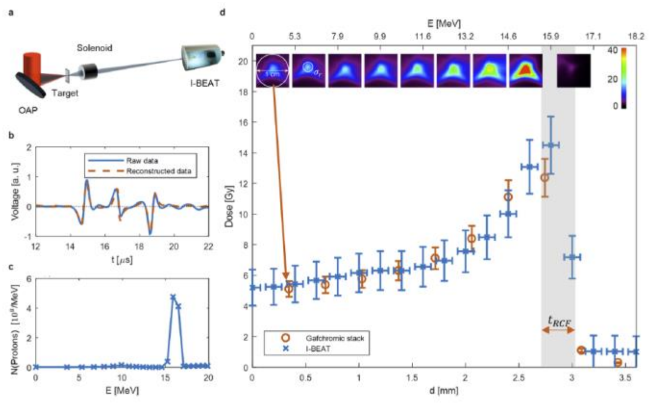
Imaging and dose reconstruction of low energy proton beams

20 MeV pulsed protons from tandem accelerator





~15 MeV focused protons from laser-driven source



Promising dosimeter for FLASH applications

Kellnberger, … Parodi, Ntziachristos, Sci. Rep. 2016

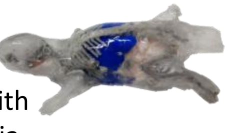
Haffa, … Parodi, …Schreiber, Sci. Rep. 2019

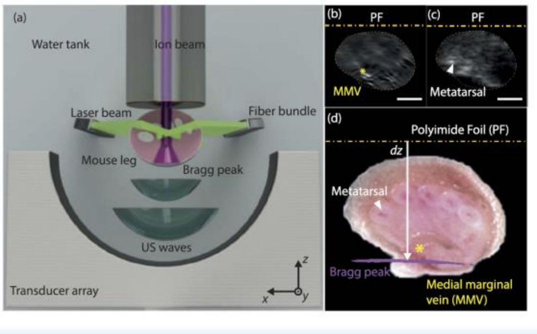
Co-registration

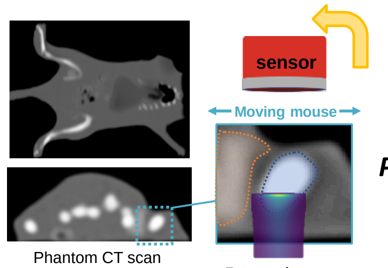
20 MeV pulsed protons from tandem accelerator

Co-registration with optoacoustics (same curved transducer) and US (linear array transducer) in leg of sacrificed mouse

3D printed multimodal mouse
Ionoacoustics/US co-registration with single sensor in heterogenous media







Phantom CT scan
(top: coronal & bottom: axial planes) Proton beam

Preliminary Exp. results

See also TU-A-TRACK 3-0

Kellnberger, … Parodi, Ntziachristos, Sci. Rep. 2016

Lascaud … Parodi, talk at Small Animal Precision IGRT conference;
Lascaud … Parodi, submitted to IEEE MIC 2020; Dash MSc thesis

Conclusions & Outlook

Radiation acoustics for beam diagnostics, dosimetry and treatment monitoring envisioned since 1980s

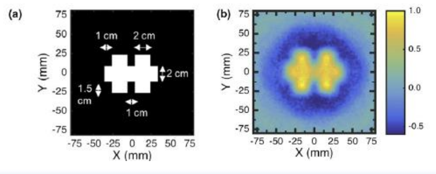
Current renaissance for medical application mainly due to wider availability of

- Pulsed radiation sources (LINACs, synchrocyclotrons, laser-driven accelerators, …)
- Improved sensor technologies and computer power

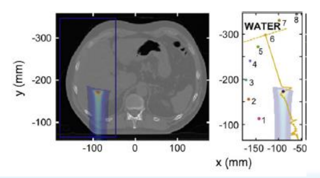
Several ongoing projects for pre-clinical and clinical applications, including promise for FLASH therapy

Next talks will review applications in

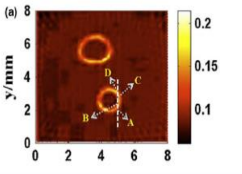
Photon therapy (S. Hickling)



Proton therapy (S. Avery)



X-ray imaging (L. Xiang)



Hickling et al Med Phys 45, e707 (2018)

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Munich Tandem Accelerator, Nov. 2019

See also PO-GeP-T-80, PO-GeP-T-463, TU-A-TRACK 3-0

Further reading

Ionizing radiation-induced acoustics for radiotherapy and diagnostic radiology applications

Med. Phys. 45 (7), July 2018

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Thank you for your attention!