Accelerators,
a history of
Innovation & Spin-off

P.J. Bryant

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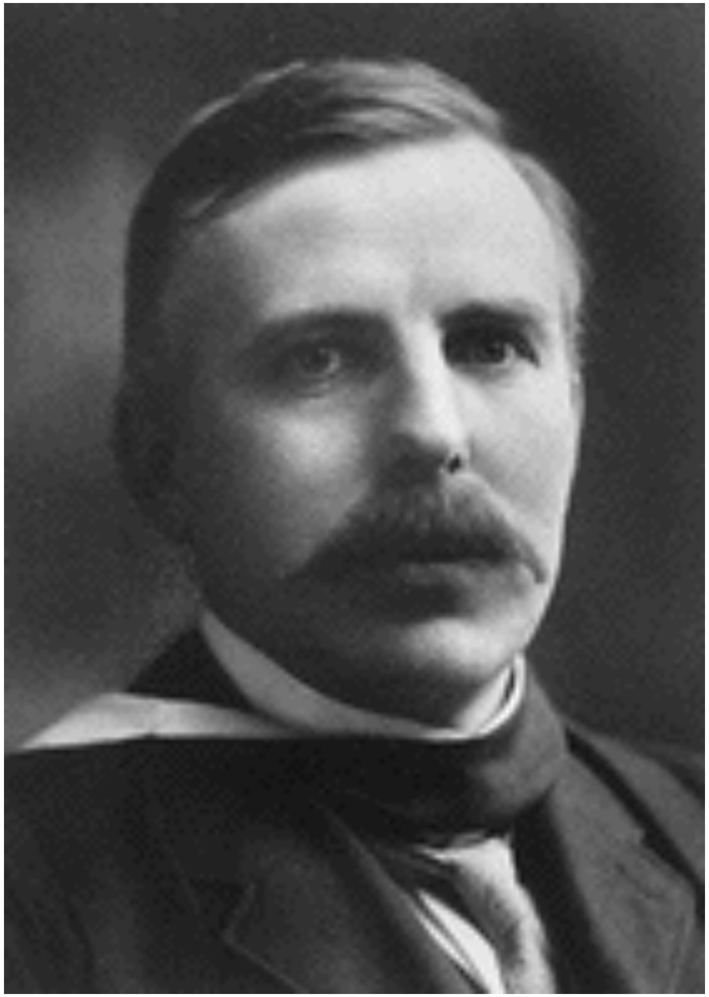
Contents

The first birth

- When speaking of the birth of accelerators and high-energy physics, **Ernest Rutherford** is frequently named as the father:

- Born 30/8/1871 in Nelson, New Zealand.
- Died in Cambridge, UK in 1937.
- Professor of physics at McGill University, Montréal (1898-1907).
- Professor of physics at University of Manchester, UK (1907-1919).
- Professor of experimental physics and Director of the Cavendish Lab., University of Cambridge, UK.



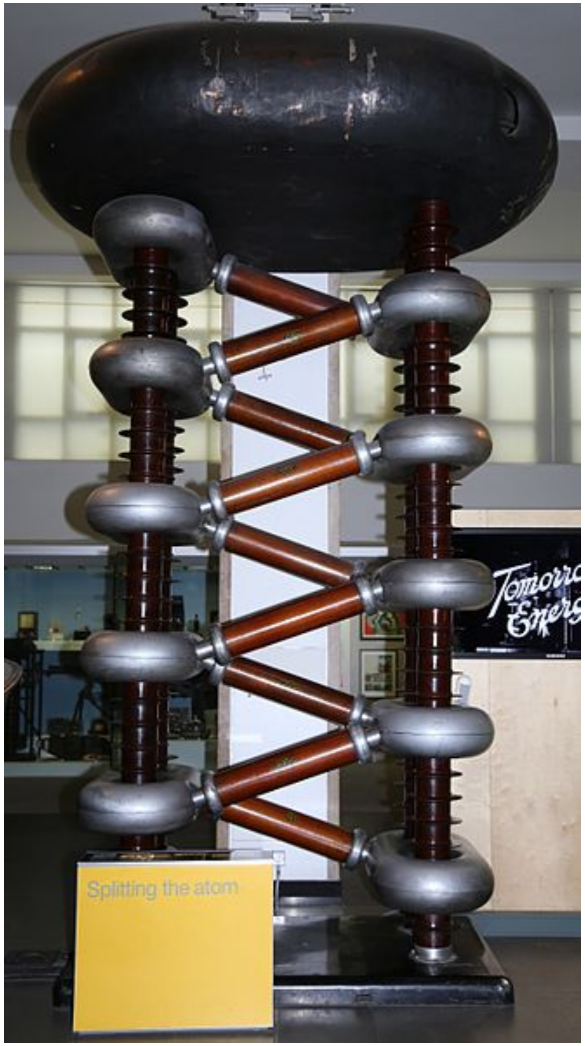
The first birth (continued)

- In 1906, Rutherford bombards a mica sheet with natural alphas of a few MeV and in 1919 he induces a nuclear reaction.
- Rutherford believes that he needs a controllable source of many MeV to continue his research on the nucleus and this is far beyond the electrostatic machines then existing, but in …
- **1928 George Gamov predicts 'tunnelling' and perhaps 500 keV would suffice ?**
- 500 keV appeared to be feasible and so a project for the first accelerator for physics research was launched at Cavendish Lab.
- In 1928, encouraged by Rutherford, John Cockcroft & Ernest Walton start designing an 800 keV generator. By 1932 the generator reaches 700 keV and Cockcroft & Walton split the lithium atom with protons of only 400 keV. **They receive the Nobel Prize in 1951**.

The first birth (continued)

- For the next four decades, every accelerator complex around the globe had a Cockcroft Walton Generator as its front end.
- As an engineering solution, it was reliable, robust and highly successful, although for some it was only a power converter and not a true accelerator.
- **The conception and construction of the Cockcroft Walton is a text book example. A need was identified, a specification made and the equipment was built to a budget and schedule.**

  It does not always work out this way…



Cockcroft–Walton generator in the London Science Museum - WikiMedia Commons

The second birth

- In 1924, Gustav Ising proposes time-varying fields across drift tubes as an acceleration mechanism. This is a 'true' accelerator that can achieve energies above the highest voltage in the system.

- In 1928, Rolf Widerøe (a Norwegian PhD student in Aachen) demonstrates Ising's principle with a 1 MHz, 25 kV oscillator and makes 50 keV potassium ions; the first linac.

- In 1929, Ernest Lawrence, inspired by Widerøe and Ising, conceives the cyclotron; a 'coiled' linac and, in 1931, Stanley Livingston demonstrates the cyclotron by accelerating hydrogen ions to 80 keV.

- In 1932, Lawrence's cyclotron produces 1.25 MeV protons and he splits the atom just a few weeks after Cockcroft & Walton. Lawrence received the Nobel Prize in 1939.

- **This tale appears slick and efficient with the bonus that it stems from an extremely important theoretical invention.**

  However, the fuller story is more confused and somewhat serendipitous.

The second birth (continued)

Another would-be cyclotron inventor

- Jean Thibaud is a young physicist in Maurice de Broglie's lab. in Paris, who is also impatient with natural radioactive sources. He uses the ideas of Ising to reach 145 keV after passing positive ions through no less than 11 rf gaps driven at 3 MHz. His aim was to reach 10 MeV.
- Realising the practical problems of a linear structure, Thibaud built a cyclotron and in 1932 claimed observation of the 'resonance condition' before Lawrence at Berkeley.
- Lawrence was in contact with Thibaud after the 1933 Solvay Conference, but **lack of support and encouragement from Thibaud's bosses stopped all cyclotron work in France**.

The second birth (continued)

More would-be cyclotron inventors

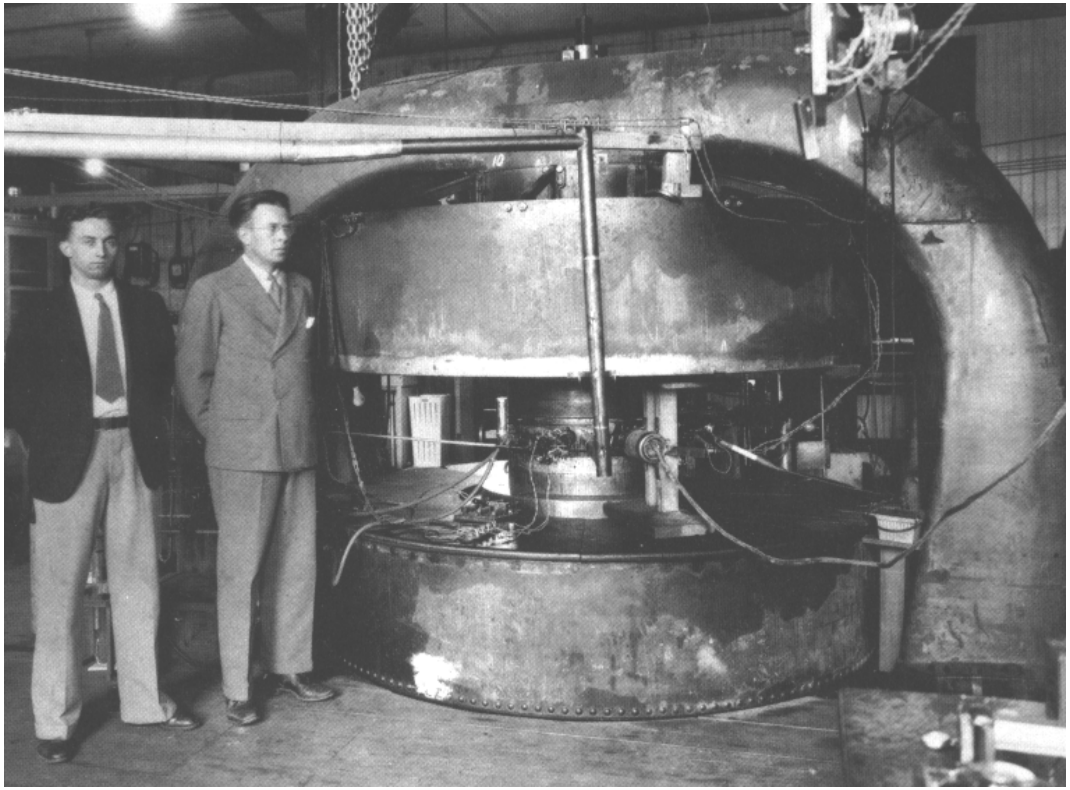
- Denis Gabor claimed to have thought of it in 1924, but was too busy to act at the time.
- Eugen Flegler, a colleague of Widerøe, had proposed the use of a magnetic field as early as 1924, but was discouraged by Widerøe over doubts about orbit stability.
- **On January 5 1929, Leo Szilard filed a patent for a cyclotron and contacted Gabor, who was working for Siemens at the time, but Gabor (Siemens?) took no further action.**
- Max Steenbeck recounts that during his PhD (1927) he solved a numerical problem for a student for what was essentially a 20 cm 1.4 T cyclotron. Later Steenbeck went to work for Siemens and was encouraged to write up his idea, but his chief returned the manuscript requesting to see Steenbeck. **The latter felt that this was a rejection and Siemen's lost the cyclotron for a second time.**

The second birth (continued)

Lawrence and the cyclotron

- Lawrence saw (early 1929) Widerøe's article in *'Arkiv für Electrotechnik'* and was inspired to build a cyclotron.
- Yes, but it seems he had taken the journal to pass the time in a boring meeting and with the possible intention of looking at an article by Rogowski on Kerr cells – a subject closer to Lawrence's work at that time. Moreover, he did not speak German and was limited to looking at pictures and equations.
- Lawrence was slow to react possibly because he had reservations about stability and possibly because this represented a significant change from his earlier work. It was Otto Stern who finally encouraged him into action.
- His first graduate student, Niels Edlefsen, was only partially successful and it fell to a second student, Stanley Livingston, who was looking for a PhD topic, to provide the proof-of-principle experiment.

The second birth (continued)



Stanley Livingston and Ernest O. Lawrence (left to right) beside the 27 inch cyclotron at Berkeley circa 1933. The peculiar shape of the magnet's yoke arises from its conversion from a Poulson arc generator of RF current, formerly used in radio communication.

The second birth (continued)

Comments

- **When all the factors needed for an invention are in place, it often happens that the idea erupts in several places at the same time.**

- **Informal discussions can make it difficult to determine the exact provenance of an idea especially when the players are very close, e.g. Widerøe was Rogowski's PhD student, Flegler was Rogowski's chief assistant.**

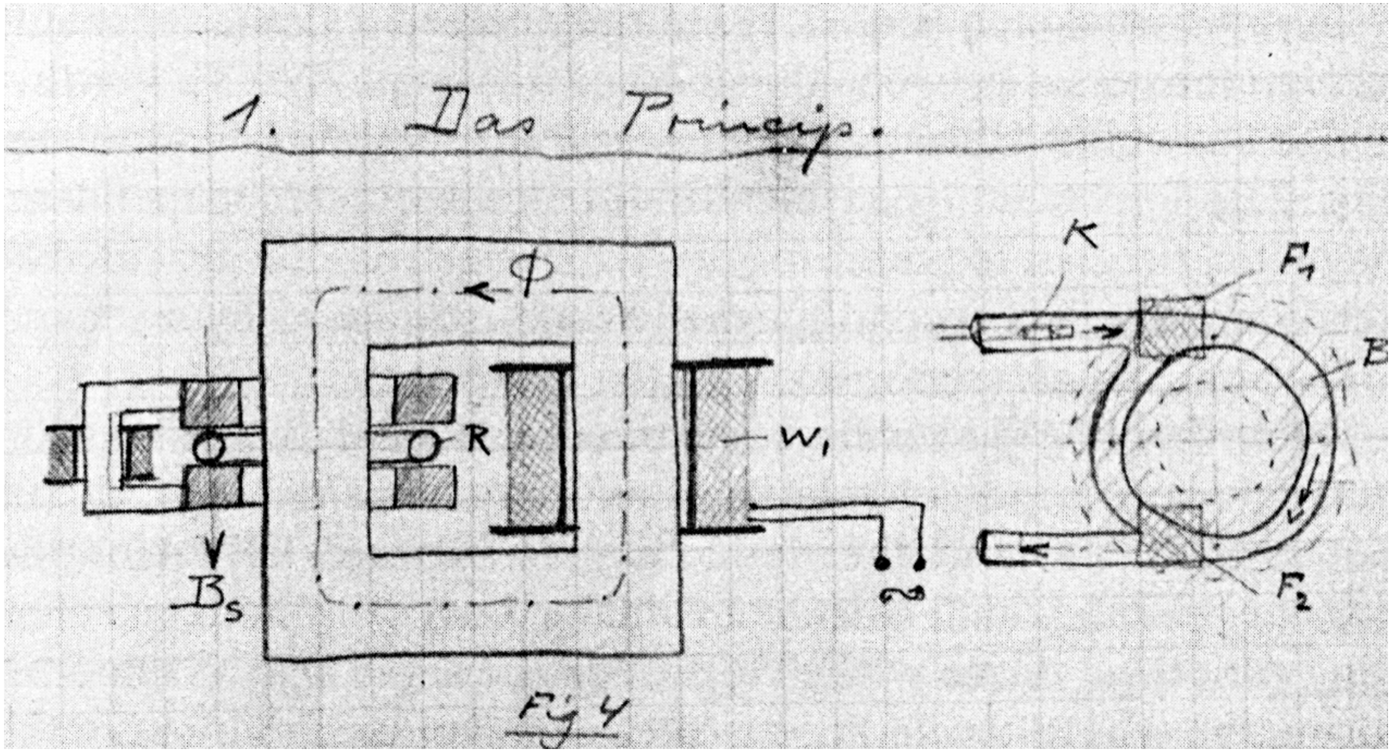
- **Informal discussions can also create an unchallenged consensus against an idea, e.g. Eric Baron in a Ganil report says that Lawrence was lucky not to know that the Europeans had decided the cyclotron would not work and that Flegler lost the Nobel prize because of this.**

- **The last word lies with Szilard who said *"The merit lies in the carrying out and not in the thinking out of the experiment"*.**

The third birth

- In 1923, Widerøe, a young student, draws in his laboratory notebook the design of the betatron with the well-known 2-to-1 rule. He adds the condition for radial stability 2 years later, but does not publish.
- In 1927 in Aachen, Widerøe makes a model betatron, but it does not work. Discouraged, he changes course and builds the world's first linac (see previous history line). **His betatron lies forgotten in his drawer.**
- All is quiet until 1940, when Donald Kerst re-invents the betatron and builds the first working machine for 2.2 MeV electrons (University of Illinois).
- 1950 Kerst also builds the world's largest betatron (300 MeV).
- **Widerøe's tale is well known and everyone smiles. Surely such a thing could not happen again, or could it?**

The third birth (continued)



Widerøe called this device a "Strahlung Transformator" because the beam effectively forms the secondary winding of a transformer. The above diagram is taken from his unpublished notebook (1923). This device is insensitive to relativistic effects and is therefore ideal for accelerating electrons. It is also robust and simple.

Laboratory drawers

Leaving papers in drawers is rare, but not exceptional:

- A case that passed largely unnoticed was the Hamiltonian analysis of betatron coupling. In 1976 the ‘*Complete Hamiltonian theory for sum and difference resonances in 3D fields*’ was published by G. Guignard, CERN. Shortly after publication, Phil Morton from SLAC sent us an unfinished and unpublished note that reached many of the same results concerning betatron coupling 10 years earlier.

- Another example is betatron matching into medical gantries. During the design of the Loma Linda medical facility Lee Teng invented the rotator that matches the Twiss and dispersion functions from a fixed beam line into a rotating gantry in a mathematically exact way. A diagram in a Loma Linda patent shows a structure that is clearly an early form of rotator, but it is not included in the claims nor was it ever built. Teng did write an internal note but never published. Over 20 years later, C. Carli in CERN re-discovered the mathematics behind the rotator and M. Benedikt added rules to make a practical device. In the intervening years, machines had used other less exact methods to perform this matching.

Laboratory drawers (continued)

A variant of this theme concerns Nicholas Christofilos

- In 1948, Christofilos was sending the University of California Radiation Laboratory at Berkeley letters with his ideas on accelerators. At first he received replies explaining flaws, **but in 1949 the all-important letter containing the invention of strong focusing was put in a drawer and left unanswered.**
- Undeterred Christofilos applied for a patent in 1950 (granted 1956).
- Meanwhile Courant, Livingston and Snyder independently invented strong focusing at BNL in 1952.
- In 1953, Christofilos confronted BNL, the AEC paid him 10 k$ for his patent and he was credited as the original inventor.
- In the same year, Christofilos unveils his clever new idea for controllable fusion, which later became the ASTRON machine under his leadership at Livermore. Christofilos died in September 1972 and ASTRON closed shortly after, but he is recognised as the inventor of the Reversed Field Concept for fusion.

A cautionary tale

- The Cyclotron Corporation (TCC), Berkeley was active in the spin-off technologies of PET scanners and cyclotrons. During the 1970s, TCC and Scanditronix were the two principal suppliers of cyclotrons for isotope production.
- In the late 1970s, TCC moved from first generation, positive-ion (proton) machines (e.g. CS30) to the second generation negative-ion (H minus) machines with stripping extraction (e.g. CP42). This greatly increased the beam intensity and several machines were sold before the prototype was working correctly.
- Alas, the teething problems led to the collapse of TCC in 1983 and briefly Scanditronix took the world market with the old technology. **Fatally, Scanditronix had misread the situation.**
- In reality, TCC were unlucky and all their unfinished machines were resurrected and worked faithfully for decades to come. IBA a new spin-off company in Belgium read the situation correctly and built improved versions of the TCC technology. The IBA Cyclone 30 became the de facto world standard for isotope production.
- IBA bought Scanditronix in 1998.

CT scanners

- **The foregoing tales may be entertaining, but can we recognise any inventions or innovations that are poised to break through today?**

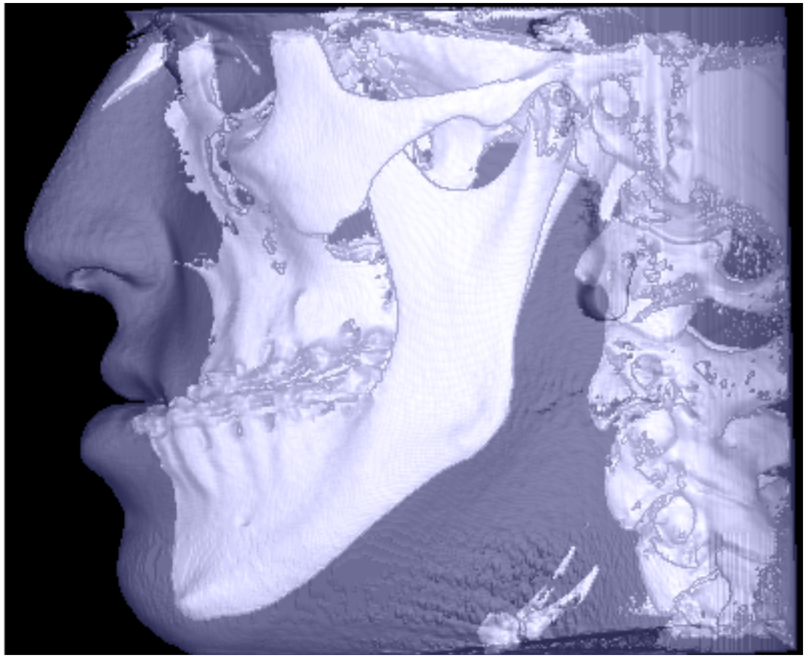
  Let us look into one of the most successful inventions ever, the CT (Computed Tomography) scanner – after 45 years and more than 6 million patents surely the system is as near perfect as it can be, or is it?

*** * ***

- In 1972, Godfrey N. Hounsfield, UK, published the X-ray CT system conceived by him in 1967 at the Thorn EMI Research Laboratories [1].
- In general, the spatial accuracy, the rectilinearity of edges, etc. are reported as being near perfect, but there are some dissenting voices concerning the accuracy of the CT numbers (i.e. the radio-density of the voxels).

CT scanner (continued)

- A CT scan is not just hundreds of X-sections
- Surfaces can be generated. Views of composite surfaces can be made (see opposite the combination of facial tissue and bone surfaces). Bones can be isolated. Sections can be created at any angle. Measurements can be made on the 3D volumes and so on.
- Who would not fall in love with such a tool?



Signs of discontent

- As early as 1982, Levi C. et al speak of the unreliability of CT numbers as absolute values [2].
- More recently in 2000, Groell R. et al quote CT number variations in a thorax phantom study made in different CT scanners. They state that **"The radiologist has to be aware of these variabilities in his own CT scanner, particularly when CT numbers are used for tissue characterization"[3].**
- Lagravère et al. (2006) warn that their results are only applicable to the NewTom QR-DVT 9000 as other machines respond differently [4].
- Loubele et al. (2006) describe in some detail the choice of thresholds for the measurement of bone thickness and complain of large variations in CT number between different bone structures in the same image, between different patients and between different scanners [5].
- **There are many possible reasons for the above, but there is one that is so basic that it is contrary to scientific method.**

A fundamental problem

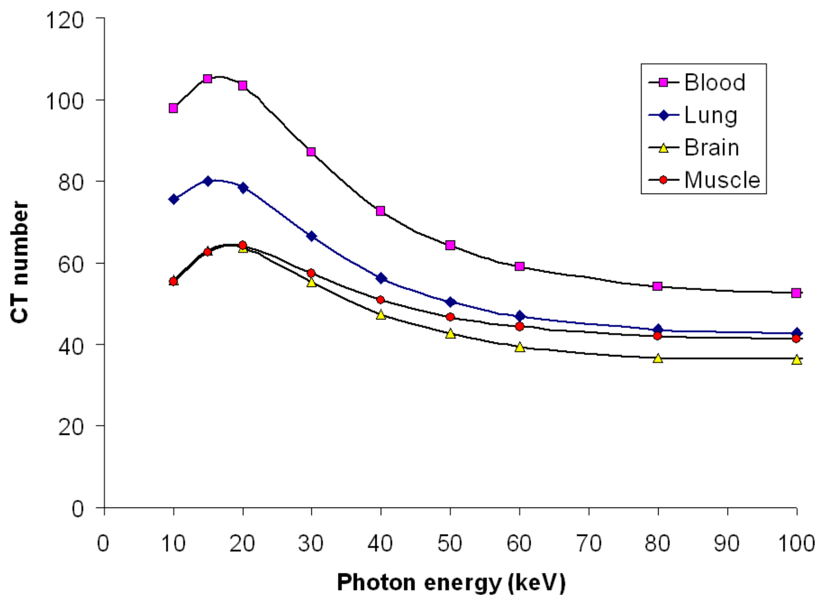
To interpret CT scans, a CT or Hounsfield number scale is used,

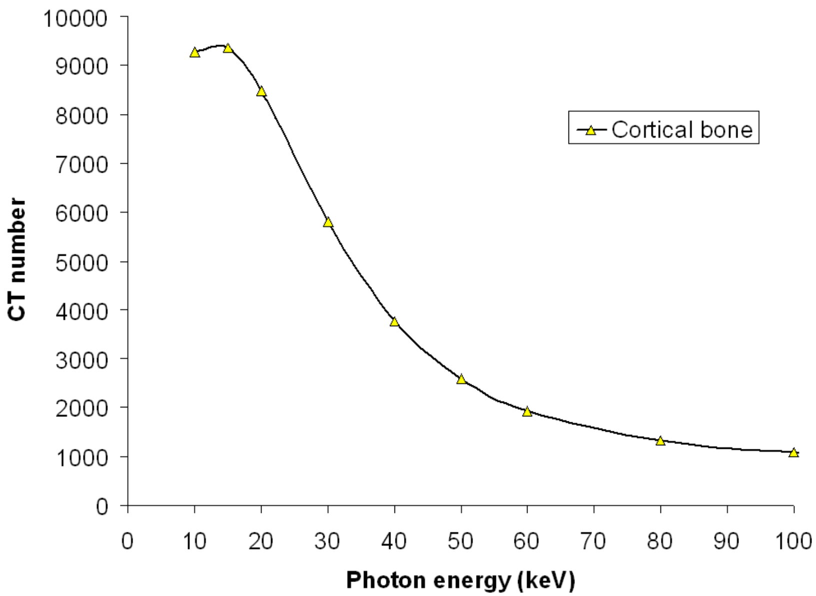
$$CT_{\text{Number}} = \frac{\mu_{\text{Material}} - \mu_{\text{Water}}}{\mu_{\text{Water}}} 1000$$

where the CT_{Number} is expressed in Hounsfield Units (HU) and μ is the attenuation coefficient for the X-ray beam. By definition, vacuum has a value of -1000 HU and water has a value of 0 HU (two energy-independent calibration points).

Unfortunately, the energy-dependence of the attenuation coefficients of other substances differ from that of water and often markedly so. This means that CT numbers are energy-dependent and hence ambiguous.

How wrong?





- The graphs show how the CT numbers of some common biological substances vary when evaluated at different photon energies [6].
- Bone is the most affected. This is largely due to traces of heavy elements.
- **Ideally, when comparing the radio density of tumours, bone density for implants etc. an accuracy of better than ±0.5 HU is needed.**

A reference energy

- **To make the Hounsfield number scale unambiguous, it would be necessary to define *a reference for the photon energy [6]*.**
- It would also be necessary to define some other aspects of a measurement, but we can neglect these for the moment.
- **The adoption of a rigorous definition would not solve all CT problems overnight, but it would create a framework that would ultimately facilitate the comparison of results and aid diagnostic research.**

  If this problem is not addressed, it will impose the ultimate limit on the precision of CT scanners.

A reference energy (continued)

- The physicists who worked on the first CT scanners understood this problem. Tofts P.S. (1981) proposed 3 distinct definitions dubbed the *"effective linear attenuation coefficient energy"*, the *"effective spectral energy"* and the *"effective Hounsfield energy"* [7].

- The problem with the above proposals is that they all depend on the shape and extent of the photon energy spectrum. This means that the X-ray window, any filters, the anode composition and the anode voltage, which are particular to each machine, would give rise to different "effective energies".   A reference energy that varies in this way is not helpful. What is required is **a unique, universally accepted standard value; probably around 45 keV**.

- See references for other papers that refer to an *"effective beam energy"* [8] or mapping values to *"some mono-chromatic energy"* which in one case is 70 keV [9].

A mono-energetic source

- One approach is to invent a tunable, mono-energetic X-ray source.
- Such a source would also be useful for K-edge imaging, angiography, mammography, small animal imaging and others.
- Cash incentives have been offered [10], but a suitable, low-cost source that would be usable in a hospital environment has not yet been found.
- **This means that it is worth looking for an alternative method.**
- **Note that even if a mono-energetic source were found, the need for a standard photon energy would be even more obvious.**

CERN MediPix & Others

- CERN frequently supports spin-off topics where it has special expertise. The MediPix Project is a case in point.
- MediPix has developed electronic circuits that count photons within a tunable energy range in contrast to the conventional current measurement from charge-coupled devices.
- Counting is fast, requires fewer photons to achieve a given accuracy and is basically noise free. In addition, there is the added feature of energy discrimination. X-ray imaging with this type of electronics has been demonstrated [11].
- Gleason et al [12] have taken one step further and used similar equipment to take a series of CT images in energy ranges and to combine them.
- **More recently (2007), Philips have taken out a patent for photon counting electronics with energy discrimination. The declared application is an innovative form of K-edge digital subtraction angiography using a polychromatic source.**

The next steps

Photon counting with energy discrimination makes it feasible to divide the X-ray spectrum into a large number of bins. This opens the way to mimicking a tuneable mono-energetic source and calibrating CT scans.

This would need:

- **An ISO or DIN standard for Hounsfield numbers. *The EPS-TIG could play a vital role in this.***
- **The ISO/DIN standard would include the standard photon energy (possibly several energies for different applications) and a decision on how to include the attenuation due to scattering.**
- **A procedure would also be needed to map all the bin readings (~50) to equivalent values at the standard energy. There are various ways of doing this with different precisions. The problem is touched on in Ref. 14 (2009).**

The coming innovation?

- Ultimately the next generation of CT scanners could be calibrated to a standard (ISO, DIN ?) photon energy (45 keV?) with a guaranteed precision of ±0.5 (?) HU.
- The mono-energetic source problem would be circumnavigated by photon counting and binning the energy spectrum into a histogram.
- Photon counting would also lead to a significant reduction in radiation dose and noise.
- And the way would be open for standard CT numbers to be published for common materials and biological substances.

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