The Effect of CT Scanning With Reduced Dose on the X-ray Tube Lifetime

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Executive summary

The X-ray tube is the most expensive "consumable" of the CT scanner. Prolonging its lifetime would bring considerable savings in the maintenance of the CT system.

The X-ray tube operates at elevated temperatures and its components are subject to wear and tear and prone to failure due to the high energies and temperatures that are the normal conditions of the tube operation.

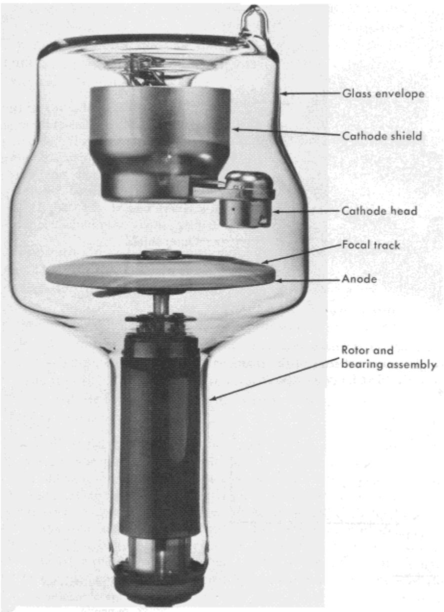
The cathode filament, the anode, the anode bearings and the tube vacuum envelope, are all adversely affected by the elevated temperatures.

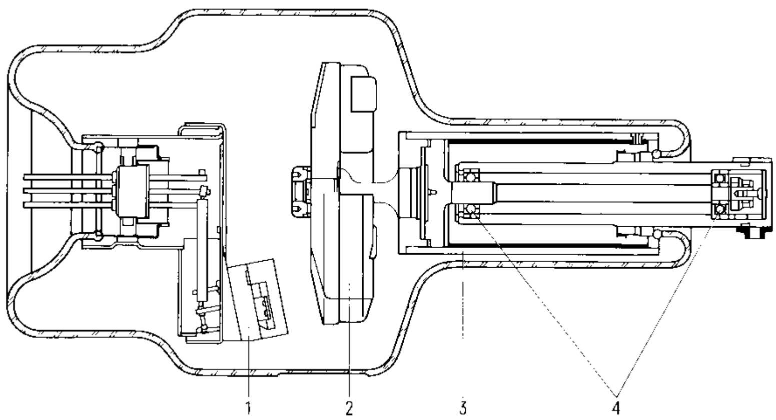
Easing the conditions of operation by lowering the energy and power requirements and consequently lowering the operating temperature would greatly benefit the X-ray tube lifetime.

Owners of CT systems observed that using low-dose protocols significantly increased the number of scans, anywhere from 40% to as much as by a factor of 4 - well beyond the expected values of the manufacturers.

The CT X-ray tube main components

CT scanners use X-ray tubes to generate the X-rays that image the body. A typical rotating anode X-ray tube is depicted below (1, 2):





1 Dual focus cathode
2 Graphite-RTM compound anode
3 Rotor
4 Ball bearings

Fig. 7.17 Cross-section through a rotating anode x-ray tube

The main elements of the X-ray tube are:

1. The **cathode assembly** contains the filament and the focusing cup. The filament is the source of the electrons that impinge on the anode and produce the X-rays. The electrons are produced by passing an electric current through the filament to heat it at a high temperature. The focusing cup concentrated the electron beam on the focal spot on the anode.
2. The electrons are accelerated by the high voltage applied on the tube and hit the focal spot on the **anode** circumference. A very small part of the electrons' energy at the focal spot is converted to X-rays that are transmitted through the patient body and measured by the detector on the other side. By far the largest part of the electrons energy is spent to heat the focal spot on the anode. The heat has to be dissipated to the external world, with great difficulty, because the anode is isolated in vacuum.
3. The **rotor** rotates the anode at high speed by an induction motor.
   The rotation brings new parts of the anode surface under the electron beam and thus spreads the heating over a larger area.
4. The **ball bearings** enable the anode to rotate at high speed with negligible friction.
   In modern high power tubes the ball bearings were replaced by liquid bearings.

Dependence of the tube's components lifetime on X-ray emission power, energy and dose

All parts of the X-ray tube are subject to wear and tear and prone to failure due to the high energies and temperatures that are the normal conditions of the tube operation. Easing the conditions of operation by lowering the energy and power requirements and consequently lowering the operating temperature would greatly benefit the components lifetime.

Cathode Filament

The relationship between the emission current density and the filament temperature is given by the Richardson-Dushman equation (3):

$$J_e = A_0 T^2 e^{-\phi/kT}$$

Where:

J_e is the emitted current density in amperes per square cm

T is the temperature of the cathode filament in degrees Kelvin

All other parameters are constants

At the high voltages that the CT X-ray tube operates, the emission current (or anode current) I_e is to a good approximation the current density J_e times the filament area A_f:

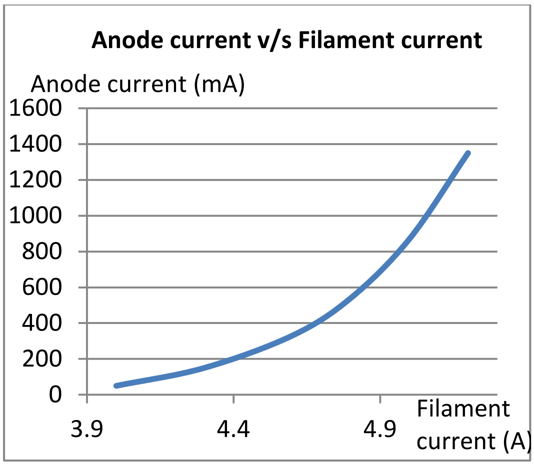
$$I_e = J_e . A_f$$

Therefore the emission (or anode) current increases with the temperature of the filament according to the following formula:

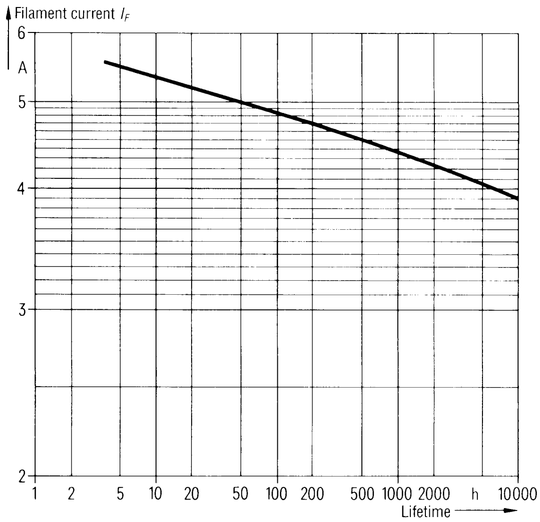
$$I_e = A_f A_0 T^2 e^{-\phi/kT}$$

To raise the filament temperature and the anode current, the filament current has to be increased.

A typical relationship between the Filament current and the Anode current is depicted in the following diagram:



The higher current decreases the filament lifetime as depicted below (1):



In conclusion, higher anode currents shorten the filament life and vice versa, lowering the anode current lengthens the filament life.

Anode focal track surface

By far the largest part of the electrons' energy is wasted in heating the anode and not in producing useful X-rays. A typical anode is depicted below (2):

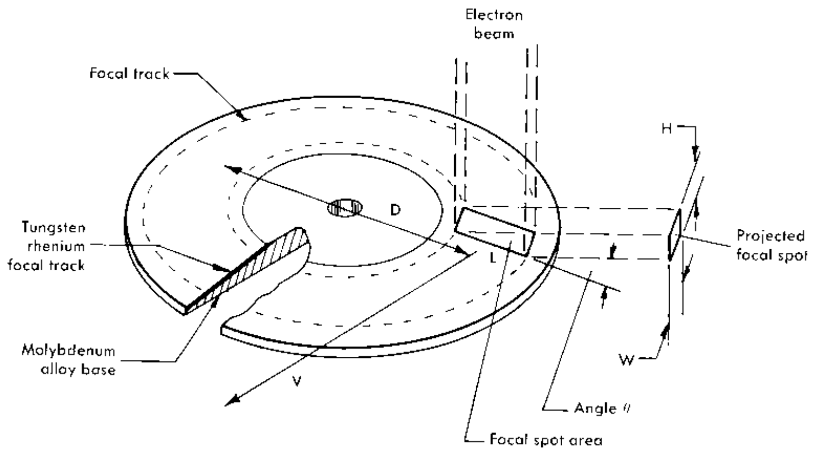


Fig. 117-18. Rotating anode focal track angle θ, mean diameter D, and velocity V in relation to the electron and x-ray focal spot of width W and height H.

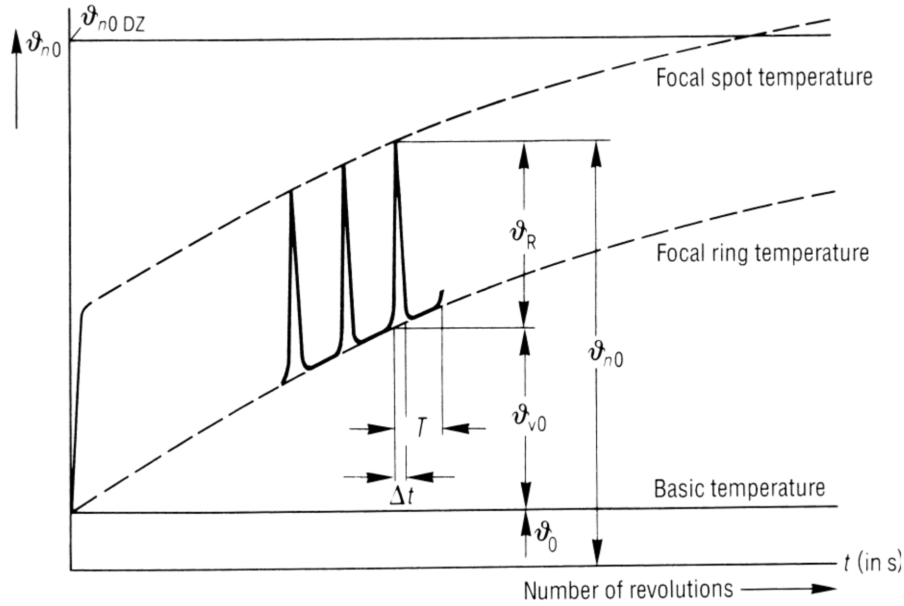
The **focal spot** is the area which is hit by the electron beam and produces X-rays. It is the hottest region of the X-ray tube.

The **focal track** (or **focal ring)** is the trail of the focal spot on the anode's circumference. As the anode rotates the electron beam successively impinges on new areas of the focal track. After the beam passes, that part of the focal track has time to cool until a rotation is completed and it returns under the electron beam again. The focal spot temperature rises with each rotation.

The **anode body** is heated slowly by convection from the anode track over many rotations.

The anode radiates most of the heat by infrared radiation to the oil in the X-ray tube housing, outside the X-ray tube insert. Some new X-ray tubes have convection methods of cooling and therefore the anode body heat is no longer a limitation to the tube performance.

The heating and cooling cycle of the anode regions with time is depicted below (1):



Where:

- ϑ_R is the temperature difference between the focal spot and the focal track (ring)
- ϑ_{v0} is the temperature difference between the focal track and the anode body
- ϑ_0 is the temperature of the anode body

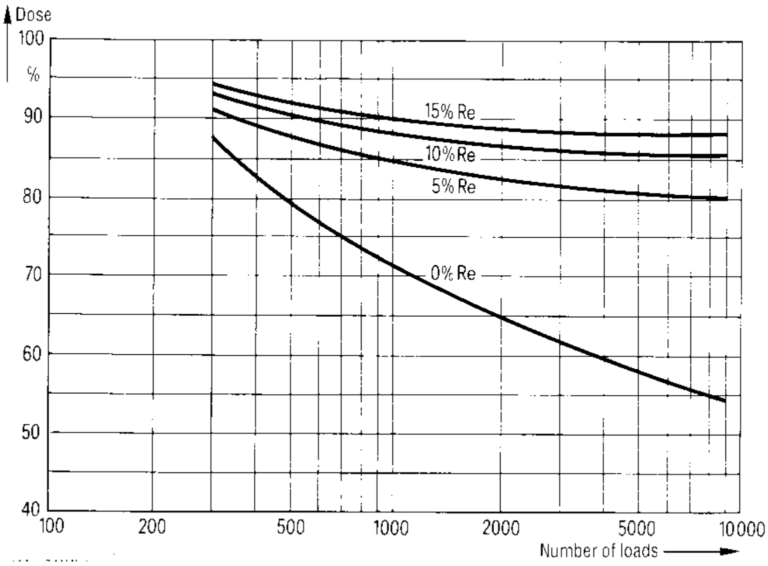
The highest temperature is at the focal spot and it is $\vartheta_R+\vartheta_{v0}+\vartheta_0$.

There are two destructive forces at work here:

1. The high temperature of the focal spot partially melts the anode surface and
2. The temperature gradients between the focal spot and track and between the focal track and the anode body give rise to mechanical stresses that destroy the anode surface at the border of the focal track.

As a result the surface of the anode becomes rough and the focal track digs itself into the anode base. The X-ray beam that exits the anode at a very sharp angle (typically 7^0) is partially absorbed by the rough surface and track "walls" and the useful beam is attenuated.

The dose reduction with the number of exposures due to the anode surface roughening is illustrated below (1):



Note: Rhenium is alloyed to the anode tungsten in order to increase its elasticity and partially relieve the thermal stresses. That reduces the dose fall with tube usage at the expense of x-ray production efficiency.

The X-ray tube has to be replaced when the dose falls below 70-80% else the image deterioration will hamper diagnosis.

Lowering the anode current reduces the thermal stresses and the resulting anode damage and dose reduction; the tube can then be utilized for a longer time.

Ball bearings

The ball bearing may seize up due to heat expansion. The lubricating liquid loss through evaporation is increased by high temperatures.

A lower anode current will keep the bearings temperature lower and enable them to work for a longer time.

Tube envelope and X-ray window

The tube envelope has to maintain a high vacuum (10^{-5} mbar) and high voltage insulation.

If the envelope is made of glass then sputtering of anode material on it increases its conductivity until arcing occurs and the tube has to be replaced (sputtering is ejection of anode material due to the electrons bombardment).

If the envelope is made of metal and ceramics, the soldering between the various parts deteriorates due to the high temperature. In addition the heating of the beryllium window (through which the useful X-ray beam passes) may puncture it or separate it from the envelope.

In both cases reducing the anode current will delay the deleterious effects.

Summary

The reduction of the thermal load on the X-ray tube is beneficial to its lifetime; all main components of the X-ray tube benefit from usage of lower anode current and dose.

Owners of CT systems observed that using low-dose protocols significantly increased the number of scans, well beyond the expected values of the manufacturers (4). By lowering CT dose the expected lifetime of X-ray tubes can be exceeded significantly – from approximately 40% to as much as by a factor of 4! While the reference study does not contain a rigorous statistical analysis, it does present a good indication of the benefits of low dose on the tube longevity.

Rigorous statistical analysis would require many years of data gathering from many scanners and thus it is exceedingly difficult, if not impossible to perform; while the data is gathered the tubes design changes, scanners are replaced and procedures evolve making the data obsolete before it can be used.

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Armin Marcovitch, MsC Physics, is a medical imaging veteran and one of the world-leading experts in that field. Mr. Marcovitch served as a Physicist and Project manager at Elscint and Philips Healtcare since 1977. He is the inventor of numerous patents in the field of computed tomography among which “Dual function CT scan,” “Asymmetric cone beam” and “A multislice CT scanner.”