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Neutron fibres and possible applications to NCT

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Abstract

We summarize previous researches regarding neutron guides of small transverse cross-section (neutron fibres), smaller than those of the standard hollow guides and collimators employed currently. Those studies may not be widely known in the neutron capture therapy (NCT) community, but they may be interesting for it. Such neutron fibres could allow to deliver and concentrate neutron beams selectively in regions of size smaller than 1 mm. We present new estimates and point out and discuss some new possible specific applications of those neutron fibres, which would not replace standard NCT but could supplement it. Thus, we entertain the possibility that neutron fibres could be useful for additional therapies (in typical NCT durations) of: (i) rather small tumours, (ii) thin borders of tumours. The use of these neutron fibres could reduce the undesirable delivery of radiation to healthy tissue around regions with malignant tissue.

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1. Introduction

Beams of slow (thermal and epithermal) neutrons, produced in nuclear reactors and in pulsed (spallation) sources, provide the basis for NCT and boron NCT (BNCT), which have gained increasing importance, of several types of cancer (Hatanaka, 1991; Proceedings of the Ninth International Symposium on NCT for Cancer, 2000; Sauerwein et al., 2002). The beams are concentrated onto malignant tissues by means of collimators (limiting the beam size at the patient position), which may have transverse dimension from about a few centimetres down to some millimetres. Most neutrons do not experience total reflection on the collimator walls. Either they scatter in the latter (as their average angle of incidence is too large) or they travel along the collimator without colliding. For scattering experiments, slow neutrons can be propagated using standard hollow guides (SHG) of relatively large transverse cross-sections. SHG are based on the multiple total reflections of the neutrons on their internal walls (typically, made up of nickel-coated boron glass) (Crist and Springer, 1962; Maier-Leibnitz and Springer, 1963). Their cross-sections may be rectangular with sides about 10 cm, and their length may be about 80 m. SHG transporting thermal neutron beams may have curvature radius R_{cu} about one to several hundred metres.

We shall summarize other developments regarding neutron guides having smaller transverse dimensions. Based upon an analogy with the confined propagation of light along optical fibers (glass-like or plastic dielectric waveguides, with transverse dimensions about tens of light wavelengths), the confined propagation of thermal neutrons along waveguides (neutron fibres) having small transverse size d_{nf} was proposed (Alvarez-

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Estrada and Calvo, 1984; Calvo and Alvarez-Estrada, 1986). d_{nf} would be smaller, by some orders of magnitude, than the transverse size of the SHG. Confined propagation is limited to those neutrons, which are: (i) either represented by rays experiencing multiple total internal reflections in the fibre walls, or, for very small d_{nf}, (ii) described by waves decreasing quickly at large distance from the fibre in transverse directions (propagation modes). In Alvarez-Estrada and Calvo (1984), some conjectures were made regarding possible applications of neutron fibres to BNCT. Later, the confined propagation and focusing of cold and thermal neutrons were established experimentally (Kumakhov and Sharov, 1992; Chen et al., 1992). Such devices employed capillaries (which, in turn, had allowed some important advances in X-ray optics) and they could be regarded as implementations of neutron fibres. In Section 2, we shall describe those devices and present some new estimates, which may be of interest. In Section 3, we shall conjecture and discuss some possible specific applications to NCT.

2. Materials and methods

Bundles of parallel polycapillary glass fibres (PGF), made of lead–silica glass (SiO_2, PbO, K_2O, etc. in the ratios: 55.0: 30.0: 9.8, etc.) were employed in Kumakhov and Sharov (1992), Chen et al. (1992) (to which we refer for more details and further references). A typical bundle had an overall transverse diameter of 15 mm and contained 721 PGF. Each single PGF had a diameter $d_{pf} = 0.4$ mm and a length $150\,\text{mm} \leqslant L_{PGF} \leqslant 200$ mm (the number of reflections, n(ref), of a neutron being $60 \leqslant n(\text{ref}) \leqslant 80$**)** and it contained more than 10^3 hollow capillary channels (HCC). Each single HCC had an internal diameter $d_{hcc} = 6\,\mu$m and could be regarded as a hollow waveguide of small cross-section, along which neutrons propagated. The average distance between two neighbouring (parallel) HCC could be estimated to be $d_{nhc} \sim 5$–$10\,\mu$m. The fibres could be straight or bent (with $R_{cu} \geqslant 0.1$ m). Each of the above HCC was surrounded by a lead–silica clad: the latter had a width about 5–10 μm. Beyond such a distance, the cladding region ended and another neighbouring parallel HCC was met. Those experimental devices in Kumakhov and Sharov (1992), Chen et al. (1992) enabled: (i) to focalize the flux of confined neutrons emerging from the exit end of a parallel assembly (bundle) of PGF into a small region (at a distance 104 mm from that end) having size about 1 mm, and (ii) to concentrate such a flux in it by a factor 7. According to Kumakhov and Sharov (1992), their devices could be eventually extended so as to focus neutron beams in a smaller region of size 30 μm, with a flux density gain up to 10^3.

In Calvo (2000), studies of a single HCC, and of PGF were reported (in particular, of their bending losses). To fix the ideas, "neutron fibre" will denote (like in Calvo (2000)) both one single HCC and one PGF (containing $\sim 10^3$ almost parallel HCC). Conjectures about applications to NCT were considered, very succinctly, in Kumakhov and Sharov (1992), Chen et al. (1992), Calvo (2001) and Calvo and Alvarez-Estrada (2002). Possible losses in neutron flux due to evanescent waves (tunnel effect) across the clad of the capillary channels in Kumakhov and Sharov (1992), Chen et al. (1992) are very small (Calvo, 2000; Rohwedder, 2002). The single reflection coefficient from the capillary walls is $R \sim 0.99$ and that for n(ref) reflections is estimated as $0.45 \leqslant R^{n(\text{ref})} \leqslant 0.55$. Experimentally, there is little loss in intensity due to multiple reflections (Kumakhov and Sharov, 1992; Chen et al., 1992). Even if, as stressed in Calvo (2000), Rohwedder (2002), wave aspects play a role for the devices in Kumakhov and Sharov (1992), Chen et al. (1992), we shall consider rays, for simplicity.

Let θ_{cr} be the maximum angle ("acceptance angle") for neutrons to enter into and to propagate confined along one HCC. θ_{cr} (which equals the critical angle) lies, numerically, between 10^{-2} and 10^{-3} rad. Let Φ_0 be an incoming thermal neutron flux (per cm^2 s) outside the fibre (HCC or PGF). Then, the flux Φ_{in} of the confined neutrons, which have entered into and propagate confined along the fibre, can be roughly estimated as $\Phi_{in} \sim \theta_{cr}^2 \cdot \Phi_0$. Then, θ_{cr}^2 reduces the flux by a factor about 10^{-5}. For $\Phi_0 \sim 10^{13}$–10^{14} neutrons/(cm^2 s), one estimates $\Phi_{in} \sim 10^8$–10^9 neutrons/(cm^2 s). A thermal flux useful in BNCT or NCT should be not smaller than 5×10^8 neutrons/(cm^2 s) (Hatanaka, 1991). Let us consider a bundle of some n_{PGF} parallel PGF, each with transverse cross-section about 0.13 mm^2. Then, such a bundle of PGF would transmit $n_{PGF} \times 10^5\,T$ to $n_{PGF} \times 10^6$. T neutrons during T seconds. For $T = 3.6 \times 10^3$ (1 h), we would have $N_{PGF} \sim 3.6.\ n_{PGF}.\ 10^8$ to $3.6.\ n_{PGF}.\ 10^9$ neutrons. As an (extreme) example, the bundle of PGF could be arranged like in Kumakhov and Sharov (1992) with $n_{PGF} \sim 720$ and transverse diameter 15 mm.

Further new estimates may be interesting:

(a) Some typical full BNCT treatment requires a total of $N_n \sim 10^{14}$ neutrons (amounting to a few dozen grays), to be delivered to a tumour of volume V_{mc} (some tens of cm^3) in a reasonable time duration T (about an hour). For instance, assume that such a full BNCT neutron flux has treated a tumour with $V_{mc} \sim 10^n$ cm^3, $1 \leqslant n \leqslant 2$. Then, another small tumour of volume $V_{mc} \sim 1$ mm^3 containing malignant cells could be treated, during about the same time as in the above full BNCT treatment, by a total of some $N_{st} = x \times 10^9$, $10 > x > 1$, neutrons (say, about $x \times 10^{-3}$ grays). N_{st} has an order of magnitude about that of N_{PGF} (for suitable n_{PGF}).

(b) Let us consider a tumour with volume V_{mc} (cm^3) and typical size L_{mc} cm so that $V_{mc} \sim L_{mc}^3$. It contains

N_{mc} malignant cells, so that $N_{mc} = V_{mc}.\rho$, ρ being the number of malignant cells per cm^3 in the tumour. The thin border of the tumour (healthy and malignant tissues being met in its external and internal sides, respectively) has area about L_{mc}^2 and some small width d (say, about some fraction of mm). Such a border contains $N_{mc;b} \sim L_{mc}^2.d.\rho$ malignant cells. Then, one has $N_{mc;b} \sim \rho^{1/3}.d.N_{mc}^{2/3} \sim 7.9 \times 10^2.\ d.\ N_{mc}^{2/3}$ malignant cells. In the last estimate, we have taken $V_{mc} \sim 10^n\,cm^3$, $1 \leqslant n \leqslant 2$, and 15 μm as a typical size for a cell, so that $\rho \sim 5 \times 10^8$ cells per cm^3. If d is $\leqslant 0.5$ mm, $N_{mc;b}$ is less than about $40.N_{mc}^{2/3}$. Let $N_{n;b}$ be the total number of neutrons required to treat, also in a standard NCT duration, all malignant cells $N_{mc;b}$ contained just in the thin border of a tumour having the above size. If N_n is the total number of neutrons required for the volume V_{mc} in a typical full BNCT treatment, it may be not unreasonable to expect that $N_{n;b} \sim \alpha.\ N_n^{2/3}$. α would be some numerical constant (the order of magnitude of which should not exceed some tens). Then, for $N_n \sim 10^{14}$, one has $N_{n;b} \sim \alpha.2 \times 10^9$ neutrons. The order of magnitude of $N_{n;b}$ is about that for N_{st} (for a small tumour of volume $\sim 1\,mm^3$) and then, that for N_{PGF} (for suitable n_{PGF}).

These estimates are expected to be adequate to within, say, one order of magnitude. Their reliability, if $\Phi_0 \sim 10^{11}$ to 10^{12} neutrons/(cm^2 s), could presumably be achieved still, by comparing with the formula for N_{PGF} and allowing larger T and n_{PGF} (within reasonable limits).

3. Discussion

Some quick overview of different problems and spatial resolutions met in NCT may be adequate (in connection to possible focalizations of neutrons in distances below 1 mm). The border of a tumour with V_{mc} about some tens of cm^3, as visualized by computed tomography (CT) using X-rays (through contrast enhancement), suggested a smaller size for it than the region really infiltrated by the tumour (Hatanaka, 1991). Thus, the tumour contrast enhancement did not indicate the whole tumour. A diffuse, low-density, area surrounding the contrast-enhanced region also contained tumour cells. See also Nakagawa (pp. 1061–1064, in Sauerwein et al. (2002)). The border of a tumour indicated by magnetic resonance imaging appears to be contained (with differences from some cm down to less than 1 cm) inside that displayed by positron emission tomography (PET): see Khan et al. pp. 551–555 in Sauerwein et al. (2002). Recall that the spatial resolution for PET is about 1–3 mm. There are various effects related to planning target volume (Wambersie et al. pp. 9–10 in Proceedings of the Ninth International Symposium on NCT for Cancer (2000)), patient positioning (Morrisey et al. pp. 177–178 in Proceedings of the Ninth International Symposium on NCT for Cancer (2000)), position displacement to within about 5 mm accuracy (Kortesniemi et al. pp. 283–284 in Proceedings of the Ninth International Symposium on NCT for Cancer (2000)), possible uncontrolled small movements, etc.

Let us consider small tumours with $V_{mc} \leqslant 1\,mm^3$ (case in Section 2). Then, one could use a neutron beam with small transverse cross-section, like that provided by some, possibly curved, PGF (or some bundle thereof), to treat such tumours, in some typical NCT duration. For a treatment of the bulk of a tumour with $V_{mc} \sim 10^n\,cm^3$, $n = 1,2$, the standard NCT treatments with collimators (Section 1) are adequate. But, once such a standard therapy of the bulk has been essentially completed, there may remain smaller subdomains still containing surviving malignant tissue. The thin border of the tumour or some thin border of the diffuse area surrounding the contrast-enhanced region could constitute examples (case b in Section 2). Then, one could try some complementary NCT in those small surviving regions using some (possibly bent) PGF or bundle thereof, also in a typical NCT duration.

Although the estimate for Φ_{in} would decrease for smaller Φ_0, one should notice that the directions of motion for those neutrons propagating confined along the fibre would be controlled by the latter. The effectiveness of NCT relies on the differential boron uptake of tumour and healthy tissues. Thus, "flooding" with neutrons all the region having potentially viable tumour is essential. However, on the other hand, it could be adequate to limit the beam to some spatial domain. So, it may be adequate to deliver neutrons selectively to a region R of interest through the PGF or bundle thereof, thereby avoiding radiation initially in regions R_1 around R (neutrons would tend subsequently to spread in tissue due to scattering, specially with hydrogen). The PGF or bundle thereof could help to find some compromise about and below 1 mm.

4. Conclusions

We have extended previous conjectures regarding the possible application of neutron fibres to NCT in sizes below the mm scale, and we have reported new estimates. Further research on these capillary glass fibers and their possible effectiveness could be interesting. It may be that not all atomic species in the materials employed in the PGF in Kumakhov and Sharov (1992), Chen et al. (1992) be equally adequate for NCT treatments. Anyway, the technologies employed to obtain the PGF in Kumakhov and Sharov (1992), Chen et al. (1992) could enable to produce new PGF more convenient for NCT.

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