Artificial Body Fluid as Tissue Substitute for Radiotherapy
Beam Analysis: A Theoretical Evaluation of its Electron Density Information

Sir,

Medical physics dosimetry protocols have recommended the use of water for calibration of radiation beam-generating machines such as high-energy linear accelerators, with the background that density and effective atomic number are near to human soft tissues, and therefore the absorbed radiation doses could be estimated with reasonable accuracy, using percentage depth dose (PDD) data. Easy availability and reproducibility of composition made worldwide use of water phantoms to simulate scattering conditions of the human body. Studies relating to breast, bone, etc., need special phantoms other than water for diagnostic radiology. Sometimes to avoid leakage effects in ion chambers, and for easy positioning convenience, “solid water” or “virtual water” phantoms are in use. The International Atomic Energy Agency recommends real water phantoms with prescribed depths for calibration of photons and electrons from clinical megavoltage equipment.

In a study, in pursuit of simulating body fluid having ion concentration and chemical composition, a few researchers have succeeded in the synthesis of a special fluid and named it as “artificial body fluid (ABF).” It was claimed that human tissue is equivalent to blood plasma and therefore these researchers prepared artificial blood plasma solution. With this concept, they tried to use them for radiation measurements. Cobalt-60 photon beam phantom measurements with ABF showed striking differences in the central axis percentage depth doses (PDDs) at larger depths and larger field sizes. There were increased profile differences in the central axis percentage depth doses (PDDs) at all depths and all field sizes. This phenomenon is interpreted as a physical density effect in terms of absorption appears to be minimal because the difference in Z_eff is 0.7% only.

Historically, natural water had been in use for phantom measurements right from the inception of radiation applications (X, gamma, electrons) for treatment and research. Human breast tissue has more fat and glandular tissue, therefore requiring different types of solid phantoms for radiography simulations. With the advent of the referred paper on ABF as an alternative to pure water, there is a need to investigate it in megavoltage X-rays and electrons from linear accelerators in addition to checking its effect on Cobalt-60 beam quality at 80 cm source to skin distance to generalize the ABF behavior to radiation beams. Therefore, the calculation of effective atomic number of ABF was necessary. In the original work designing ABF, the authors found the following in their experimental results (a) reduction in PDD in central axis of about 7%–13% compared to reported values, at larger field sizes and at larger depths b) increase in penumbral widths at all depths and all field sizes. This phenomenon is interpreted as a physical density effect by these authors. It is highlighted that, when the bulk density of the fluid is higher than water, then the penumbra has to shrink smaller (as it is apparent in lungs that penumbra becomes broader in clinical circumstances, due to 1/3rd density of the lung; therefore, the effect is expected to reverse when higher density medium is encountered). Therefore, the reported results need re-verification.

It is brought out that hydrogen element has the highest number of e/g (because of one electron to one proton in the atom), seen from the calculation (6.023 \times 10^{23} \times (1/1.008) = 5.98 \times 10^{23} e/g. (Electron density is calculated by the relation NZ/A, where N is Avogadro’s number, Z is the...
Table 1: Calculation of $Z_{\text{eff}}$ for the artificial body fluid

| Number | Chemical formula | Molecules | Fractional contents of elements | $Z_{\text{eff}}$ of the chemical | Fraction in total ABF | Weighted $Z_{\text{eff}}$ in total ABF |
|--------|------------------|-----------|---------------------------------|---------------------------------|-----------------------|--------------------------------------|
| 1      | H$_2$O           | 2H, O     | 2/18 H; 16/18 O                 | 7.685                          | 0.984000              | 7.5640                              |
| 2      | NaCl             | Na, Cl    | 23/58.5 Na; 35.5/58.5 Cl        | 15.170                         | 0.006440              | 0.0976                               |
| 3      | NaHCO$_3$        | Na, H, C, 3O | 23/84Na; 1/84H, 12/84C, 48/84O | 8.815                          | 0.002230              | 0.0197                               |
| 4      | KCl              | K, Cl     | 39/74.5K; 35.5/74.5Cl           | 29.130                         | 0.000367              | 0.0060                               |
| 5      | Na$_2$HPO$_4$(H$_2$O) | 2Na, 5H, P, 6O | 23/155Na; 5/155H, 64/155P, 96/155O | 13.416                         | 0.000175              | 0.0024                               |
| 6      | MgCl$_2$(H$_2$O) | Mg, 2Cl, 6H, 6O | 24.3/203.3Mg; 71/203.3Cl; 12/203.3H; 96/203.3O | 12.575                         | 0.000300              | 0.0038                               |
| 7      | CaCl$_2$(H$_2$O) | Ca, 2Cl, 6H, 2O | 40/147Ca; 71/147Cl; 4/147H; 32/147O | 15.242                         | 0.000362              | 0.0055                               |
| 8      | Na$_2$SO$_4$     | 2Na, S, 4O | 46/142.1Na; 32.1/142.1H; 64/142.1O | 11.627                         | 0.000070              | 0.0008                               |
| 9      | (CH$_3$OH)$_3$CNH$_2$ | 4C, 11H, 3O | 48/121C; 11/121Cl; 14/121H; 48/121O | 6.890                          | 0.000596              | 0.0411                               |

$Z_{\text{eff}}$ ABF=7.7409

Table 2: Calculation of number of electrons/g for the artificial body fluid

| Number | Name of the compound | Electrons/g×10$^{23}$ | Effective electron density×10$^{23}$ |
|--------|----------------------|------------------------|--------------------------------------|
| 1      | Water                | 3.3390                 | 3.3390×0.9843=3.2856                  |
| 2      | Sodium chloride      | 2.8814                 | 2.8814×0.0064=0.0191                  |
| 3      | Sodium bi carbonate  | 3.0100                 | 3.0100×0.00223=0.0067                 |
| 4      | Potassium chloride   | 2.9090                 | 2.9090×0.01027=0.00011                |
| 5      | Disodium hydrogen phosphate Di water | 3.0680 | 3.0680×0.0018=0.0005                    |
| 6      | Magnesium chloride hexahydrate water | 3.1387 | 3.1387×0.0030=0.0009                       |
| 7      | Sodium sulfate       | 3.0304                 | 3.0304×0.00306=0.0011                  |
| 8      | Hydroxymethyl methane | 2.4994 | 2.4994×0.00070=0.00017                    |
| 9      | Calcium chloride di water | 3.2836 | 3.2836×0.00596=0.00396                     |

ABF: Artificial body fluid

atomic number, and A is the atomic weight). But in water, when we calculate based on the constituent fractions of H$_2$O; (2/18) × ([6.023 × 10$^{23}$] × [1/1.008]) + (16/18) × ([6.023 × 10$^{23}$] × [8/16]) = (0.6635 × 10$^{23}$) + (2.6755 × 10$^{23}$), we get a value of 3.339 × 10$^{23}$ e/g. When ABF is taken, an addition of other constitutes is added to 98.43% of liquid water. So, step by step, the present author evaluated the effective electron density of ABF as 3.40 × 10$^{23}$ e/g and showed an increase of 1.82% against pure water value. The 0.7% higher $Z_{\text{eff}}$ of ABF may have effect in photoelectric effect, giving an inference that, at larger depths and bigger field sizes, the medium might be encountering softer gamma photons due to multiple interactions. If photoelectric absorption is proportional to cube of effective atomic number, then effectively the increase of absorption in ABF will be a factor 7.741$^{1/7.685}$ = 1.022 (about 2.2% higher). As Compton effect relates to the number of e/g, the ratio of electron densities in ABF vis-à-vis water is 3.400 × 10$^{23}$/3.339 × 10$^{23}$ = 1.0182 (about 1.8% higher). The total effect in absorption is accounted to be about 4%. Whether this can explain the actual difference in PDD at depths should be a point for debate. In the original work on ABF, the authors claimed a physical density of 1.075 whereas the total mass of ingredients in 1 L of water amounts to 1016 g, making it having a density of 1.016 only. This theoretical work has brought out the scope in understanding the uncertainties in extrapolating absorbed dose estimates in human patients due to the use of water-measured values, and emphasize the need for a validation using ABF. The calculated effective atomic number by the present work reveals a total effect in change in absorption only by about 4%. In the above discussion, we have taken for granted that the absorption of photoelectric effect and Compton effects is linearly additive, which is an approximation. As they are based on the probability cross-section that depends on the energy, this assumption may be still doubtful. But even in this worst case, the increased absorption cannot be more than 4% which shall be appreciated. It is, therefore, felt that detailed investigations are warranted with ABF by having ABF phantom measurements with tele-cobalt beam quality once again both at 80 cm and 100 cm distances, and also during precommissioning checks and routine calibration works in linear accelerators with radiation field analyzers in high-energy photons and electron beam qualities, to get more insight into the behavior of this new ABF solution.

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There are no conflicts of interest.

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