LOCAL ELECTRON-SAMPLE INTERACTION DURING SCANNING ELECTRON MICROSCOPY ON ORGANIC AND METALLIC OBJECTS

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Abstract: To ascertain how high energy of an electron is needed to acquire a sufficient data yield from organic and metallic sample, a Monte Carlo algorithm is used to compare the behaviour of electrons after contact with the material. Primary electron trajectory, elastic and inelastic scattering and secondary electron generation are described in this paper.

Keywords: SEM, Monte Carlo, Electron scattering, Secondary electron

1. INTRODUCTION

Scanning electron microscopy (SEM) is a method widely used on conductive anorganic materials. Because organic samples do not possess the stability and the ability to carry electric charge, displaying them via SEM requires several preparation steps in order for the method to work, including, but not limiting to, alcohol drying and coating the sample with metal (often gold) or freeze-etching. Because organic materials are prone to degradation due to exposure to high energy particles, in this case electrons, it is critical that the samples are measured with the lowest possible energy, while still getting sufficient amount of information about the object. For the purposes of finding out the differences between electron behaviour with different energies and propagation within, an organic sample is compared with a metallic one.

2. MATERIAL PROPERTIES

The organic sample used in simulation is considered to be muscle tissue dried with set of ethanol solutions of increasing concentration. After such preparation, there is very little water present in the sample [1], if the sample is handled properly, and can be completely neglected. For the purposes of the simulation itself, a muscle tissue sample prepared this way can be substituted by carbon, as it makes up the vast majority of the dried tissues. The remaining compounds within the chemical structure of tissue can be neglected in the case of electron-tissue interaction, because their presence does not make the tissue conductive and their concentration does not influence the density of the material. Majority of the interactions between electrons and the sample will therefore be with carbon atoms.

Gold is often the metal used for coating samples for scanning electron microscopy, and it was thus selected to act as the metallic sample. Preparation of the gold sample is not an issue, since obtaining relatively pure pieces of gold is, compared to the preparation of a biological sample, almost effortless, and can be purchased for the coating purposes from any company supplying electron microscopy materials.

Coating film for SEM is usually around 2-20 nm thick [2], but for better interpretation of the results, the thickness of samples from both materials is considered to be around 100 nm.

2.1. CRUCIAL PAREMETERS FOR SIMULATION

Atomic weight and number of the material play a pivotal role in the calculation of electron scattering, together with material density, and are invariant to the changing of the incident electron energy.

The electron energy variant parameters are elastic and inelastic mean free path, the average distance the particle travels before elastic or inelastic scattering. It is possible to calculate the former by using the equation:

$$\lambda_e = \frac{A}{Na * \rho * \sigma_e}, \tag{1}$$

where A is the atomic weight of the material, Na is Avogadro constant, ρ is material density and σ_e is elastic scattering cross-section. The inelastic mean free path is usually only measured, and cannot be calculated precisely enough. There are databases of inelastic mean free paths of materials for different electron energies and articles regarding calculation and the specific values [3].

	Organic sample (carbon)	Metallic sample (gold)
Atomic weight A	12	197
Material density ρ [kg/m^3]	1230	19320
Inelastic mean free path λ_i [Å] at 15 keV	171.3	116.8
Inelastic mean free path λ_i [Å] at 1500 eV	24.8	18.0
Inelastic mean free path λ_i [Å] at 150 eV	5.1	4.6

Table 1: Material parameters used in the simulation.

3. MONTE CARLO SIMULATION

Standard Monte Carlo method is used to calculate the trajectory and energy levels of the electrons in the simulation. Behaviour patterns of each electron are calculated separately, including energy loss of the primary electron and starting energy and the angle of the secondary electron in the case of inelastic scattering, The calculation itself somewhat simplified, compared to other versions with more electron-matter interaction possibilities [4], but it is suitable for the purpose of data yield, stability and energy level determination.

3.1. ALGORITHM STRUCTURE

Initial coordinates for each electron are set with three dimensional vector in the beginning of the axis – the [0, 0, 0] coordinates, with direction vector in the z axis to represent the incident primary electron beam being perpendicular to the sample. After loading in and calculation of the material parameters and the initial energy of the electrons, the algorithm enters the loop phase, which performs the same calculation for each iteration, gradually moving and adjusting the electron properties along the way.

In each step, the first thing to determine is whether the last step moved the electron outside of the allowed area, and if the energy of the electron is below the set energy threshold, and if so, terminate the loop. After that the scattering itself comes. From the inelastic and elastic mean free paths a frequency of scattering events is determined, and which scattering will happen. If the elastic scattering is selected, a scattering angle is calculated, and the electron is moved along its new direction vector to a new position given by the equation 2, beginning the whole process anew.

$$\begin{matrix} x_{n+1} \\ y_{n+1} \\ z_{n+1} \end{matrix}' = \begin{pmatrix} x_n \\ y_n \\ z_n \end{pmatrix} + s_n \begin{pmatrix} \sin\theta_n \cos\phi_n \\ \sin\theta_n \sin\phi_n \\ \cos\theta_n \end{pmatrix}, \tag{2}$$

where θ is the scattering angle, ϕ is the azimuthal angle and n is the number of the steps being performed.

In the case of the inelastic scattering, the calculation is split into three phases. First, the scattering angle is determined and the electron is moved, in a similar manner as with the elastic scattering, then the energy loss is quantified and the electron data is adjusted. The last part is the creating of secondary electron due to ionization. The angle and the energy are dependant on the scattering angle and the energy loss of the primary electron, and they are stored for further processing. The energy of the primary electron after the scattering is given by the following equation:

$$E' = E * \cos^2\theta, \tag{3}$$

while the energy of the created secondary electron can be established by the equation:

$$E'' = E * \sin^2\theta. \tag{4}$$

After the single primary electron trajectories and energies at each step are established, the databank of secondary electrons from this part of the simulation is treated the same way, as if they were primary electrons as well, for the sake of the calculation. Each secondary electron can create more secondary electrons, and the simulation runs, until every entry in the databank has been cleared. After that a new primary electron can enter the algorithm and the whole process repeats itself, until the set number of primary electrons has been simulated.

3.2. SIMULATION RESULTS

Simulations were run with 100 electrons each, 100 times over to achieve dependable results. From the final count of the data yield, in Table 2., we can see that while the median energy of BSE is for both organic and metallic sample very close to the original energy of the primary electron, the mean energy drops in the metallic sample on 1500 eV in contrast to the dried tissue sample, where the BSE mean is still close to 1500 eV. That shows that while most of the backscattered electrons in the gold object still return very soon and largely unaffected, there are more that undergo several inelastic scatterings on this energy level. This is further supported by Figure 1, where the multiple inelastic scatterings and secondary electron generation are clearly visible. Under lower energies the primary electron shows significantly smaller penetration into the gold sample in comparison to the dried muscle tissue. If we gathered information not only from backscattered primary and secondary electrons, but from the ones that pass the sample as well, gold would be much less useful, if we were to disregard conductivity. While secondary electrons help with the material analysis, they carry very little information about topography, due to the level of their energy and the directions they travel. Dried muscle tissue can still provide topographical data, but the secondary electron yield is considerably smaller than in metallic or gold coated samples.

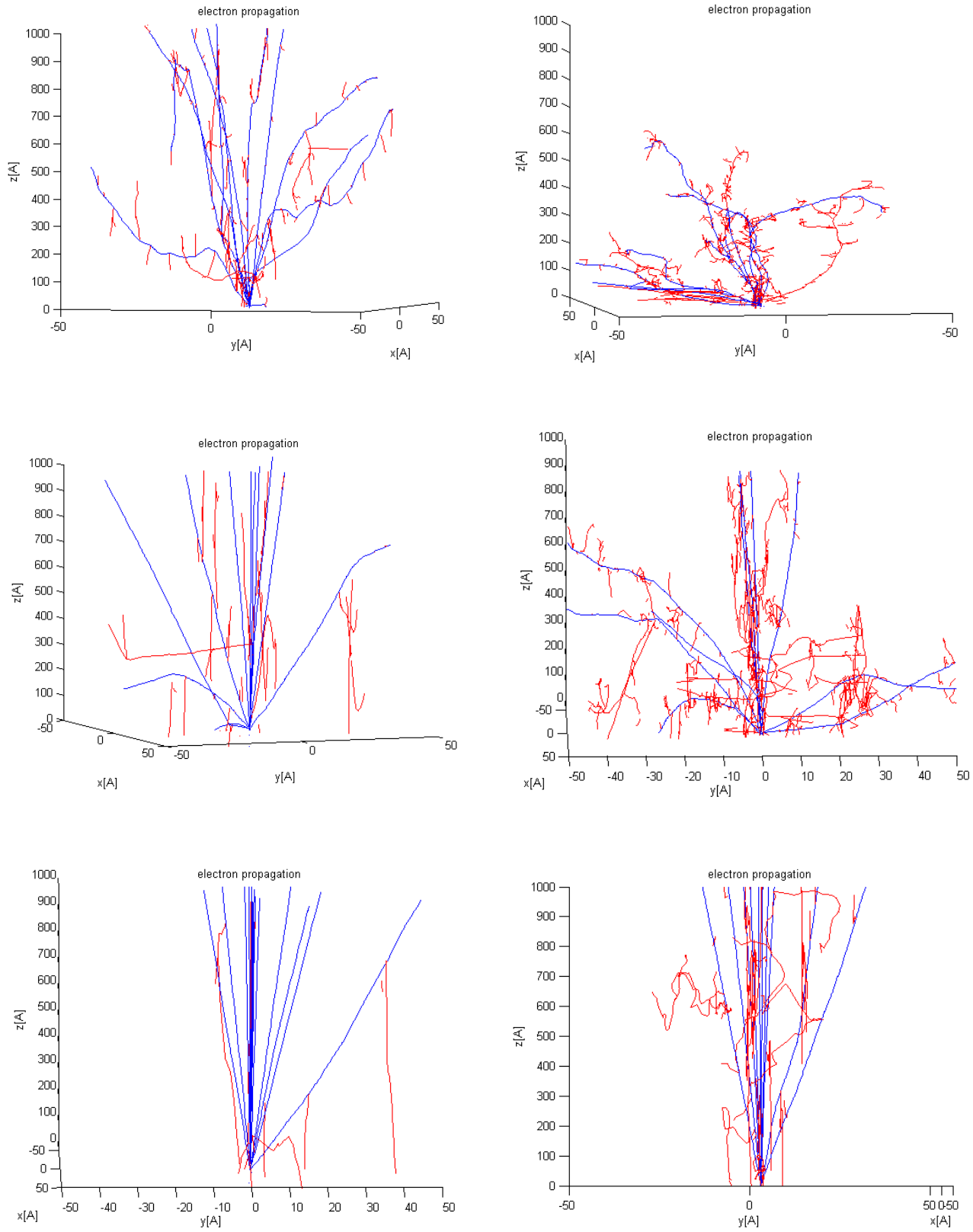

Figure 1: Comparison of propagation of 20 electrons in dried organic tissue (left) and gold (right) with electron energy of 15 keV (first row), 1500 eV (second row) and 150 eV (third row). Primary electrons are depicted in blue, while secondary are in red colour.

	Organic 15 keV	Organic 1500 eV	Organic 150 eV	Metallic 15 keV	Metallic 1500 eV	Metallic 150 eV
Backscattered electrons BSE [%]	48 ± 11	59 ± 13	63 ± 17	48 ± 7	56 ± 10	53 ± 12
Mean energy of BSE [eV]	15000 ± 0.10	1499.97 ± 1.46	141.80 ± 26.82	15000 ± 0.11	1428.90 ± 273.72	121.33 ± 25.65
Median BSE energy [eV]	15000	1500	149.92	15000	1499.83	129.86
Backscattered secondary electrons BSSE	17 ± 5	28 ± 8	22 ± 21	36 ± 7	75 ± 21	64 ± 12
Mean energy of BSSE [eV]	6.34 ± 6.99	5.44 ± 7.92	3.45 ± 6.02	7.44 ± 12.31	11.34 ± 45.97	3.04 ± 4.15
Median energy of BSSE [eV]	3.40	2.23	1.38	2.40	1.97	1.95

Table 2: Data yield on detector from 100 simulations with 100 electrons

4. CONCLUSION

The Monte Carlo model created for this paper proved stable for simulating electron propagation in dried muscle tissue and gold samples. The results demonstrated that in the gold sample far more secondary electrons are created, but cannot be successfully detected due to the speed of their energy dissipation, thus the energy yield of backscattered electrons from the gold sample drops faster with lower energy of the primary electron beam than in the organic sample. Any water molecules in the dried muscle tissue are neglected for the purposes of this simulation.

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