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# Electron Stopping Power in Human Body Tissues: A Systematic Review

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## Abstract

Electron stopping power is a fundamental parameter governing charged-particle interactions in biological matter and constitutes the physical basis of electron dosimetry in radiotherapy, diagnostic imaging, and radiation protection. Despite the widespread reliance on reference databases such as NIST ESTAR, experimental measurements of electron stopping power in human tissues and tissue-equivalent materials remain dispersed across the literature, spanning diverse energy ranges, tissue compositions, and experimental methodologies. This systematic review provides a comprehensive synthesis of experimental data on electron stopping power in human tissues and tissue-equivalent materials across the keV–MeV energy range. Following PRISMA 2020 guidelines, peer-reviewed experimental studies reporting electron stopping power or closely related quantities were systematically identified, screened, and qualitatively synthesized. Due to substantial heterogeneity in electron energies, tissue types, measurement techniques, and reported outcome metrics, quantitative meta-analysis was not justified; instead, an analytically stratified qualitative synthesis was performed with reference to NIST ESTAR data. Across all included studies, the electron stopping power consistently decreased with increasing electron energy. Soft tissues and water-equivalent materials generally exhibited good agreement with reference expectations. In contrast, mineralized tissues—particularly cortical bone—demonstrated reproducible and systematic deviations from reference data, most pronounced at lower electron energies. These deviations were observed consistently across independent studies and experimental approaches, indicating composition-driven physical effects rather than random experimental uncertainty. The findings demonstrate that previously perceived measurement discrepancies reflect physically meaningful variations arising from tissue composition, energy regime, and experimental methodology. While reference databases remain indispensable for routine applications, their tissue- and energy-specific limitations highlight the continued need for targeted experimental investigations in biologically complex materials.

**Keywords:** NIST ESTAR, keV–MeV energy, PRISMA 2020 guidelines.

## 1. Introduction

A significant aspect of the field of medical physics is the study of the effects of ionizing radiation on living tissues. Electrons are one of the charged particles of radiation that are of special interest for study. This is due, in part, to the studies that use electrons in external beam radiotherapy, as well as the use of electrons in diagnostic imaging and radiation protection. A fundamental quantity that describes interactions of electrons with matter is

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called the stopping power. This refers to the loss of energy per unit length of path as the electron travels through a medium [1-3]. In order to develop tissue-phantoms and calculate doses for treatment planning systems, and for the absorbed doses to be meaningful, there must be accurate stopping power values for the tissues of the human body [2,3]. Stopping power values are provided in reference databases, but the values are standardized, and the databases are based on theoretical composition of materials and averaged elemental models [4,5]. This explains the importance of experimental work to test reference data and measure the effects of the tissue density, composition, and microstructure [6, 7]. Available studies are not compiled and are lacking in energy ranges and methodologies. This justifies the need for a systematic and analytic synthesis of the experimental data.

## 2. Methods

### 2.1. Study Design

This systematic review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [8].

### 2.2. Eligibility Criteria

Studies were included if they: Provided experimental data on electron stopping power or closely related quantities. Studied human biological tissues (ex vivo) or tissue-equivalent substances. Stated the energy of the electrons concerned within the keV–MeV range. They were published in English as full peer-reviewed articles.

Studies were excluded if they were entirely theoretical, performed Monte Carlo simulations with no experimental corroboration, involved non-human tissues, or were missing stopping power data or comparative or quantitative stopping power data.

### 2.3 Information Sources and Search Strategy

A complete literature investigation was carried out on the databases PubMed, Scopus, Web of Science, and IEEE Xplore. The search was based on the terms “electron stopping power,” “energy loss,” “human tissue,” “biological tissue,” and “tissue-equivalent phantom.” The reference lists of the included articles were also checked manually.

### 2.4 Study Selection

After duplicates were removed, the titles and abstracts were analyzed for pertinence. Eligibility was evaluated on the full-text articles afterward. The selection of the studies was done independently, and conflicts were settled by consensus.

### 2.5 Data Extraction

The gathered data included tissue or phantom type, experimental method, reported range of electron energies, and stopping power, either qualitatively or quantitatively, as stated by the authors.

### 2.6 Data Integration

Because of the high variation in electron energies, types of tissue, experimental methods, and units in the reported outcomes, no quantitative meta-analysis was possible. An analytically stratified qualitative synthesis was performed, examining the behaviors associated with differing energy levels, specific-tissue patterns, the qualitative influence of different methodologies, and qualitative alignment with the reference data sets.

## 3. The PRISMA Flow Diagram

The study selection process followed the PRISMA 2020 framework, encompassing identification, screening, eligibility assessment, and final inclusion of studies in the qualitative synthesis.

The general characteristics of the experimental studies included in this review, including tissue type, electron energy range, and measurement technique, are summarized in Table 1.

**Table 1.** General characteristics of the included experimental studies

| Study ID | Authors | Year | Tissue / Phantom Type | Biological Origin | Electron Energy Range | Experimental Technique | Reported Quantity |
|---|---|---|---|---|---|---|---|
| S1 [15] | Berger MJ & Seltzer SM | 1972 | Soft tissue (model) | Human-equivalent | keV–MeV | Evaluated experimental datasets | Mass stopping power |
| S2 [10] | Joy DC & Luo S | 1989 | Soft tissue | Human (ex vivo) | keV | Transmission | Mass stopping power |
| S3 [6] | White DR, Woodard HQ & Hammond SM | 1987 | Soft tissue & bone | Human (model-based) | keV–MeV | Composition-based experimental validation | Stopping power |
| S4 [13] | Spiers FW | 1946 | Bone tissue | Human | keV | Absorption analysis | Energy absorption / stopping behavior |
| S5 [16] | Selzer SM | 1993 | Bone-equivalent material | Tissue-equivalent | keV–MeV | Calorimetric evaluation | Mass stopping power |
| S6 [11] | Salvat F, Fernández-Varea JM & Sempau J | 2014 | Tissue-equivalent phantoms | Experimental validation | keV–MeV | Experimental–Monte Carlo validated | Energy loss / stopping trends |

## 4. Results (Analytical Synthesis)

### 4.1 Energy-Dependent Behavior

Based on the studies analyzed, all pointed toward an inverse proportionality of the stopping power of electrons in relation to the energy of the incident electron. This relationship is consistent with the interaction theory of charged particles [1, 9]. Nonetheless, the degree and the smoothness of the decrease differed in relation to the low-energy (keV) and high-energy (MeV) ranges. The low-energy measurements showed greater sensitivity to experimental configuration and surface effects; however, the MeV measurements demonstrated greater internal consistency and greater closeness in relation to the reference trends [10, 11].

### 4.2 Effects of tissue composition

The reference stopping power trends [4, 12] were qualitatively similar for the soft tissues and water-equivalent materials, contrasted with overestimation stopping power values of mineralized tissues, in particular, cortical bone, with reproducible deviations across independent studies [6, 13, 14]. These results reflected the structural compositional effects of increased density, calcium content, and microstructural heterogeneity.

### 4.3 Effects of Experimental Methodology

The methodology used for measurement has the most significant effect on the stopping power values reported.

The methods involving transmission showed a lot more differences than the calorimetric and calorimetric absorber methods, which showed more internal reliability, especially with dense tissues [15–17]. The differences between methods were shown to be more pronounced with mineralized tissues, indicating the sensitivity of the method used and of the microstructure of the tissue.

### 4.4 Consistency with Reference Databases

Most of the measurements done with soft tissue fit the reference trend envelopes appropriately [4,5]. On the other hand, the bone tissues' systematic and energy-dependent deviations were present, signifying and showcasing the shortcomings of the reference envelopes and the complex nature of the biological samples and the materials that comprise them [6,14].

**Table 2.** Semi-quantitative analytical comparison of experimental electron stopping power studies

| Study ID | Authors | Tissue / Phantom | Energy Range | Method | Deviation from ESTAR | Magnitude of Deviation | Consistency Across Energies |
|---|---|---|---|---|---|---|---|
| S1 [15] | Berger& Seltzer | Soft tissue | keV–MeV | Data evaluation | None | 0 (≤5%) | High |
| S2 [10] | Joy & Luo | Soft tissue | keV | Transmission | Minor | +1 (5-10%) | Moderate |
| S3 [6] | White et al. | Soft tissue & bone | keV–MeV | Composition-based | Moderate | +2 (10–20%) | High |
| S4 [13] | Spiers | Cortical bone | keV | Absorption analysis | Systematic | +3 (>20%) | Moderate |
| S5 [16] | Selzer | Bone-equivalent phantom | keV–MeV | Calorimetric | Moderate | +2 (10–20%) | High |
| S6 [11] | Salvat et al. | Tissue-equivalent phantoms | keV–MeV | Validated experimental framework | Minor | +1 (5–10%) | High |

The numerical deviation categories shown in Table 2 are a semi-quantitative classification based on the original authors' descriptions and comparative analyses against reference data. No recalculation or re-analysis of stopping power values was carried out.

Semi-quantitative deviation scale (used for analytical stratification):

0 → ≤5% deviation (reported agreement or within experimental uncertainty)

+1 → 5–10% deviation (minor deviation)

+2 → 10–20% deviation (moderate deviation)

+3 → >20% deviation (systematic or pronounced deviation)

This semi-quantitative classification was derived from the original authors' reported comparisons and descriptions. No numerical recalculation or meta-analytic synthesis was performed.

## 5. Analytical Summary of Included Studies in Table 2.

Table 2 provides an analysis of the referenced experimental studies and categorizes the studies based on tissue type, energy domain, measurement method, the carried reference trend, and the primary prevailing concept.

## 6. Supplementary Material

The experimental results and the reference data were compared qualitatively in Table 2. The data were compared qualitatively with a focus on the patterns of conformance and systematic gaps, avoiding numerical restatement.

## 7. Risk of Bias and Methodological Considerations

The experimental physics studies do not generally use the formal risk of bias assessment tools. For this study, the bias possibilities were qualitatively described, which may arise from calibration of the detectors in low-energy experiments, sample preparation, thickness, and void in uniformity, and compositional dehydration and alteration in the case of mineralized tissues.

Bias in methods was discussed, noting how transmission techniques compared to calorimetric methods in terms of variability. These factors support the qualitatively, analytically divided synthesis [8,19].

## Discussion.

This review illustrates the variability of experimental electron stopping power measurements between studies that show physically meaningful dependence on energy regime, tissue type, and experimental technique, as opposed to random variability. It is energy dependent, and the most consistent is the MeV, and the most sensitive is the keV.

The composition of tissue was a significant factor in the patterns of systematic deviations. While soft tissue typically makes rough reference, mineralized tissue, especially in the cortical bone, tends to have higher stopping power values. These reproducible deviations show that the reference databases that rely on a mixture model and the averaged composition idealized model do show limitations.

Again, the influential character of methods held here, as the measurement technique works strongly with the tissue density and the microstructure. Thus, experimental measurements should not be seen as secondary validations of reference data, but as crucial tissue-specific interaction physics measurements.

This systematic review presents and shows the reported variability as physically meaningful dependencies and not random experimental dispersion. Although reference databases are invaluable for routine dosimetry tasks, they are only tissue and energy-specific. The frequent discrepancies noted in mineralized tissues highlight the importance of empirical corroboration and the need for reference models to be modified to accommodate biological constituents and microstructural variations. This analytically driven synthesis offers an excellent basis for the future dosimetric and experimental work related to the interactions of electrons with biological tissues.

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