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Abstract

Computational modeling can play an important role both in designing laser-tissue interaction experiments and in understanding the underlying mechanisms. This can lead to more rapid and less expensive development of new procedures and instruments, and a better understanding of their operation. At the Lawrence Livermore National Laboratory, we have recently directed computer programs and associated expertise developed over many years to model high intensity laser-matter interactions for fusion research towards the laser-tissue interaction problem. A program called LATIS is being developed to specifically treat laser-tissue interaction phenomena, such as highly scattering light transport, thermal coagulation, and hydrodynamic motion. The structure and contents of LATIS are described in this paper. Examples of computational simulations for several problems such as thermal coagulation, tissue welding, and hard-tissue ablation are presented.

Introduction. Laser surgery involves complex nonlinear processes. As a result, the design and testing of new instruments and procedures typically involves extensive experimental and clinical studies covering wide ranges of system parameters. Computational modeling of laser-tissue interaction events can be used to explore the system parameter space, (e.g. laser wavelength, pulse length and pulse energy) and to gain a deeper understanding of specific laser-medical processes. However, modeling will only be useful if it is used in a closely-linked program along with experiments. A schema for such use is illustrated by the flowchart in Figure 1. A project to develop an instrument for a specific purpose will involve iteration between modeling and experiment before reaching a desired goal. The project will be a success, if after several cycles of improvement in the modeling and experiments, the design goal is met, for example, the specification of optimal parameters for a prototype system which can be used for clinical trials.

Materials and Methods. The models presented in this paper have been calculated with a computer program recently constructed for laser-tissue interaction research, called LATIS[1]. It is based on approximately 25 years of research in the field of laser fusion. LATIS treats 4 groups of physical processes:laser light transport, thermal response and transport, material response, and hydrodynamics. LATIS simulates time-dependent laser-tissue interaction events assuming 1-D, or 2-D spatial symmetry. Several models for light transport can be used, such as diffusion, 1-D wave propagation, and, most commonly, Monte Carlo. Heat transport is calculated with a diffusion equation including blood perfusion and surface water evaporation.

Dynamic properties, both optical and thermal, are included. The material response models include tabular equations-of-state (EOS) which specify the material pressure and internal energy as functions of the density and temperature, and time-dependent rate equations for tissue chemistry, such as coagulation. The hydrodynamic response is calculated with a Lagrangian finite-difference method, allowing the description of both elastic waves and material ablation. Material strength and failure models are incorporated in the hydrodynamics. LATIS runs on both UNIX workstations and Cray super computers at LLNL. A new program ("LATIS3D") is currently under development. It is fully 3-dimensional, and will run on a variety of computers, including massively parallel machines, and be available for collaborative use.

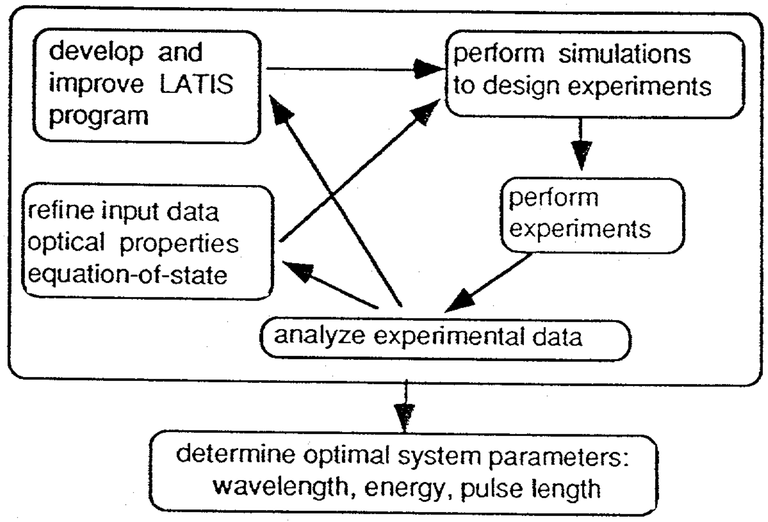

Figure 1. A design goal is reached by several cycles around this loop showing the relationship of modeling and experiment.

Results. We are pursuing several projects involving computational modeling: the role of dynamic optical properties on laser dosimetry[1], laser-tissue welding[2,3], dosimetry in a benign prostate hyperplasia (BPH) therapy device, the design of a laser thrombolysis system for stroke therapy[4], and a study of high precision hard-tissue removal with ultra-short laser pulses[5]. To illustrate the use of modeling we discuss two examples.

Laser dosimetry with dynamic optical properties. We have modeled a tissue irradiated on the surface by a circular laser spot for times of order one minute, in order to investigate the importance of dynamic optics for laser-thermo therapy, such as BPH therapy. Light transport is modeled with the Monte-Carlo technique using anisotropic scattering cross sections. Tissue coagulation is calculated with an Arrhenius rate model. In the case of dynamic optics, we assume that the scattering cross section increases by a factor of 7 as the tissue is coagulated. The inclusion of dynamic optics in the model reduces the depth of the coagulated region by an amount which depends on the laser parameters, such as spot size and pulse length, and on tissue parameters such as the degree of blood perfusion. On average the reduction of the coagulated region is 33%. The largest effects of dynamic optics occur for very small spots, in which case the reduction can be 60%. Similar modeling is currently being applied to design and characterize a specific BPH therapy system.

Ultra-short-pulse ablation of hard tissue. High intensity pulses in the fsec to psec regime can be used for very high precision ablation, due to their very short absorption length (.01 to 1 μm) and low fluence ablation threshold (~1 J/cm^2). Applications to dental tissues have been proposed. We have used LATIS to model the hydrodynamic ablation occurring in this pulse regime. We calculate the movement of the tissue following the absorption of the laser light, using an EOS which allows for the transition from the solid to the vapor phase of the material at high temperatures. Laser absorption is mediated by a multi-photon initiated plasma. Ablation occurs via a super-critical heating of the outer tissue layers. We also calculate the mechanical and thermal coupling to the underlying tissue in order to predict and minimize undesired damage. We describe the role of modeling in the design of an optimal system for high-precision surgery.

Conclusion. We propose that computational modeling can play an important role in the design and analysis of laser-tissue interaction experiments. Modeling can lead to faster and less expensive instrument and procedure development.

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