광 간섭계를 이용한 광음향 단층촬영 기법

Optical Interferometry based Optoacoustic Tomography

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Light as a means of visualizing pressure waves has been exploited as an alternative to traditional piezoelectric transducers, where optical interferometry played an important role and is presently the object of active developments.(1),(2) There are also non-interferometric techniques but are well developed or of limited applications.(3) Optical interferometry has many advantages over conventional piezoelectric devices. Minimally invasive non-contact measurement is possible without acoustic medium.(4) In addition to the electromagnetic interference immunity, device calibration for nonlinearity inherent with piezoelectric sensors is not necessary due to the direct conversion from interference signals into the measurand using optical wavelength as a measure.(5) The use of laser interferometry for calibrating hydrophones has already become standard practice.(6) Scalable measurement with imaging optics and backward configuration are also easily achieved posing clinical potentials. Even with those benefits the system stability, and alignment difficulties place optical interferometry still in growth stage in optoacoustic applications.

A proper understanding of the capabilities of optical interferometry is essential for accurate pressure field characterization. Emphasis is given to explaining basic principles of interferometers reported in biomedical optoacoustics according to the classical categorization of optical interferometry. Homodyne interferometry popular for its simple and intuitive setup is explained followed by heterodyne interferometry and its advantages in optoacoustics. Confocal Fabry-Perot interferometers and their high immunity to speckle noise are also explained. Several applications are described in each method and their strengths over other methods as well as limitations are addressed. Future directions and the choice of a particular technique for a given purpose will be discussed in conclusions.

Optoacoustic effect is a phenomenon where pressure waves are generated as a result of optical absorption from a light source, in general pulsed laser. The absorbed optical energy causes rapid localized heating and thermal expansion resulting in pressure waves. One can detect pressure waves or accompanying displacements with suitable sensors to characterize the object properties. Using the optoacoustic measurements at multiple locations, inhomogeneous optical absorption distribution within the object can be visualized with appropriate reconstruction algorithms, which is a subsurface imaging modality termed optoacoustic tomography. Direct detection of pressure waves using contacting transducers like piezoelectric ceramic or polyvinylidene difluoride(PVDF) film informs transient amplitude profile which is a measure of spatial temperature gradient. Optical interferometry, on the other hand, detects surface displacement due to pressure transient governed by thermoelastic wave equation. Numerical estimation by solving time-dependent three-dimensional wave equation correlates displacement with energy distribution. An equivalent form of the wave equation using potential function is usually applied for deriving explicit expressions of the pressure or displacement. The internal pressure equals density multiplied by acceleration which can be integrated twice to obtain displacement as a function of time and position. Optoacoustic surface displacement modulates the optical path length or phase of the interferometric probe laser beam focused at the interrogating spot and this change can be demodulated by interference with reference beam.

Common feature of the interferometers presented so far is that they are all point displacement sensors. High bandwidth photo detectors convey time-rich interferometric signals, and scanning mechanisms such as translation stages or galvanomirrors enable measurements at multiple locations. A space-sparsely collected data set is used to obtain physical properties or tomographic images of the sample. These systems taking a few tens of minutes for the whole scan of 3D target may not be adequate for time critical situations, as the physical and chemical properties of the biomedical sample change as time lapses or even during the measurement. Functional optoacoustic imaging requires several times more data from repeated measurements by varying experimental conditions, and minimizing the total time will be important. Contrary to piezoelectric transducers where array detection has long been practiced for fast and high resolution imaging, optical way of parallel sensing is still under development with various methods. Two-dimensional photo detector array can be used to capture interference signals at multiple locations, but the number of sensors are limited to a few hundreds and entailed electronics are costly.(7) Using a line CCD camera synchronized with a sinusoidally modulated pump laser can detect optoacoustic displacement effectively, but not appropriate for pulsed optoacoustics in biomedical applications.(8) Mapping out Fabry-Perot polymer sensor using a standard CCD camera is an affordable method to increase the measurement speed.(9) A time-gated CCD camera can be used taking advantage of its fast shuttering capability and the high resolution of a standard CCD camera. Paltauf and co-workers demonstrated the use of a gated CCD camera, where variations of optical reflectance due to optoacoustic pressure was measured using Fresnel formula.(10) Optical interferometry is exploring its own realm in biomedical optoacoustic fields, not just as an alternative to piezoelectric transducers. Enhancing the performance of interferometers like speed and stability, while inheriting non-contact precision detectability, will be the future directions toward clinical applications.

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