

Infrared molecular fingerprinting: an emerging frontier for rapid health screening

Abstract

Vibrational Spectroscopy shows magnificent usage in varying applications such as chemical engineering, metallurgy, healthcare etc. The two main components, namely Raman Spectroscopy and Infrared Spectroscopy, hold immense potential in sensing a myriad of analytes. The very feeble signal of Raman sometimes obstructs its use. Meanwhile, its counterpart Infrared shows immense potential in terms of sensitivity as well as easy handling. As far as their use in health care sector is concerned, emerging frontiers are slowly evolving. This work highlights an emerging frontier of infrared spectroscopy, namely infrared molecular fingerprinting, which shows promise as a rapid screening tool capable of extracting information relevant to multiple health conditions from a single blood-based measurement. Shedding a glimpse into its enormous potential, this works briefly describe the future prospects too along with real case application.

Keywords: infrared, molecular fingerprinting, health screening, effective, spectroscopy

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Introduction

Healthcare industries are progressing very rapidly. With the advent of technology and new technologies, there is value added in the upcoming innovations. Whatever it may be, users are in general drawn to technologies which can give a very fast diagnosis so that preventive measure can be administered. As such, there is a strong need to supplement current medical diagnostics with quick, affordable, non-invasive, or minimally invasive technologies that may result in new screening and detection strategies prior to tissue-biopsy-based molecular profile or prognosis. Human serum and plasma molecular studies offer systemic molecular information and open new diagnostic avenues. As of right now, most liquid biopsies primarily depend on the examination of a small number of pre-selected analytes and biomarkers. Even though thousands of distinct biomarker candidates have been found thanks to the development of extremely sensitive and molecule-specific techniques in the disciplines of proteomics and metabolomics, only a small number of them have been verified and brought to the clinic thus far. The last ten years have seen a paradigm shift in liquid biopsies due to technological advancements. Recent methods concentrate on integrating data from a wide variety of molecules rather than depending on a single molecular marker to examine alterations in molecular patterns and pinpoint physiologies unique to diseases. Nevertheless, the integration of many omics' techniques (i.e., multi-omics) still necessitates intricate methods of combining disparate datasets as well as extensive and target-specific sample preparation. Furthermore, adding more analytical techniques frequently results in costs that are too high for widespread clinical application.¹⁻³

This is where infrared molecular spectroscopy shines since it can record signals from every kind of molecule in a sample in a single, label-free, time-efficient measurement. Infrared spectroscopy, infrared molecular fingerprinting, liquid biopsy, and conventional biomarker-based diagnostics represent related but distinct approaches to disease assessment. Infrared spectroscopy is an analytical technique that measures the absorption of infrared radiation by molecular bonds, thereby providing information about the biochemical composition of a sample. Infrared molecular fingerprinting (IMF) is a specific application of infrared spectroscopy in which complex spectral

patterns obtained from biological fluids, such as blood plasma or serum, are used to generate a holistic molecular signature that reflects an individual's physiological state. In contrast, liquid biopsy refers to the analysis of disease-related components circulating in body fluids, including circulating tumor DNA, extracellular vesicles, proteins, or other molecular biomarkers. Conventional biomarker-based approaches typically focus on the measurement of a limited number of predefined molecular targets whose clinical relevance has been established. Unlike these targeted methods, IMF adopts a global and untar geted strategy, capturing the collective biochemical information contained within a sample through a single spectral measurement. While this broader molecular view offers the potential to identify disease-associated biochemical alterations and support health screening, the precise molecular interpretation of spectral features remains an active area of research, and further validation is required before widespread clinical implementation can be achieved. When infrared spectroscopy is used on blood serum or plasma samples, it produces what is known as an infrared molecular fingerprint (IMF) that represents the chemical makeup of a sample, or the molecular blood phenotype of an individual. Even though the molecular origin of the IMF of a highly complex biofluid, such blood serum or plasma, can only be partially determined, it can provide a wealth of information that is sensitive to and unique to an individual's health.³⁻⁶

This work reveals a new area of infrared spectroscopy that makes molecular fingerprinting easier. with the capacity to diagnose a wide range of illnesses at once. Further, it also provides a brief description of future prospects, offering a look into its immense potential.

Infrared molecular fingerprinting as an emerging frontier

Infrared molecular fingerprinting has been one of the recent breakthroughs of the decade so far as health care diagnostics are concerned. Stemming directly from Infrared spectroscopy, the technique extends to blood serum or plasma. As we know that infrared spectroscopy is widely used in chemical analysis, its application towards diagnosis of vital parameters of human being is continuously rising. This leads to a total paradigm shift as one important aspect of fingerprinting, known as infrared molecular fingerprinting. Figure 1

demonstrates the schematic representation of molecular fingerprinting with Figure 2 directly portrays the schematic representation of infrared molecular fingerprinting where the analyte is chiefly blood or related components.



Figure 1 Schematic illustration of molecular fingerprinting. As seen in the schematics, the fingerprint leads to the DNA profile—thereby facilitating a small step in diagnostics.

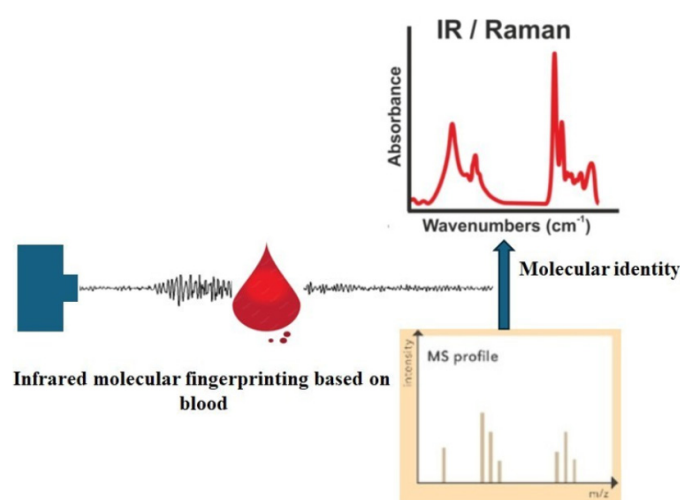


Figure 2 Blood based infrared molecular fingerprinting. Infrared source is shone on blood sample or biological fluid which leads to the IR spectra—thereby giving a potential biochemical sketch of the patient/user.

As of now, infrared molecular fingerprinting is emerging as a powerful, minimally invasive approach for disease detection and health monitoring. With the use of infrared light, invisible to human eye, users assess the vibrational and rotational motions of molecules in a sample. This way, one gets a complete biochemical sketch of the sample analyzed. This technique has demonstrated significant potential for detecting and characterizing various pathological conditions, including cancer and metabolic disorders.⁵⁻⁹

A real case study of Molecular fingerprinting

In terms of real application, researchers have implemented this emerging tool as a health screening probe. German researchers investigated the viability of infrared (IR) molecular fingerprinting as a possible method for health screening. Over 5,100 blood plasma samples from a naturally diverse patient group were profiled using Fourier transform infrared (FTIR) spectroscopy and machine learning.¹⁰

According to the findings, IR fingerprinting may reliably identify healthy people and identify common medical disorders with just one measurement. The method may eventually increase the effectiveness

and speed of medical diagnostic procedures, but it still requires more evaluation. It can take a lot of time and resources to measure several biomarkers from a single sample, even though blood-based laboratory test panels are frequently utilized in clinics. For high-throughput health diagnostics, a “shotgun” strategy that simultaneously checks for numerous medical disorders is therefore preferred. At the same time, adult populations often come with health aberrations with multiple coexisting conditions. There must be a proper diagnosis which can differentiate multimorbid states from rich conditions.

Taking these existing complexities into account, Léigman and her associates set out to create a new minimally invasive screening and risk-assessment tool. They decided to investigate a theory based on FTIR spectroscopy, which generates an infrared spectrum with absorption peaks that match the vibrational frequencies of molecular fragments. One way to conceptualize the IR absorption spectrum is as a molecular fingerprint that represents the overall molecular makeup of a material. Remarkably, IR fingerprinting successfully differentiated between dyslipidemia, hypertension, prediabetes, type 2 diabetes, and healthy states when tested on untested datasets.

Researchers analyzed 5,184 blood plasma specimens collected from 3,169 participants, making it the largest study to date, according to the authors, to utilize infrared (IR) fingerprinting on a population scale. The scientists combined each participant’s IR spectral profile with corresponding clinical records to develop a multi-label machine learning model capable of identifying and differentiating several health conditions simultaneously. Validation on independent datasets showed that the approach could accurately distinguish healthy individuals from those with dyslipidemia, hypertension, prediabetes, or type 2 diabetes. Furthermore, the technique was able to identify individuals affected by multiple disorders at the same time and predict the future emergence of metabolic syndrome several years before its clinical diagnosis.¹⁰

Compared to carefully chosen case-control studies, the study cohort’s representation of a naturally diverse adult population offered a chance to assess the effectiveness of infrared molecular fingerprinting in settings more akin to actual clinical practice. The researchers created and assessed predictive models using separate validation datasets to gauge their generalizability by fusing machine-learning techniques with FTIR-derived spectral fingerprints. The method’s ability to distinguish between healthy people and those with common metabolic diseases, such as dyslipidemia, hypertension, prediabetes, and type 2 diabetes, was demonstrated by the published results. Although the diagnostic performance metrics reported in the study were encouraging, the authors emphasized that sensitivity and specificity may vary according to disease category, cohort composition, and validation strategy. The main benefit of this method from a clinical standpoint is its capacity to gather data on several medical disorders from a single blood test, which may help with risk assessment and screening at the population level. However, before infrared molecular fingerprinting can be taken into consideration for normal clinical implementation, further extensive prospective investigations, external validation across geographically different populations, and direct comparisons with established clinical diagnostic procedures are still required.¹⁰

Future landscape and concluding remark

Infrared molecular fingerprinting has a bright future landscape. Some of the future prospects are outlined below.

- a) **Synthetic datasets:** The synthetic database could be a game changer. They retain the statistical and physical properties of real

molecular fingerprints. Consequently, these data sets are helpful in the development and validation of analytical methods where the privacy of patients remain intact. At the same time, it could pave the way for easier reproducible results as well as potential collaboration among stakeholders.

- b) Database involving diverse populations:** Like the previous one, if there happens to be a repository of molecular fingerprinting database which comprises of people with diverse genetic and lifestyle background, it could prove beneficial in the long run as far as quick noninvasive diagnosis is concerned. Meanwhile, the proper handling of these is a major concern as there are possibilities overlapping as well as biases.
- c) Integration ML and artificial intelligence:** Leveraging Machine learning (ML) and artificial intelligence (AI) into Infrared molecular fingerprinting can prove immensely promising as it can lead to discerning complex biomarker within a very short span of time. However, it comes up with limitations which requires attention. The performance of ML models is highly dependent on the quality, diversity of training datasets, making them susceptible to dataset bias when certain demographic or clinical groups are underrepresented. In addition, the high dimensionality of spectral data may increase the risk of overfitting, whereby a model performs well on training data but exhibits reduced generalizability when applied to independent populations. Another important challenge is model explainability, as many advanced AI approaches function as “black-box” systems, making it difficult to establish clear relationships between spectral features and underlying biological processes. Furthermore, robust external validation across multiple clinical centers, instruments, and patient cohorts is essential to demonstrate reproducibility and clinical reliability. Addressing these concerns through standardized datasets, transparent analytical frameworks, explainable AI methodologies, and rigorous multicenter validation studies will be critical for the successful translation of AI-assisted infrared molecular fingerprinting into routine healthcare practice.

The application of infrared molecular fingerprinting in human health is promising, offering a practical solution for overcoming ethical barriers in clinical data sharing and advancing the study of blood-based molecular diagnostics. Despite its considerable promise, several important challenges must be addressed before infrared molecular fingerprinting can achieve widespread clinical implementation. First, biological variability arising from differences in age, sex, ethnicity, genetic background, lifestyle, diet, and comorbidities may influence infrared spectral signatures, necessitating validation across large and diverse populations. Second, the lack of standardized protocols for sample collection, preparation, storage, spectral acquisition, and data preprocessing can introduce variability and hinder the comparability of results obtained across different institutions and instrumentation platforms. Third, reproducibility remains a critical concern, as laboratory-to-laboratory variations may affect the robustness of predictive models developed using infrared spectra. Another major challenge lies in the interpretation of complex molecular fingerprints, where spectral features often represent the

collective contribution of numerous biomolecules rather than specific analytes. Consequently, advanced chemometric and machine-learning approaches, while powerful, may suffer from limited interpretability, potentially restricting clinical acceptance. Furthermore, regulatory approval pathways for diagnostic technologies require rigorous demonstration of analytical validity, clinical validity, and real-world utility, which demands extensive multicenter studies and long-term validation. Finally, although infrared molecular fingerprinting offers rapid and multiplexed analysis, its diagnostic performance must be continuously benchmarked against established clinical methods, including biochemical assays, immunoassays, molecular diagnostics, and imaging techniques. Addressing these challenges through standardization initiatives, transparent analytical workflows, large-scale validation studies, and interdisciplinary collaboration will be essential for translating this promising technology from research laboratories into routine clinical practice.

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None.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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