



Original Article

Raman spectroscopy in quality control of Chinese herbal medicine

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Abstract

Background: Chinese herbal medicine (CHM) is of noteworthy international interest due to its potential impact on healthcare and manifests numerous opportunities for new drug development. However, solid scientific evidence is still lacking regarding the safety, efficacy, and quality of CHM-derived medicines. Success in the modernization and globalization of CHM is heavily dependent on the achievements in advanced analytical techniques for in-line checks of CHM quality. Raman spectroscopy has become increasingly valued as an analytical technique in the pharmaceutical sector because it can provide a detailed chemical fingerprint. However, earlier research suggests that inadequate attention has been paid to the applications of Raman spectroscopy in CHM.

Methods: Chinese and English literatures were reviewed via PubMed and Medicine databases, and through manual searches using keywords including traditional Chinese medicines, herbs, quality control, and Raman spectroscopy.

Results: Applications of Raman spectroscopy in various aspects of CHM, including the identification and analysis of raw materials, in-line checks of formulation, characterization of adulterants, and detection of counterfeits, were reviewed systematically.

Conclusion: An updated systematic review of the published literature has been conducted to analyze the most important milestones and latest achievements in this topic. Raman spectroscopy is playing an increasingly important role in the quality control of CHM and effectively promotes the modernization of CHM.

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Keywords: analytical technique; Chinese herbal medicine; modernization; Raman spectroscopy

1. Introduction

Chinese herbal medicine (CHM) is attracting global attention due to its potential impact on healthcare and burgeoning opportunities for new drug development.^{1,2} Over the past two decades, the CHM field has witnessed great progress in modern research directed at clinical trial evaluation,

pharmacological mechanisms/pharmaceutics investigations, and new drug discovery.^{2–5} However, we are still facing challenges in shifting experience-based CHM to evidence-based medicine, to promote its modernization and worldwide acceptance. These challenges primarily lie in the multi-component and multispecies composition features of many CHMs, and the widely reported deficiencies in CHM standardization and quality control. Solid scientific evidence of safety, efficacy, and quality is still lacking, although highly desirable.^{1,3,4} The success of these medicines is no doubt strongly dependent on the achievements of the fundamental understanding of pharmacology/pharmaceutics, rigorous

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quality control of herb medicine, and effective development of new drugs. CHM quality control takes priority in the whole chain of research toward its modernization. The herbs should be correctly authenticated to confirm their botanical origin prior to any designed biological and clinical research. Active pharmaceutical ingredients (APIs) should be well identified and their changes during manufacturing process should be well monitored to assure clinical effectiveness and safety. Therefore, development of comprehensive quality control approaches that are suitable for the multiple-component feature of CHM is extremely important.

Analytical methods such as thin-layer chromatography,⁶ high-performance liquid chromatography,⁷ ultra-high-performance liquid chromatography,⁸ and liquid or gas chromatography–mass spectrometry^{9,10} have been proposed, developed, and used in the fingerprinting of herbal medicines. These approaches can provide results with high reliability and accuracy, but generally require a cumbersome pretreatment and a time-consuming procedure. In addition, experimental conditions are rigorous and instruments are expensive, which limit their practical application. The use of spectroscopic techniques in terms of infrared (IR) and Raman spectroscopy is advantageous because the analyses are rapid, nondestructive, noninvasive, and simple for purposes of sample preparation.^{11–13} These techniques provide fingerprint information (such as molecular conformation, structure, intermolecular interaction, and chemical bonding) by way of probing the associated molecular vibration and rotational energy changes.^{14,15} IR spectroscopy is based on absorption, while Raman spectroscopy is based on inelastic light scattering. These vibrations with molecular dipole moment changes are IR active, and those with polarization potential changes are Raman active.^{16,17}

Raman spectroscopy is complementary to IR spectroscopy and is of particular interest in the pharmaceutical sector due to the following reasons: (1) inherently high chemical specificity and ability to provide molecular information without requiring staining or labeling,^{17,18} and (2) low sensitivity to water, consequently making analysis of aqueous or damp materials, including illegal narcotics, possible.¹⁹ These advantages, coupled with fiber optics and microscopes, have enabled Raman spectroscopy to be an effective quality control tool in the pharmaceutical industry.^{18,20} It serves as an ideal instrument for the characterization and authentication of herbs, detection of counterfeits, and facilitation of new drug development. Raman spectroscopy with probes can also be used for continuous quality control in formulation manufacturing. Applications of Raman spectroscopy in the pharmaceutical industry range from use in the laboratory to on dock to production lines until the product is shelved.²¹ There are many excellent review articles dealing with the basic principles and applications of Raman spectroscopy.^{14,18,21–26} However, among several published reviews, little attention has been paid to the applications of Raman spectroscopy in CHM.

Taking into account the quality and safety requirements of modern CHM, this review aims to summarize and critically discuss the applications of Raman spectroscopy in various aspects of CHM, including the identification and analysis of raw

materials, in-line formulation checks, characterization of adulterants, and detection of counterfeits (Fig. 1). A brief introduction to the theory and mechanism of the Raman scatter is also included. Potential areas of future advancements and applications of Raman spectroscopic techniques are also discussed.

2. Methods

This review paper is based on a literature search focusing on PubMed and Medline databases, as well as other resource materials. The key search words used included traditional Chinese medicine, herbs, herbal, quality control, and Raman spectroscopy. In addition, specific searches were carried out using the above keywords with the common and scientific names of the plant products.

3. Results

3.1. Theory of Raman spectroscopy

Irradiation of the electron orbits within the constituent molecules with a monochromatic light always gives rise to two types of light scattering: elastic and inelastic.²⁷ The elastic scattering that takes place at the same wavelength as that of irradiated light is also known as Rayleigh scattering.^{28,29} The inelastic scattering is always accompanied by a shift in photon frequency and a change in wavelength, upon gain or loss of some amount of energy. This phenomenon results in Raman scattering (Fig. 1). In Raman scattering, an incident photon excites a molecule from the ground state to the virtual energy state. Immediate relaxation of the excited molecule to ground electronic or vibrational states would emit photons that undergo a wavelength shift. If the scattered light is of a higher wavelength than the irradiated light, it results in a Stokes–Raman shift; conversely, it is known as an anti-Stokes shift (Fig. 1).^{27–29}

The history of Raman spectroscopy began in 1928 when the Indian scientist Sir CV Raman, along with his student Krishnan, discovered the “Raman effect.”³⁰ For decades, it was not possible to obtain successful Raman spectroscopy of pharmaceutical materials due to its intrinsically low efficiency (Raman cross sections are typically in the order of 10^{-28} – 10^{-30} cm²).¹⁶ However, the advancements in new experiments and technical approaches, including Fourier transform (FT) spectrometers and charge coupled device-based experiments, provide a viable strategy to address this limitation.^{17,18,21} Various novel types of techniques such as FT-Raman spectroscopy,^{31,32} transmission Raman spectroscopy,^{22,33,34} and surface-enhanced Raman scattering (SERS)^{35–38} have been developed. These technological variations open up a new era for Raman spectroscopy applications in mainstream pharmaceutical analysis.

3.2. Applications of Raman spectroscopy in quality control of CHM

Accurate detection, identification, and quantification of raw materials and APIs; in-process checks of CHM quality; and

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