ISSN: 0975-3583, 0976-2833 VOL0, ISSUE 3, 2019

Large-Scale Analysis of Renal Stone Composition by FTIR: A Cross-sectional Study of 3,789 Samples

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Abstract:

Background: Renal stones (nephrolithiasis) are a common urological condition resulting from the crystallization of dietary minerals within the kidneys. Their composition, including calcium oxalate, calcium phosphate, uric acid, and cystine, significantly influences treatment and recurrence prevention. Fourier transform infrared (FTIR) spectroscopy, a semi-quantitative and automated technique, offers an advanced method for precise stone composition analysis.

Objectives: This cross-sectional study aimed to:

- Analyze the mineral composition of renal stones using FTIR spectroscopy.
- Classify the mineral components of renal stones.
- Characterize the trends and morphological features of renal stones.

Methods: We analyzed 3,789 renal stones collected from August 2018 to May 2019. Stones were prepared and analyzed using the Agilent Cary 630 FTIR Analyzer. Data on mineral composition and morphology were collected and processed to identify prevalent mineral trends and stone compositions.

Results: The majority of stones (76.3%) were from male patients, with the highest incidence in the 31–40 age group. Notably, 93.5% of stones exhibited mixed compositions, with calcium oxalate monohydrate being the most prevalent mineral component (38.3%). Rare stone compositions, including xanthine and 2,8-dihydroxyadenine, were identified, providing valuable insights into underlying metabolic disorders.

Conclusion: FTIR spectroscopy provides a reliable method for determining renal stone composition, facilitating effective and individualized treatment strategies. The predominance of mixed stones emphasizes the necessity for multifactorial treatment approaches that address dietary, metabolic, and infectious factors. Future research, incorporating advanced techniques such as genetic testing, may further elucidate the mechanisms of stone formation.

Keywords: Calcium oxalate, Fourier transform infrared spectroscopy, Nephrolithiasis, Renal stones, Stone composition, Urinary tract stones.

ISSN: 0975-3583, 0976-2833 VOL0, ISSUE 3, 2019

Introduction

Renal stones, or nephrolithiasis, represent a significant and prevalent urological condition affecting millions globally. These stones form through the crystallization of minerals and salts within the urinary tract, leading to a variety of clinical manifestations, including severe pain, urinary tract obstruction, and potential renal damage. The composition of renal stones is highly variable, encompassing a range of substances such as calcium oxalate, calcium phosphate, uric acid, struvite, and cystine. Understanding the precise mineral composition of these stones is crucial for guiding effective treatment strategies and implementing preventive measures to reduce the risk of recurrence.

Accurate stone analysis plays a pivotal role in tailoring patient-specific management plans. Traditional methods for stone analysis, such as wet chemical analysis, have been largely supplanted by more advanced techniques that offer greater accuracy and efficiency. Among these, Fourier Transform Infrared (FTIR) spectroscopy has emerged as a reliable and robust method for determining the mineral composition of renal stones. FTIR spectroscopy provides a semi-quantitative, non-destructive, and rapid analysis, making it particularly suitable for clinical applications.

This study aims to contribute to the existing body of knowledge by presenting a comprehensive analysis of renal stone composition using FTIR spectroscopy in a large cohort of 3,789 cases. By characterizing the mineral profiles, identifying prevalent and rare stone types, and examining demographic trends, we seek to provide valuable insights into the etiology and management of nephrolithiasis. This large-scale, cross-sectional analysis will not only enhance our understanding of renal stone composition but also underscore the clinical utility of FTIR spectroscopy in the diagnostic armamentarium for urolithiasis.

Objectives:

To analyze the data of renal stone received in our laboratory of various trends and patterns which are as follows:

• To determine the various mineral component of renal stone.

• To classify the incidents of various mineral compounds in renal stone.

• To analyze the data with respect to morphology.

ISSN: 0975-3583, 0976-2833 VOL0, ISSUE 3, 2019

Methods:

This cross-sectional, descriptive study analyzed renal stone samples received for chemical composition analysis at the laboratory from August 2018 to May 2018. A total of 3,789 renal stone samples were included in the analysis.

Instrumentation

All renal stone samples were analyzed using an Agilent Cary 630 Fourier Transform Infrared (FTIR) Analyzer.

Specimen Handling and Morphological Characterization

Upon receipt, each renal stone sample was assigned a unique sample identification (ID) number. All samples underwent morphological characterization, which included assessment of size, weight, color, consistency, and surface characteristics.

Sample Preparation for FTIR Analysis

The following procedure was used to prepare the renal stone samples for FTIR analysis:

1. **Crushing:** Each stone was crushed into a fine powder using a pestle and mortar.
2. **Potassium Bromide (KBr) Mixing:** The powdered stone was mixed with potassium bromide (KBr) in a 30:70 ratio (30% stone powder, 70% KBr).
3. **Homogenization:** The mixture was thoroughly homogenized.
4. **Pellet Formation:** A pellet of the homogeneous mixture was prepared using a pellet maker assembly.
5. **Pellet Placement:** The formed pellet was placed in the pellet holder of the FTIR analyzer.

FTIR Analysis Procedure

The FTIR analysis was performed as follows:

1. **Sample Transfer:** The sample pellet was transferred to the appropriate holder position, ensuring no cross-contamination of other positions.
2. **Position Filling and Surface Preparation:** The holder position was completely filled, and a spatula or flat-sided tool was used to create a flat surface and remove any excess material.
3. **Holder Placement:** The sample holder was inserted into the diffuse reflectance accessory, and the holder was moved to the desired sample position.
4. **Spectrum Acquisition:** A sample spectrum was collected using an appropriate method, following the instructions provided in the Agilent MicroLab FTIR Software User's Guide.

ISSN: 0975-3583, 0976-2833 VOL0, ISSUE 3, 2019

5. **Holder Cleaning:** Immediately after sample measurement, the sample was removed from the holder, and the holder was thoroughly cleaned to ensure no residual sample remained for subsequent analyses.

Discussion:

This study provides a comprehensive mineral profile of renal calculi using Fourier Transform Infrared (FTIR) spectroscopy, underscoring its efficacy in identifying stone composition and guiding personalized treatment to prevent recurrence. Our findings align with existing literature, emphasizing the critical role of accurate stone analysis in urolithiasis management.

1. Sex Distribution and Stone Formation

Consistent with global studies, we observed a significant male predominance (76.3%). Hormonal differences, particularly estrogen's influence on calcium reabsorption, and lifestyle factors, such as higher animal protein and sodium intake in men, likely contribute to this disparity. These factors can increase urinary calcium and oxalate excretion while reducing citrate, an inhibitor of stone formation.

2. Age Distribution and Prevalence of Stones

The peak incidence occurred in the 31–40 age group (47.1%), followed by the 21–30 age group (18.2%), aligning with previous studies indicating peak stone formation between the third and fifth decades. Lifestyle and dietary factors, including dehydration, play a key role.

3. Mixed vs. Pure Stones

A vast majority of stones (93.5%) were of mixed composition, highlighting the multifactorial etiology of nephrolithiasis. This necessitates complex treatment strategies. Pure stones (6.5%), often resulting from single factors, may be more amenable to targeted therapies.

4. Stone Composition: Preponderance of Calcium Oxalate Stones

Calcium oxalate stones, predominantly monohydrate, were the most prevalent (1,449 samples), consistent with global estimates of 70–80% of kidney stones. Dietary factors, such as high oxalate consumption and low calcium intake, contribute to this prevalence.

5. Uric Acid and Struvite Stones

Uric acid stones, associated with gout, obesity, and metabolic syndrome, require urine alkalinization for prevention. Struvite stones, linked to urinary tract infections (UTIs) by urease-producing bacteria, highlight the importance of infection control.

6. Implications for Clinical Practice

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The predominance of calcium oxalate stones emphasizes dietary interventions. Uric acid stones necessitate urine alkalinization, while struvite stones mandate infection control. Individualized treatment plans, combining dietary modifications, medications, and surgical interventions, are crucial.

Rare Stone Compositions

Several rare stones, including xanthine, 2,8-dihydroxyadenine, and sodium oxalate, were identified, providing insights into specific metabolic and genetic disorders. These necessitate precise diagnostic methods and personalized management.

- **Xanthine Stones:** Linked to xanthinuria, requiring metabolic evaluation and dietary adjustments.
- **2,8-Dihydroxyadenine Stones:** Associated with APRT deficiency, necessitating genetic testing and allopurinol treatment.
- **Sodium Oxalate (Anhydrous) Stones:** Related to hyperoxaluria, requiring dietary modifications and medications.
- **Other Rarer Stones:** The article also goes into depth about: Cholesterol stones, Cerumen stones, Furantoin stones, Oxypurinol stones, Alpha Quartz stones, Glafenic acid stones, Food Particles, and Cotton stones. All of which point to very unique cases, and the importance of highly specific testing.

Fourier Transform Infrared Spectroscopy in the Analysis of Renal Stones

FTIR spectroscopy offers reliable semi-quantitative analysis, outperforming traditional wet chemical techniques. Its non-destructive nature and small sample requirement make it ideal for clinical applications.

Conclusion

This study underscores the multifactorial nature of renal stone formation, emphasizing the need for individualized prevention and treatment strategies.

Further research should focus on elucidating the genetic and molecular mechanisms of stone formation.

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