Systematic Review on Current Technologies for Kidney Stone Disease Detection and Management

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Abstract

Detection of stones in the kidney through imaging is a predominant screening method and the foremost step in choosing the ideal treatment for kidney stone disease. The best first imaging modalities to employ to assess patients with suspected obstructive urolithiasis vary according to the recommendations offered by the American Urological Association (AUA), European Association of Urology (EAU) and American College of Radiology (ACR); the best definitive diagnosis is regularly made with non-contrast Computed Tomography of the abdomen and pelvis, however, doing so exposes individuals to ionizing radiation. Ultrasonography-derived compounds have less radiation than C.T. but have poorer specificity and accuracy. However, randomized controlled experiments comparing these imaging modalities revealed comparable diagnostic accuracy in the emergency unit. Each modality has benefits and drawbacks. Plain radiography of the kidney, ureter and bladder (KUB) is less beneficial in acute stones and perhaps most useful in assessing interval stone development in patients with established stone disease. Although MRI offers the prospect of 3D imaging without radioactive contamination, it is expensive, and at the moment, it is challenging to see stones. Future advancements are anticipated to improve all the imaging modalities for the diagnosis and management of stones in the kidney. Clinicians may benefit from a suggested approach for detecting patients with stone former in consideration of the recommended practices and a random control study.

Keywords: Kidney stone, Detection, Computed tomography, Ultrasonography, Magnetic resonance imaging, Radiography.

Introduction

A crystallized mass that concentrates inside the kidney is referred to as a kidney stone. It is also referred to as renal calculi, nephrolithiasis or urolithiasis. Urinary stones are the most prevalent ailment of the urinary system. It is a rising urological disease that has affected human health for 12% of the global population. Nearly 50% of cases recur, and urolithiasis is expensive for both the patient and society. Urolithiasis affects as many as one in eleven Americans, and in the last 15 years, the frequency has climbed by over 70%. Additionally, more imaging tests are being requested to check for kidney stones; from 1992 to 2009, the usage of C.T. to image kidney stone patients quadrupled. With the help of imaging, determining the size and position of stones in patients with probable kidney stones helps in the diagnosis and offers the first step in management.

Clinicians from a variety of specializations will see people with kidney stones. Thanks to recent technological advancements, it is much simpler to identify the source of stone sickness. Furthermore, the management of urolithiasis is becoming increasingly clear. The medical environment, patient body habitus, cost, and radiation tolerance are just a few of the many parameters to be considered while the treatment is being prescribed. Even though there are several imaging modalities, currently, ultrasonography, computed tomography, and kidney ureter bladder (KUB) plain film radiography are used to a huge extent in hospitals. This review describes the fundamentals of each imaging modality used in today's technology and its sensitivity, specificity, benefits, drawbacks, and expense [1].

Causes and Symptoms

The most common causes of kidney stone production are inherited and external conditions. Stone risk is influenced by hereditary variables; Reduced hydration is a well-established risk factor. It has also been shown that consuming more oxalate encourages the development of stones. According to epidemiologic research, higher salt and animal protein consumption increase the risk of stone formation. However, a randomized, prospective lifestyle intervention research found that dietary calcium consumption was maintained, but sodium and animal protein intake were reduced in those who frequently generate hypercalciuric stones. Although external changes are many and complicated, their impact is more noticeable since changes in them happen more often [2]. Stone development does not immediately result in any symptoms. Eventually, flank pain, and hematuria, are indications and symptoms of urolithiasis. The other symptoms also include severe pain in the lumbar region, cloudy or gritty urination, changes in the color of the urine, trouble urinating, nausea, fever and chills. Consequently, the cost of therapies and time has a detrimental impact on the nation's economy and quality of life. According to research, metabolic syndrome may be a systemic disorder linked to urolithiasis. Renal stone frequency has been associated with chronic kidney disease, end-stage renal illness, obesity, and diabetes mellitus [3].

Classification

Based on size

Simple renal calculi include those with normal renal architecture and a stone load of less than 2 cm (composite diameter). Stones larger than 2 cm, such as staghorn calculi, stones arising in kidneys with aberrant morphology, and stones resistant to disintegration, are all examples of complex renal calculi. Ureteral calculi frequently exhibit acute renal colic complaints [4].

Based on their constituents

The names of the principal components identify the four primary categories of stones. The most prevalent stones are calcium stones, which can be either alone or in conjunction with CaOx and CaP crystals. CaOx, which may be found as a monohydrate or dihydrate, makes up the majority of urolithiasis, either totally or partly. CaOx monohydrate (COM) crystals are thin, plate-like, and typically twinned, as observed in urinary sedimentation, where they take on a "dumb-bell" appearance. COM crystals are placed radially within the stones into fan-shaped features with prominent concentric laminations, demonstrating the crystals' and the stones' outwards development (Figure 1).

CaO_x dihydrate (COD) crystals in kidney stones and urine sediments exhibit the distinctive tetragonal bipyramidal form. Small and lustrous on the outside, CaOx stones typically include both COM and COD crystals. In comparison to pure COD stones, COM stones are more prevalent. In mixed stones, the top of the stone, which has a jagged appearance, is predominantly covered with COD crystal. Pure COM stones, on the other hand, have smooth edges. CaOx stone creation involves several steps, which are clearly described with the help of the schematic representation given below. Significant risk factors include hypercalciuria, hyperoxaluria, and hypocitraturia.

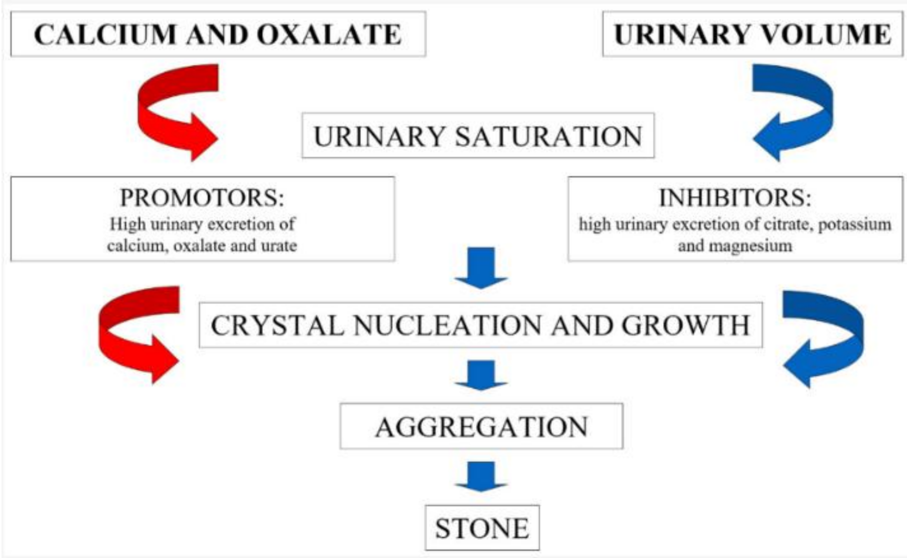

Figure 1: Representation of the urinary stone formation from the calcium and oxalate reproduced with permission from [5].

The diagnosis and location of kidney stones can often be estimated based on the patient's physical examination without image processing, even though abdomen imaging is commonly done on people diagnosed in the emergency department with flank pain and blood in the urine. Nevertheless, stones are mostly undetectable if they develop in the renal calyces, although stone formation can be highly complex and will deviate between various stone components. Urinary flow is obstructed by entry into the ureter, which causes the ureter and renal pelvis to enlarge upwards. As ureteral motility rises due to this blockage, the discomfort of the colic variety typically develops.

Generally, around the ureteropelvic interjection, at the spot that the renal pelvis constricts to the ureter's calibre, a stone impedes. A blockage causes pain in the back at this location. As the stones travel distally, it narrows at two more spots: first, in which the ureter traverses the iliac arteries, and subsequently, at the bladder, or ureterovesical confluence. The imaging techniques normally accessible are C.T., KUB radiographs, ultrasonography, and MRI. Different detection modalities have various ranges of precision, ionizingradiation exposure, and sensitive and proportional costs [7].

Radiography

Using a single source of energy, KUB plain film radiographs and fluoroscopy generate photons that travel through tissue anteriorly to posteriorly before colliding with a contralateral sensor. In a single plane, this method applies its same core ideas as C.T. In the past, an intravenous pyelogram using KUB radiography was performed to assess the existence of hydronephrosis and blockage. This modality was supplanted when C.T. was developed as an imaging technology. It is estimated that typical KUB radiography has a specificity and sensitivity of 57% and 76%, correspondingly. KUB radiography benefits from economical cost (10% of ultrasonography) and a fairly low ionizing radiation dose when compared to CT (0.15 mSv). If stones are detected with KUB images, they are likely to be observed throughout fluoroscopy, which is used as a reference during shockwave lithotripsy or ureteroscopy. However, as this imaging method only views stone from one angle, reliability diminishes, reducing its sensitivity and specificity and limiting its application. KUB imaging can be used to visualize many different stone types. Still, cystine and struvite stones are frequently only marginally visible, while uric acid and matrix stones cannot be seen at all [8]. Ultrasonography and KUB radiography can be used in tandem to counteract this problem, allowing the extreme susceptibility of ultrasonography to supplement the better sensitivity of KUB radiology. When evaluating ureteral stone illness throughout stone migration or following therapy, the AUA advises using this integrated imaging method. For instance, following surgery, a blocking stone may be seen to migrate. Smaller stones can be hidden if placed over bony structures or when intestinal gas is present.

KUB radiography has a responsiveness of 37.0% for stones less than 5 mm in size. However, this rises by 87.5% for stones larger than 5 mm. KUB radiography is more affordable than other methods for assessing stone size in patients undergoing medical treatment. KUB radiography advancements combine C.T.'s analytical scanning power and KUB's low dose of radiation. Like a C.T. scan, digital tomosynthesis combines computer-integrated picture data from an opposing detector with KUB radiography scout images captured in an arc all around the subject. This technique, which has been widely utilized in mammography as an alternate screening method to mammograms, allows viewing stones from numerous angles instead of just anterior to posterior. Scanning from various angles enhances sensitivity and specificity for renal stone patients while slightly increasing the irradiation dose. Although these analytical technologies are still in the prototype phase, they suggest that KUB radiography may still be a crucial imaging method for kidney stones. In general, KUB imaging is less beneficial when treating acute stones and more helpful when assessing a patient with a known stone illness. But the low sensitivities of this imaging technique can be increased by combining it with ultrasound and by modern innovations like digital tomosynthesis [9].

Ultrasonography

Clinicians in the USA are now also embracing ultrasonography, a low-cost scanning modality that doesn't rely on ionizing radiation and is quickly replacing C.T. in other countries. Short bursts of sonic radiation are applied to the patient via a receiver to create the images used in ultrasonography. When flowing through materials with varying densities and/or characteristic acoustic impedance, this energy is transmitted into the tissue as vibrations that partly bounce back into the source. Images can be created using wave intensity and travel periods by detecting the reflected waves using a sensor. Stones may look bright with a dark distal shadow in the brightness operating mode of ultrasonography, which is the common grayscale image. Harmonic mode, which means that the sent signal has a smaller wavelength than the receiver end, can also be utilized in B-mode to increase resolution and reduce clutter. When using Doppler ultrasonography, color can be presented on top of the B-mode imaging to represent the amplitude or intensity of the Doppler signal. However, the existence of stones can cause an artifact in Doppler ultrasonographic scanning that causes the color in the imaging at the position of the stone. The Doppler ultrasound signal is especially sensitive to movement, such as fluid flow in a ureteral jet. Similar to C.T., B-mode ultrasound looks for stones by comparing the physical properties of the stones to the tissues around them. In contrast to soft tissues, stones show large echogenic structures in the ultrasound images and significantly bounce ultrasonic waves. [10]. Stones block the passage of ultrasonic waves, leaving non-echogenic shadows in the image further than the stone. Doppler ultrasonography can be utilized to identify substitutes for blocking stones, including renal damage and a lack of a ureteral jet. Ultrasonography has been linked to a diverse range of hypersensitivity and particularities, likely due to methodological differences, body habits, patient demographics, and specifications. As bowel gas obstruction and increasing penetration depth make it challenging to scan the length of an undilated ureter, imaging stones in the renal pelvis and the ureter also provides unique obstacles. The identification of the sensitivity and specificity for renal calculi are 45% and 88%, respectively, and for ureteric calculi, they are 45% and 94%, respectively, according to a pooled analysis of the literature. Due to the difficulties in differentiating between echogenic stones and echogenic central sinus fat in the kidneys, sensitivity is decreased for stones smaller than 3 mm, which may not cast a shadow, and stones can be overlooked in a defragmented system. Integrating KUB radiography with ultrasonography can increase sensitivity [11].

There was no observed discernible difference in the number of high-risk diagnoses with side effects, the total number of adverse outcomes, or related serious complications between the ultrasonography and CT groups of patients in a study by Bindman *et al* [12]. The differences between diagnostic techniques, such as ultrasonography and computed tomography, were explained in detail in their research. Additionally, there were no discernible differences between the groups for the critical secondary outcomes of pain ratings, hospitalizations, and emergency department re-admissions throughout the follow-up. However, their findings do not imply that patients must only undergo ultrasound imaging; they do propose that ultrasonography be utilized as the primary diagnostic imaging test, with any additional imaging investigations being carried out at the doctor's discretion based on his or her clinical opinion. Every study group included some patients who received further imaging, but the ultrasonography groups had a higher percentage. There was no rise in any classification of significant adverse outcomes among patients allocated to ultrasonography, despite the fact that the majority of patients in the ultrasonography groups did not get CT. The radiation dose in the ultrasonography groups was more than zero because some patients in those groups subsequently had CT.

Kanno *et al* [13] have examined the identification of renal stone in 428 patients in order to evaluate the performance of ultrasonography (US) for identifying renal stones using noncontrast enhanced computed tomography (NCCT) as a standard reference. With a sensitivity of 70.0% and a specificity of 94.4%, ultrasonography has discovered stones in 332 of 474 calculi diagnosed by noncontrast enhanced computed tomography. Interestingly, it was discovered that the detection rate increased with stone size and that there was a positive correlation between the sizes of stones evaluated by US and CT. These findings suggest that US is equally suitable for the detection of renal stones and can help with clinically significant decisions involving the assessment of renal stone.

Non-contrast Computer tomography (C.T)

According to the research topic that needs to be addressed, several forms of imaging studies with varying quantities of contrast—or perhaps no contrast at all—and various picture timing fall under the general heading of C.T. The very commonly used radiography methods in individuals with nephrolithiasis are non-contrast C.T. or CT-KUB. In the United States, the utilization of CT for the detection of suspected kidney stones has grown by a factor of 10 over the past 15 years, likely due to its higher sensitivity and the fact that it can be done at any time in the majority of emergency rooms.

C.T. uses the different speeds at which the body's cells absorb radiation. Multiple information signals are generated by rotating a radioactive source and a contralateral detector around the person. These data signals are subsequently processed by software to create 3D images. Owing to their distinctly different architecture, kidney stones accumulate far more irradiation than renal parenchyma and urine, rendering them much simpler to identify without the aid of differentiation. The most sensitive modality for detecting kidney disease is computed tomography (C.T.), and accurate predictions indicate that it is about 95%. Small stones (less than 3 mm) may slither between scanned tissue surfaces and go undetected, while C.T. rarely misses large stones. The ACR calculates that when a patient complains of severe flank discomfort that an impending stone may cause, C.T. has a 98% accuracy rate. Except for a few pebbles brought on by the deposition of protease-inhibitor drugs in the urine, mostly all pebbles may be seen on a C.T. scan. Another benefit of C.T. is the acquired comprehensive anatomical images, which allow assessment of various probable explanations of the patient's clinical presentation.

Additionally, CT imaging can reveal details about the density of stones. The concentration of items that photons traveling from the radioactive source to the detectors meet is described by retardation. The attenuation is measured in Hounsfield units (H.U.). Water is assigned a value of 0HU, the air is minus 1,000HU, and dense tissue is 1,000HU on this measure. Given that various stone components absorb varying amounts of irradiation, a stone's Hounsfield units can be used to identify its kind. Calcium oxalate stones range from 700 to 1,200 HU, while uric acid pebbles are commonly between 200 and 400 HU. Increasing absorbance is correlated with an increasing number of shocks needed and with lower treatment outcomes; it could also be used to forecast sensitivity to shockwave lithotripsy [14].

Utilizing dual-energy C.T. scanners that allow the scanning of human tissues at 2 distinct voltages and comparing results from two separate detectors. These detectors also allow for the assessment of tissue at various energy levels, increasing the precision of stone composition calculations. Furthermore, when assessing obese patients, the reliability of C.T. is a crucial factor. There hasn't been a conclusive study comparing the two scanning techniques for urolithiasis in obese patients. Still, C.T. is typically more accurate than ultrasonography because it's challenging to image obese patients with ultrasonography. Screening individuals with urolithiasis, by which C.T. were found to be very particular and sensitive than ultrasonography, has conclusively proven the challenge of scanning obese patients. Based on the ACR, AUA, and EAU, conventional C.T. is the preferred imaging technique for individuals with a BMI greater than 30. C.T. has some drawbacks, such as a high price and radioactive exposure. Discussions on expenses frequently need to be clarified by various factors, including rates, costs, and payment, in addition to the numerous stakeholders comprising medical centers, health insurers, and patients.Cost-wise, low-dose C.T. is comparable to standard C.T. Although price is still a key distinction between C.T. and ultrasonography, radiation exposure is still crucial to consider [15].

Magnetic Resonance Imaging (MRI)

A magnetic force is used in MRI to coordinate the patient's protons in the free water at the field's axis. The region to be scanned is covered by a radiofrequency antenna, known as a coil, which emits frequency impulses that cause the protons' orientation to be disturbed. Protons efficiently transmit whenever the pulses end as they reconnect with the magnetic field; this information can be recorded as a picture. Like ultrasonography, hydronephrosis can enhance the sensitivity of MRI for stone imaging. Stones present as a nonspecific signal void in typical MRI images; however, by changing the imaging pattern, stones can be more reliably recognized. With a selectivity of 82%, MRI is more sensitive than ultrasound and KUB radiography is a little less wise as compared to Computed Tomography since the kidney stones are harder to see with MRI compared to C.T. Although stones may not always constitute the root of the blockage, hydronephrosis is readily apparent. The treatment options for accidentally found hydronephrosis comprises ureteral stone illness and blockage by known cancer. A C.T. scan may be necessary for a firm determination of the condition. Precision for the modalities is excellent at 98.3% when stones are visible on MRI. The capacity to give 3D scanning without irradiation is a significant benefit of MRI. Sadly, the limitations of MRI hinder its extensive application in stone scanning.

For instance, MRI is much more than a C.T. scan, has lesser precision, and requires significantly more time to acquire images. In pregnant patients, MRI is generally best used as an additional test to ultrasonography. The normal dilation of the kidneys that develops during pregnancy eliminates hydronephrosis as a stand-in indicator of blockage. When stones can be seen by ultrasonography, but there are medical doubts about obstructive kidney stones, MRI has been utilized as a diagnostic tool.

Magnetic resonance imaging (MRI) is of little use in the examination of renal calculi as compared to CT. The short imaging time and lack of ionizing radiation danger are two benefits of MRI. Additionally, since the collecting system may be seen by stretching it with intravenous frusemide, there's no requirement for intravenous contrast agents. Sudah *et al* [16] observed a sensitivity of 97% and a specificity of 100% for MRI urogram for stones in the urinary system, such as those in the ureter, in a study comparing gadolinium-enhanced MRI, non-contrast CT, and IVU. Better sensitivity is produced when using gadolinium to identify the obstruction's etiology. The sensitivity becomes even more when other parameters are included, such peri-renal signal intensity. Consider that stones appear on an MRI as a signal void and are not distinguished from a tumor or a blood clot. Small calyceal stones may be missed by an MRI. In the examination of renal and ureteric stones, CT often outperforms MRI. When it's best to minimize radiation exposure during pregnancy, MRI can be quite helpful.

The C.R., AUA, and EAU recommendations advise using MRI as a second-line modality in pregnant patients when ultrasonography is non-diagnostic. Smaller dosages of C.T. were applied to these patients; nevertheless, the patient needs to be informed of the dangers of radioactive contamination. Developing ultrashort-echo MRI sequencing may enhance the sensitivities, selectivity, and precision of MRI-based stone sizing [17].

Conclusion

Patients with flank pain and haemorrhage are evaluated depending on the patient's age, BMI, and whether or not it is expectant. For children under 14 and pregnant women, ultrasonography must be regarded as the benchmark, first-line imaging modality. Any person with a growing likelihood of having stones and those with a low body mass index (BMI) should be evaluated with ultrasonography. The AUA and ACR presently regard C.T. as the gold-standard technology for evaluating patients experiencing acute flank pain when there is a medical indication of urolithiasis. The EAU also advises C.T. as the modality of preference after ambiguous ultrasonography Doctors must try to keep radiation exposure as minimal as possible, whatever the first imaging method. When assessing an individual using ultrasonography, certain ambiguous results are to be expected; in such situations, low-dose Imaging techniques are suitable. Additionally, developments in ultrasound, KUB radiographic, C.T. and MRI technologies are ongoing and are anticipated to enhance all current techniques.

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