

Abdominal CT for the study of hepatocarcinoma: examination technique with dual energy GSI protocol

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ABSTRACT

The CT examination after the administration of a contrast medium has, since its inception, been one of the reference methods for diagnosing hepatic HCC (Hepatocellular Carcinoma). Thanks to the intravenous administration of iodinated contrast and the application of appropriately timed study protocols, it is possible to detect the presence of the characteristic post-contrast pattern of neoplastic nodules. Gemstone Spectral Imaging (GSI) is a new application of Dual-energy CT technology (Dual Energy Computed Tomography, DECT) that uses a rapid change in kilovoltage (from 80 to 140 kVp) to almost simultaneously acquire two samples at different energy levels, making it possible to obtain data related to the density of different substances, which are then used to separate materials and produce monochromatic spectral images. The principle behind DECT technology is, in fact, to detect density differences between substances based on differences in photon attenuation coefficients at different energy levels. GSI represents an evolution of the current DECT with two X-ray tubes and two detectors, as it uses a single source that, thanks to the rapid transition from low kVp to high kVp energy and a detector system with at least 128 layers, allows data to be acquired very quickly, decomposing matter into its different components such as calcium, iodine, and water. This descriptive article provides a technical review of the Dual Energy GSI protocol for HCC imaging, summarising its current principles, protocol and clinical applications.

INTRODUCTION

Hepatocellular carcinoma (HCC) is the most common primary malignant liver disease (80-90%); it has a global incidence of approximately 750,000 new cases per year with a high mortality rate. It is the second leading cause of cancer-related death in men and the sixth in women worldwide. Its incidence varies significantly depending on the geographical region: in the United States, Australia, and Northern Europe, the incidence is less than 5 cases per 100,000 inhabitants, whereas it is much higher in Africa and Asia with an incidence of 20-28 cases per 100,000 inhabitants. In Italy, the morbidity rate for HCC is 10-12 new cases per 100,000 inhabitants per year, with an annual mortality rate of 8 deaths per 100,000 inhabitants. The incidence of HCC increases progressively with age, although, in countries with high incidence, the average age at diagnosis is in the third decade of life, whereas in other countries, it is postponed to the following two or three decades. In this context, there are several techniques and methods that allow for early diagnosis in a short time: ultrasound, computed tomography (CT), and magnetic resonance imaging (MRI). During diagnosis, it is important to understand and classify the stage of the disease to determine the most appropriate therapeutic strategy. CT with contrast medium is the most widely used exam in suspected HCC liver neoplasms due to its fast execution time, diagnostic reliability, the typical intrinsic behavior of the lesion (rapid wash-in and rapid wash-out), and the relatively low cost of the exam. In particular, in recent years, the Dual-Energy CT technique with the GSI protocol (Gemstone Spectral Imaging) has been

increasingly expanding: it is a new application of dual-energy CT technology (Dual Energy Computed Tomography, DECT) that uses a rapid change in kilovoltage (from 80 kVp to 140 kVp) to almost simultaneously acquire two samples at different energy levels, allowing for the collection of data related to the density of various substances, which can be used to separate materials and produce monochromatic spectral images. The principle of DECT technology is to detect density differences between substances based on differences in photon attenuation coefficients at different energy levels. The goal is to artificially modulate the energy of the beam to produce images with varying contrast, attenuation, and noise characteristics, customized based on the clinical question. This ability to "play" with energy—and therefore with densities—makes virtual monochromatic images (VMI) an extraordinarily useful tool in oncological liver diagnostics, especially in the characterization of HCC. These reconstructions can simulate low-energy images to maximize the iodinated contrast effect or high-energy images to reduce artifacts and improve penetration in hyperdense tissues. VMI reconstructions can be integrated with another type of reconstruction: iodine maps. These maps allow for the early identification of HCC, assessment of washout, lesion characterization, and post-treatment follow-up: thus, they offer an objective and measurable evaluation of the therapeutic response. This document aims to illustrate the anatomical basis of the liver and hepatocellular carcinoma, with the goal of analyzing and describing the GSI technique using the CT protocol for HCC studies, focusing on the



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diagnostic advantages offered by this technique, and highlighting its ability to improve diagnostic accuracy. The descriptive nature of this paper analyses and describes the Dual Energy GSI protocol for HCC imaging, focusing on the diagnostic advantages offered by this technique and highlighting its ability to improve diagnostic accuracy and clinical applications.

GSI (Gemstone Spectral Imaging): is a new application of Dual-Energy CT technology (Dual Energy Computed Tomography, DECT) that uses a rapid change in kilovoltage (from 80 kVp to 140 kVp) to almost simultaneously acquire two samples at different energy levels, allowing for the extraction of data related to the density of different substances. This data is then used to separate materials and produce monochromatic spectral images. The principle of DECT technology is to detect density differences between substances based on differences in photon attenuation coefficients at different energy levels. In other words, by knowing the energy emission spectrum of the X-ray source (Dual in 2nd generation DSCT scanners, single as we will see in the GSI scanner), it is possible, through decomposition algorithms, to reconstruct "virtual" datasets corresponding to different energies. For example, by combining the raw data obtained at 80 keV and 140 keV, it is possible to generate "virtual" images corresponding to an average voltage of 120 keV or create subtraction images.

GSI represents an evolution of the current DECT with two X-ray tubes and two detectors, as it uses a single source that, thanks to the rapid transition from low kVp to high kVp energy ("Ultra-fast Dual Energy Switching") and a 128-layer detector system, allows data acquisition in less than 0.5 milliseconds, which is 165 times faster than previous technologies. This system also allows for the decomposition of matter into its different components such as cal-

cium, iodine, and water. The advantage offered by the use of a single energy source architecture is that it allows for the decomposition of matter over the entire field of view (50 cm SFOV). Furthermore, the GSI technology reduces beam hardening artifacts by up to 50%, which are typically caused by bone, metal, and other high-density materials such as iodine. Finally, it allows for the accurate detection of very small iodine concentrations, with densities lower than 0.5%, and enables the creation of a series of virtual images without contrast medium (virtual unenhanced scan) by subtracting the actual attenuation profiles, measured after the administration of the contrast medium, from those of iodine (iodine map), which are determined a priori using the knowledge of the applied energy spectrum. The understanding of the material decomposition process achievable through Dual-Energy technology is based on specific assumptions:

- The attenuation of X-rays through matter is a function of the beam energy and is determined by two types of atomic interactions: the photoelectric effect, which prevails at lower energies (<140 keV), and the Compton effect, which is dominant at higher energies.
- Different materials (calcium, water, iodine) attenuate the X-ray beam differently at different energy levels.
- The attenuation of X-rays through matter can be graphically represented as a curve, with the attenuation coefficients of the materials (cm^2/mg) on the y-axis and the energy values of the X-ray beam (keV) on the x-axis. It is important to note that the curve corresponding to the attenuation of X-rays through a given material can be represented as a linear combination of the attenuation curves of two other materials (commonly referring to base materials like water and iodine); for example, the attenuation curve of bone tissue can be represented as a linear combination of iodine and water (Fig. 1).

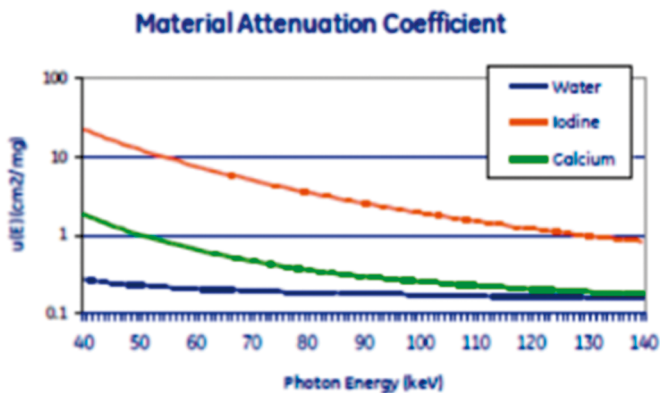


Fig.1 Material attenuation curve

Therefore, if we measure the attenuation of the X-ray beam through an object using two different energy spectra (low kVp and high kVp) rapidly alternated, we can mathematically transform, thanks to a specific software for material decomposition, the attenuation measurement into the density measurement of the two “base” materials that would have produced the measured attenuation. This process is known as material decomposition and provides images made using the density of a pair of base materials (material density basis-pair images). The most commonly used base material pairs in diagnostics are water and iodine, as they cover the atomic number range of the tissues typically studied, providing easily interpretable images. Other possible pairs include iodine-calcium or water-calcium. As previously mentioned, the GSI technology allows for the creation of monochromatic images, which is a significant advancement in image quality compared to what current CT scanners can offer. Conventional CT imaging measures the attenuation of X-rays through an object, and the quality of an X-ray beam is defined in terms of kVp (kilovoltage peak), specifying the maximum energy of the photons, as an X-ray beam is a collection of photons with different energies. Standard CT acquisitions are defined as polychromatic, meaning that when, for example, the kVp is set to 80 kVp, the photon beam generated has an energy range between 0 and 80 keV. It is important to emphasize that kVp defines the maximum energy present in a polychromatic X-ray beam, while keV specifies the energy of the photons generated by a monochromatic X-ray source. When the X-ray beam passes through the patient, its average energy increases because lower-energy photons are absorbed by body tissues more than higher-energy ones. Therefore, the emerging beam, detected by the detectors, has a higher average energy than the one entering the patient. This phenomenon is called beam hardening and depends mainly on the thickness of the object being examined and its composition. It increases with greater thickness or density. Beam hardening can alter the HU values of materials measured within the field of view (SFOV), causing artifacts in the image. This phenomenon can be reduced using CT calibration algorithms that correct beam hardening for water density but not for other materials. Monochromatic imaging can be achieved through precise mathematical calculations using dedicated software, starting from data related to material density images, the so-called “raw data.” It represents how the object being examined would appear if the X-ray source produced only X-rays at a single energy. GSI technology enables the production of monochromatic images by choosing from 101 different keV energy levels (40 keV - 140 keV), transitioning from low energy levels that produce images with higher contrast and noise, to high energy levels that produce images with lower contrast and

noise. Generally, the optimal energy level to achieve a good balance between contrast and noise is around 65-77 keV, although the choice depends on which phase is being evaluated (arterial, venous, or delayed) and the anatomical region of interest. In conclusion, monochromatic imaging guarantees better image quality thanks to the ability to select the optimal keV value for the clinical question being examined, resulting in a reduction in beam hardening artifacts and improved contrast resolution. Additionally, it represents a significant step toward achieving quantitative imaging.

Study protocol with gsi dual energy technique:

Computed tomography (CT) with Dual Energy technology, particularly the Gemstone Spectral Imaging (GSI) technique developed by GE Healthcare, has introduced a significant advancement in medical imaging diagnostics. GSI allows for the acquisition of data at two different energy levels (80 and 140 kVp) in a single scan, thanks to rapid switching of the X-ray tube. The equipment used is the GE CT Discovery 750 HD in helical spectral imaging mode, which takes advantage of the rapid alternation between the two energy levels (Dual Energy). In this mode, the X-ray tube switches between the two energies every 0.25 milliseconds, providing data for the generation of virtual monochromatic imaging (VMI) and material maps (e.g., iodine, water, calcium). Material maps are quantitative reconstructions obtained from spectral CT, which allow for the separation and quantification of materials such as iodine, calcium, fat, and water. These maps are expressed in mg/mL and are visualized as color-scaled images. They are used to assess enhancement, characterize lesions, and monitor treatments. Polar maps, on the other hand, represent a graphical and analytical tool of significant importance for the quantitative and regional evaluation of tissues and lesions. They are circular representations divided into radial sectors that allow for the concise and effective visualization of the distribution of functional parameters or materials within a region of interest, such as a suspected or known liver lesion. In the case of hepatocellular carcinoma (HCC), polar maps are typically used to quantify and represent the concentration of iodine within the lesion and the surrounding hepatic parenchyma, based on data acquired during iodinated contrast imaging. This information is directly derived from iodine maps, generated from spectral analysis of the data acquired using Dual-Energy scanning. During the spectral scan, the acquired data is processed by material decomposition algorithms, which separate the signal based on the chemical composition of the tissues. One of the key materials for liver analysis is iodine, and its distribution is mapped in milligrams per milliliter (mg/mL). By defining a region of interest, the system can:



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- Analyze the regional distribution of iodine within the lesion (enhancement pattern);
- Assess areas of higher or lower vascularization;
- Graphically represent, in the form of a polar map with circular segments, the heterogeneity of enhancement, which is useful, for example, in post-treatment follow-up (TACE, ablation, systemic therapy).

This type of analysis can be applied to each of the acquisition phases (arterial, portal, and delayed) and at different energy levels (e.g., 40, 70, 100 keV), providing a much more detailed reading compared to conventional visual analysis. Polar maps (Fig. 2) are particularly effective in distinguishing enhancement patterns typical of HCC (arterial hyperconcentration with portal-delayed washout), assessing intralesional heterogeneity, hemorrhage, or residual viable tissue; quantifying the response to loco-regional treatment (TACE or thermal ablation) by comparing pre- and post-treatment iodine distribution. The innovative aspect is that the radial visualization allows for the immediate identification of potential “cold” areas (hypo-iodated) or “hot” areas (hyper-iodated), which could indicate suspicious residual active tissue. Unlike conventional CT, which produces single-energy images, GSI allows for the reconstruction of images with optimized monochromatic energy (e.g., 40, 50, 70 keV), improving the contrast between the lesion and surrounding liver parenchyma. Furthermore, the acquired data allow for the generation of iodine distribution maps by evaluating iodine uptake and sensitivity in detecting small hypervascular lesions, which are often difficult to identify with conventional techniques. This is crucial for quantifying the vascular enhancement of lesions.

This modality also allows for the reduction of beam hardening artifacts, improving image quality even in the presence of metallic bodies or concentrated contrast agents. The contrast agent used is iodinated, non-ionic, with a concentration equal to or greater than 300 mgI/mL. Administration is carried out through an automatic injector at an infusion rate between 4 and 5 mL/sec, followed by a bolus of saline solution (30-40 mL) at the same flow rate to ensure uniform distribution of the agent. The amount of contrast varies based on body weight, typically 1.5 mL/kg, with a maximum limit adjusted according to the patient’s renal function. The patient should fast for at least six hours to reduce the risk of nausea and optimize gastric and intestinal distension. It is also recommended to use a peripheral venous access of 18G caliber to ensure the required flow during the arterial phase. The use of Dual Energy GSI technology eliminates the need for baseline acquisition by generating Virtual Non-Contrast (VNC) images, which are simulated reconstructions of the pre-contrast phase, obtained from data acquired during the contrast phase. The VNC technique is based on the ability of the GSI system to decompose the absorption of iodinated contrast relative to other materials present in the tissues. Through spectral reconstruction algorithms, the image is processed to “digitally” remove the effect of iodine, leaving an image that accurately reproduces the appearance of the liver parenchyma as if the contrast agent had never been administered. Reconstruction algorithms involve the use of Regions of Interest (ROI) in which the concentration of a specific material per unit mass/volume is calculated. Thanks to this calculation, the different pre-selected materials (e.g., iodine, fat, calcium) can be

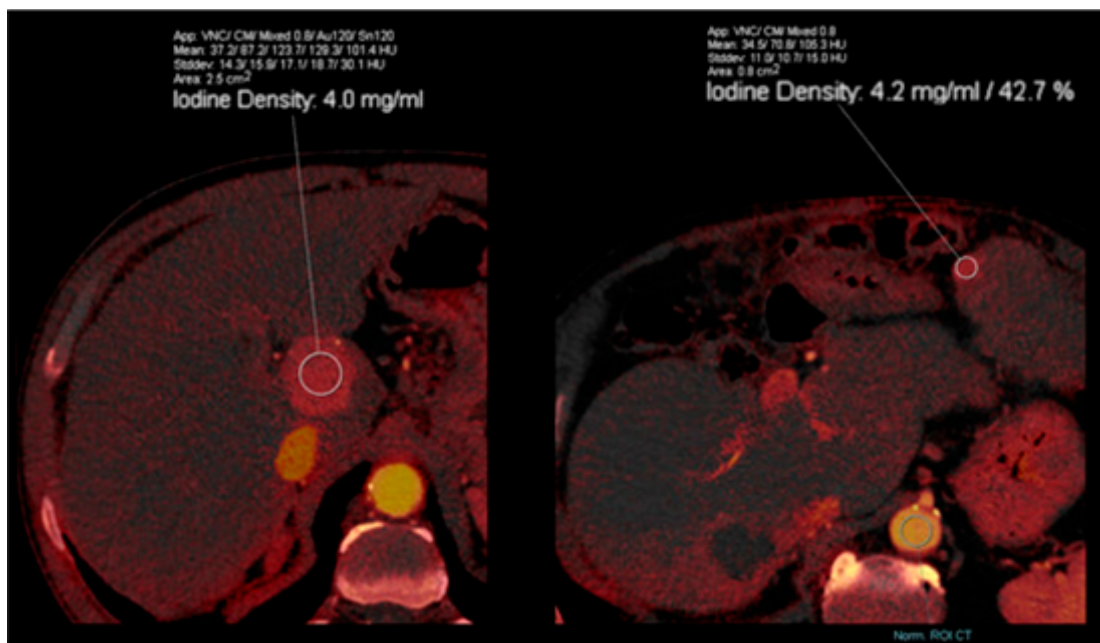


Fig. 2 Quantification of iodine in hepatocellular carcinomas (HCC). Intratumoral iodine concentration (left image) and normalised iodine concentration (right image) in HCC in two different patients, measured in the arterial phase. Higher pre-operative arterial phase iodine concentrations predict early recurrence after resection, meaning they may be valuable predictive biomarkers.

quantified, color-coded, or subtracted. In the case of Virtual Non-Contrast images, the iodine concentration is subtracted from an image acquired with iodinated contrast medium. This is highly advantageous when the primary objective is vascular evaluation and enhancement, but it may not be sufficient on its own for the complete characterization of some lesions or in complex disease contexts. Another feature of this methodology is the ability to generate virtual single-energy images, called Virtual Monochromatic Imaging (VMI, Fig. 2). This type of reconstruction simulates the acquisition of CT images as if they were obtained with a single photon energy beam (in keV), rather than the traditional polychromatic mixture. The goal is to artificially modulate the energy of the beam to obtain images with different contrast, attenuation, and noise characteristics, customized according to the clinical question. This ability to “play” with energy makes VMIs an extraordinarily useful tool in oncological liver diagnostics, particularly in the characterization of HCC. These reconstructions can simulate low-energy images (40–50 keV) to maximize iodinated contrast effect or high-energy images (100–140 keV) to reduce artifacts and improve penetration in hyperdense tissues. Low-energy images (40–60 keV, Fig. 3): These images allow for increased iodine-tissue contrast, optimal for the arterial phase as they enhance the sensitivity of iodinated contrast, improving the contrast-to-noise ratio and enabling optimal visualization of even the smallest lesions that might not be visible at 70 keV. They are also useful during the portal phase in cases where contrast between the lesion and liver is weak, improving washout visibility and reducing the risk of false negatives; finally, they are useful in the delayed phase to accentuate the contrast

between the pseudocapsule and parenchyma, making details visible that might otherwise be missed. Medium-energy images (70 keV, Fig. 3): These simulate the average energy of a 120 kVp CT scan, and thus are used as the standard reference. They offer the best contrast-to-noise ratio and are excellent for the overall evaluation of liver morphology and dynamic phases, facilitating the identification of washout in the case of HCC. High-energy images (100–140 keV, Fig. 3): Unlike low-energy images (40–50 keV), which maximize iodinated contrast but increase noise, high-energy images provide a more homogeneous view with reduced noise and significant attenuation of artifacts. In this case, iodine absorption decreases, and the iodinated contrast appears less pronounced; however, the effect of electronic noise and beam-hardening artifacts is reduced, improving the overall readability of the image. This allows for a clearer assessment of liver segments adjacent to high-density structures, which under normal conditions would appear distorted or overexposed. Furthermore, although iodinated contrast appears attenuated, high-energy images allow for confirmation of lesion margins observed at low energy, avoiding false positives due to noise or pseudoenhancement. The portal vein, the hepatic veins, and the inferior vena cava can be more accurately evaluated in the presence of high contrast flow, as the reduction in attenuation allows for a clearer distinction between blood flow and the vascular wall. Finally, in the case of portal thrombosis, evaluation with high-energy images can help more clearly identify the thrombotic or neoplastic component, eliminating the confounding effect of adjacent enhancement.

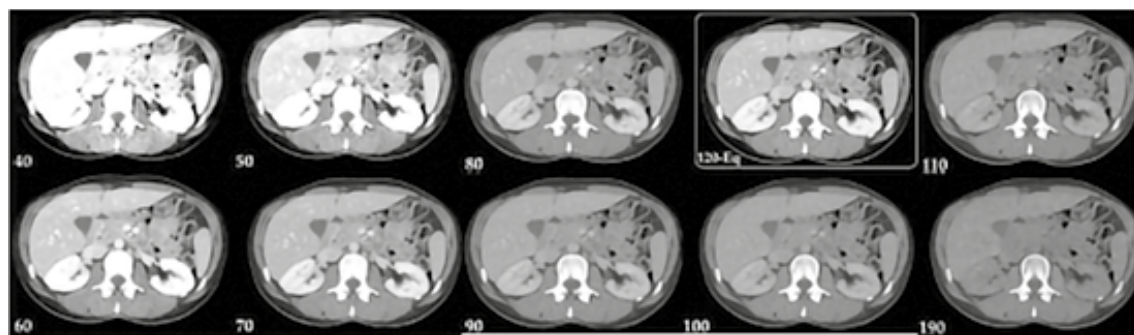


Fig.3 Virtual monochromatic images (advanced Monoenergetic Plus algorithm with noise optimisation) from 40 keV to 190 keV in the axial plane (portal venous phase) and mixed image at 120 kVp-equivalent (120-Eq). Window settings were kept constant for more realistic comparability. Note the increased noise with low keV images and the similarity of the 70 keV VMI images to the 120 kVp-equivalent (120-Eq) mixed image.



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VMI reconstructions can be integrated with another type of reconstructions: iodine maps (Fig. 4). These create color-scale or grayscale images representing the local concentration of iodine (expressed in mg/mL) in various tissues. Areas that have absorbed more iodinated contrast (e.g., hypervascular tissues, such as HCC in the arterial phase) appear more colorful or hyperdense in the maps; areas with little or no iodinated uptake (such as necrosis, thrombi, fibrotic tissue) appear hypo- or achromatic; subtractive maps can also be visualized, highlighting only variations related to contrast distribution, eliminating the anatomical background. These maps allow for:

- Early identification of HCC: As HCC is typically a hypervascular arterial lesion, in the iodine maps of the arterial phase, an increased iodine concentration is observed compared to normal liver parenchyma. This phenomenon is particularly useful for detecting very small or doubtful lesions, differentiating HCC from dysplastic or regenerative nodules, and confirming arterial enhancement even in atypical patterns.
- Assessment of washout: By comparing iodine maps between the arterial phase and the portal or delayed phases, iodine loss in the lesion can be quantified, confirming washout, which is one of the main criteria of the LI-RADS 5 classification.
- Lesional characterization: Lesions like hepatic hemangioma or focal nodular hyperplasia show typical uptake behaviors distinct from HCC. Iodine maps allow for safer distinction between benign and malignant lesions, even in the presence of equivocal enhancement patterns.

Another type of reconstruction is MIP (Maximum Intensity Projection), which emphasizes hyperdense structures, such as contrast-enhanced vessels, calcifications, and hypervascular lesions (e.g., HCC in the arterial phase). In the study of HCC,

MIPs are useful for visualizing the vascular pattern of the lesion, helping to assess neoplastic vascular invasion (e.g., portal thrombosis), facilitating the visualization of the hepatic arterial tree (useful for procedures like TACE), and effectively integrating the information obtained from iodine maps. Then there are MinIP (Minimum Intensity Projection), the opposite of MIP, useful for visualizing and highlighting hypodense structures such as bile ducts, dilated intrahepatic bile ducts, areas of necrosis, or cystic lesions. In HCC, they are used for:

- Identifying central necrosis in advanced or treated HCC (e.g., post-TACE).
- Assessing biliary obstructions secondary to tumor compression.
- Differentiating between active vascularization and avascular zones (necrosis).

Finally, there are VR (Volume Rendering), which utilize the entire acquired volume to generate a realistic three-dimensional visualization of body structures, assigning transparency and color values to different tissues. Applications in the hepatic context include:

- 3D visualization of relationships between the tumor and vascular structures.
- Preoperative planning: liver resection, transplantation, thermal ablation.
- Assessment of multiple lesions or lobar/segmental distribution.
- Effective communication with the multidisciplinary team (surgeons, oncologists).

In the context of GSI, 3D rendering can be performed based on low-energy VMI images or iodine maps, improving the selective visibility of vascular structures or lesions. Post-treatment follow-up: After thermal ablation, TACE, or radioembolization, iodine maps help detect residual active tumor tissue, distinguish complete necrosis (no iodine) from vital tissue (iodine present), and objectively and measurably assess the response to therapy."

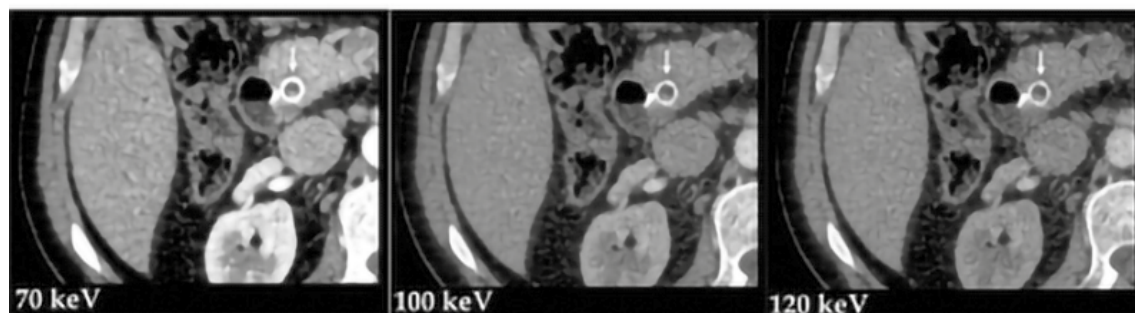


Fig. 4 Reduction of metallic artefacts with high-energy VMI. Virtual monochromatic images (advanced Monoenergetic Plus algorithm with noise optimisation) at 70, 100 and 120 keV on the axial plane (portal venous phase) show improved luminal representation of a metallic biliary stent (arrow) with higher monoenergetic levels due to the reduction of metallic artefacts.

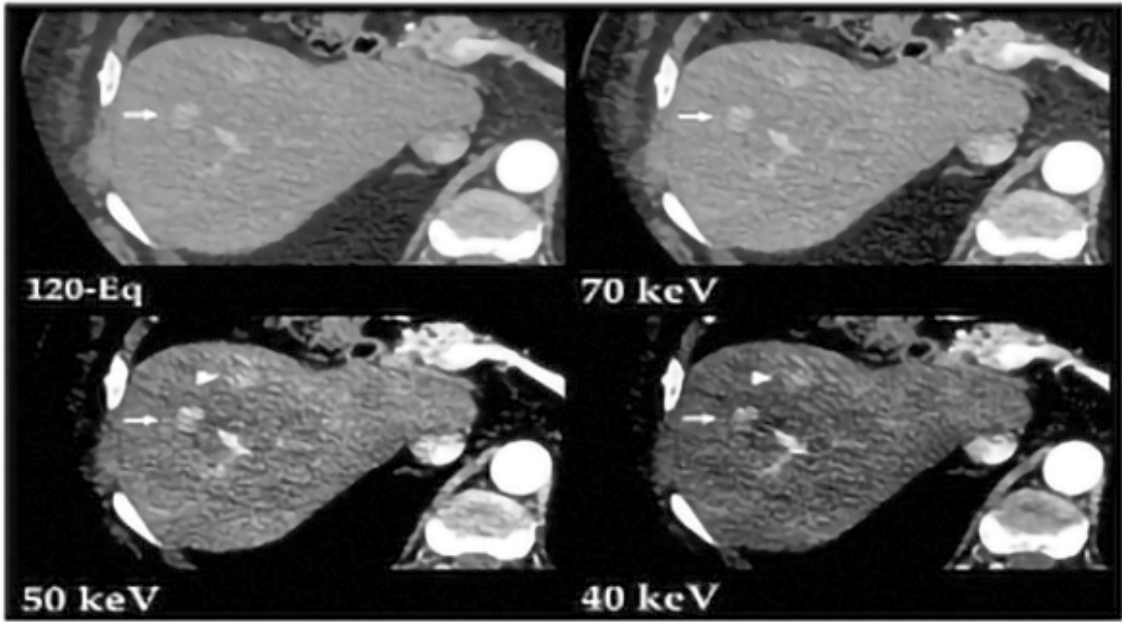


Fig.5 Multifocal hepatocellular carcinoma, best represented with low-energy VMI images (70, 50 and 40 keV) obtained from DECT with contrast medium in the arterial phase. Post-processed low-energy VMI images (advanced Monoenergetic Plus algorithm with noise optimisation) show greater visibility of the largest lesion (arrow) compared to the combined 120 kVp-equivalent (120 Eq) image and allow the visualisation of smaller and less obvious lesions at lower keV (arrowhead), at the cost of increased image noise.

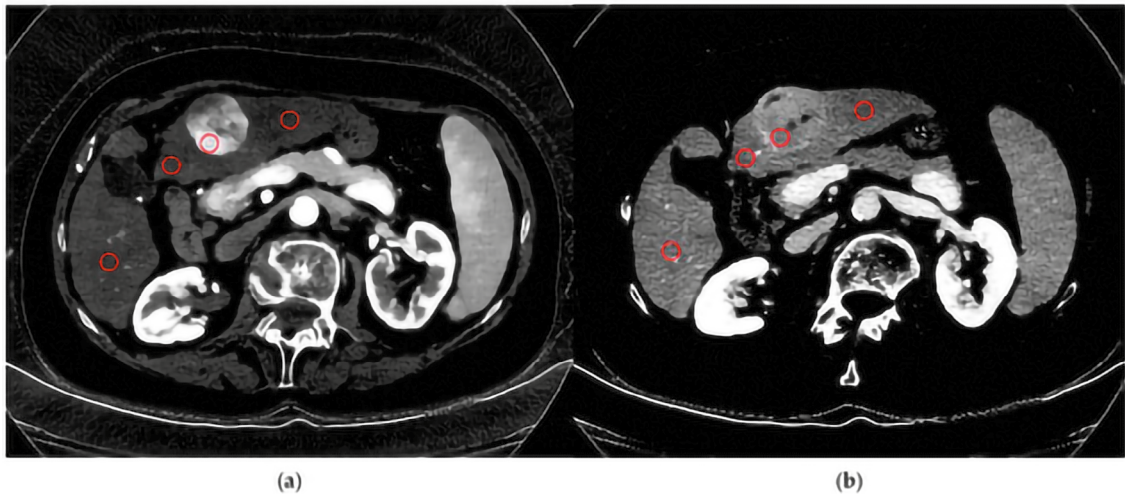


Fig. 6 Image showing an iodine map derived from the arterial phase (a) and venous phase (b). ROIs are present to calculate tissue density..

In summary: using a GE 128-slice CT scanner

FOV	300-400 mm
Pitch	<1
Thickness	1,5 mm
Rotation Time	0,7 s
Filter	Body Filter
Reconstruction Thickness	0,625 mm
Scanning mode	Helical
ROI Value Smart Prep	Depending on MDC used

CONCLUSIONS

The advantage offered by the use of a single-energy source architecture is the ability to achieve material decomposition across the entire field of view (FOV), while also reducing up to 50% of beam hardening artifacts caused by bone, metal, and other high-density materials. Dual Energy CT (DECT) with spectral imaging provides high-quality images that enhance the detection of hypervascular hepatic lesions, improving the accuracy of HCC diagnosis. Specifically, the “iodine-water” series highlights iodine-containing structures, providing images that enhance the method’s sensitivity in HCC diagnostics (>80%) without compromising specificity. The utility of GSI technology in HCC diagnosti-



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cs is particularly evident in detecting small neoplastic nodules (≤ 3 cm) that exhibit “atypical” behavior in traditional dynamic imaging, offering superior image quality in terms of contrast resolution and contrast-to-noise ratio. Furthermore, thanks to the ability to decompose materials, it is possible to identify, separate, and quantify the iodine component within the lesion, which reflects its arterial vascularization. Unlike conventional CT, GSI allows for dose reduction due to its ability to generate Virtual Non-Contrast images during post-processing. On the other hand, the disadvantages of this method are:

- the need for specialised hardware, which makes the system expensive;
- the 90° shift between low- and high-energy data, which does not allow projection data to be obtained coupled to the same positions on the z-axis and, consequently, primary post-processing to be carried out;
- it requires the implementation of a scatter correction algorithm. In fact, since both tubes are energised simultaneously, the scattered radiation, whose photons come from one tube, can be detected by the other tube’s detector and vice versa. This degrades spectral separation;
- The algorithm uses a small portion of the detector elements to measure and correct this radiation, but may not eliminate it completely;

- The limited space in the gantry, which is only sufficient for a second, smaller detector, causes a narrowing of the field of view of the second detector compared to the first, which is 26, 33 or 35 cm, depending on the generation of the Dual-Source system. Despite this, the target organ is usually included within the field of view, and the anatomy outside it can be evaluated by using data from the larger detector for single-energy image reconstruction. Another major limitation of this technique is the lack of a truly standardised protocol, emphasising that the full applicability of this protocol is still being studied. It has also become a method of choice in patients who are unable to undergo MRI exams, due to its diagnostic accuracy, which is comparable to that of MRI. The future of the Dual Energy CT GSI protocol for Hepatocellular Carcinoma (HCC) diagnosis is likely to play an increasingly prominent role in traditional diagnostic pathways due to its low dose, the ability to provide highly predictive information in short timeframes, and the acquisition of higher-quality images. The biggest challenge for the future of this protocol will undoubtedly be to standardize the diagnostic protocol, allowing its application to a greater number of patients.

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