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Clinical application and future prospects of SPECT-CT imaging technology

Yarong Xu

School of Medical Imaging, Qilu Medical University, Zibo, China

13963493909@163.com

Abstract. Against the backdrop of the rapid development of medical imaging technology, a variety of mature imaging examination methods have been widely applied in clinical practice. Single Photon Emission Computed Tomography-Computed Tomography (SPECT-CT) features the integration of functional imaging and anatomical imaging, exhibiting unique advantages in the early diagnosis of diseases, precise localization of lesions, and therapeutic effect evaluation. However, in the process of clinical promotion of SPECT-CT, practical problems still exist, including immature quantitative image analysis, inconsistent radiation doses and diagnostic criteria, and high equipment costs, which objectively restrict its popularization in primary medical institutions and the full exertion of its diagnostic efficacy. On this basis, this paper systematically elaborates on the basic concepts, technical principles and development history of SPECT-CT imaging technology, with a focus on sorting out its current clinical application status in neurological diseases, cardiovascular diseases, tumor diseases, intrahepatic biliary system diseases and musculoskeletal system diseases. Furthermore, it conducts comprehensive analysis, summary and prospect outlook, aiming to provide evidence-based references for the standardized application and subsequent innovative development of this technology.

Keywords: SPECT, CT, clinical application, prospect outlook

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1. Introduction

With the continuous development of modern medical imaging technology, the early diagnosis and precise treatment of diseases have put forward higher requirements for imaging examinations. Traditional imaging methods such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) can clearly display human anatomical structures, yet they have certain limitations in reflecting tissue function and metabolic changes. SPECT-CT imaging technology combines the functional imaging of SPECT with the structural imaging of CT, enabling the simultaneous acquisition of human functional and anatomical information. It therefore possesses remarkable advantages in improving lesion localization and reducing false-positive or false-negative results [1]. Since its development, SPECT-CT has demonstrated important clinical value in myocardial perfusion imaging, lesion localization of neurological diseases, differential diagnosis of benign and malignant tumors, and screening of bone metastases, gradually becoming an indispensable part of modern medical imaging.

Nevertheless, SPECT-CT imaging technology still faces problems and challenges in clinical application, such as imperfect quantitative image analysis, inconsistent radiation dose control and diagnostic standardization, as well as high equipment costs [2]. In addition, with the proposal of the concept of precision medicine, how to further improve the application value of SPECT-CT in the early diagnosis of diseases and individualized treatment decision-making remains to be further studied.

Based on this, focusing on SPECT-CT imaging technology, this paper systematically reviews its basic concepts, technical principles and development history, emphatically expounds its application status in the field of modern medical imaging, and analyzes and prospects its future development directions and prospects.

2. Overview of SPECT-CT imaging technology

2.1. Basic concepts

SPECT-CT is an innovative technology integrating nuclear medicine imaging and radiological imaging. Its core essence lies in combining the functional and metabolic detection advantages of SPECT with the precise anatomical localization capability of CT, so as to construct a dual-mode imaging system featuring integrated function and anatomy. Compared with standalone SPECT or CT technology, it breaks through the traditional limitation of separation between functional and anatomical imaging. It can not only capture functional information such as metabolic activity and blood perfusion of tissues and organs via SPECT, but also provide high-resolution anatomical images through CT. It realizes the accurate matching of functionally abnormal regions with anatomical locations, providing comprehensive multi-dimensional evidence for clinical diagnosis [3].

2.2. Technical principles

The technical principles of SPECT-CT can be decomposed into two core components: multimodal imaging mechanism and image fusion technology. In terms of the imaging mechanism, SPECT detects gamma rays released by the nuclear decay of radionuclide-labeled tracers distributed in the human body, so as to generate tomographic images reflecting the functional and metabolic status of tissues. CT, by contrast, reconstructs anatomical images of the human transverse, coronal and sagittal planes based on the attenuation difference of X-rays penetrating the human body.

The functional images of SPECT and anatomical images of CT are registered and fused. Algorithms such as spatial coordinate calibration and gray level adjustment are adopted to eliminate spatial deviation between the two modal images, ultimately producing fused images that integrate both functional metabolic information and anatomical localization value. This realizes the integrated diagnosis of qualitative analysis, localization and quantification [4].

2.3. Development history

The development history of SPECT-CT dates back to the technical exploration stage in the 1990s. In the early period, preliminary integration was realized by simply splicing SPECT and CT devices. Although it solved the problem of combined application of functional and anatomical images, it had drawbacks such as low spatial registration accuracy and cumbersome scanning procedures. From the late 1990s to the early 21st century, the advent of integrated SPECT-CT equipment marked a new stage of technological development. With the hardware design of a shared gantry and a common scanning bed, synchronous acquisition of images from the two modalities was achieved, greatly improving registration accuracy and examination efficiency. In recent years, with advances in detector technology, image reconstruction algorithms and the research and development of radionuclide tracers, the spatial resolution and sensitivity of SPECT-CT have been continuously improved, while the radiation dose has been significantly reduced, making it a core component of the modern medical imaging diagnosis system [5].

3. Application of SPECT-CT imaging technology in medical imaging

3.1. Application of SPECT-CT imaging in neurological disease imaging

The core value of SPECT-CT in neurological diseases lies in its functional-anatomical integration. It achieves precise fusion of cerebral blood flow perfusion, neurotransmitter function and brain anatomical structures, effectively compensating for the limitation of conventional CT and MRI, which mainly reflect morphological changes and lack sufficient sensitivity to early functional abnormalities [6].

In the analysis of the impacts of Parkinson's disease, multimodal imaging technology combining SPECT with Diffusion Tensor Imaging (DTI) was adopted to quantify the group differences between Normal Controls (NC) and Parkinson's Disease (PD) patients. Further, within the partial least squares regression framework, multimodal imaging features were integrated to reveal the key brain regions and neural connections of Parkinson's disease, enabling comprehensive imaging analysis of Parkinson's disease [7].

In the diagnosis of Alzheimer's Disease (AD), with cerebral blood flow perfusion tracers such as 99mTc-Ethyl Cysteinate Dimer (99mTc-ECD) and 99mTc-Hexamethylpropyleneamine Oxime (99mTc-HMPAO), this technology can detect typical functional abnormalities at the stage of mild cognitive impairment, mainly including decreased blood perfusion in the parietal lobe, temporal lobe and posterior cingulate gyrus [8].

In the differentiation of Parkinson's Disease (PD) and Parkinsonism, ^{123}I-FP-CIT Dopamine Transporter (DAT) imaging serves as the core application technique. Due to the progressive degeneration of the nigrostriatal pathway in PD patients, tracer uptake in the striatum is significantly reduced, and the uptake level is negatively correlated with disease severity. It can be applied to the early diagnosis and progression evaluation of the disease. Combined with CT to rule out secondary causes such as brain tumors and cerebrovascular diseases, it can markedly improve the differential diagnostic accuracy among various Parkinsonian syndromes [9].

SPECT-CT also possesses important clinical value in the preoperative evaluation of epilepsy. As an advanced diagnostic modality, it is adopted to detect the epileptogenic onset zone in the preoperative assessment of epilepsy patients. By integrating ictal-interictal SPECT functional images with CT anatomical images, the location and scope of the epileptogenic focus as well as its spatial relationship with important surrounding anatomical structures such as cerebral sulci and ventricles can be clarified, thereby providing imaging evidence for formulating surgical resection plans for patients with drug-refractory epilepsy [10].

3.2. Application of SPECT-CT imaging in cardiovascular disease imaging

In cardiovascular disease imaging, by integrating information on myocardial blood perfusion, metabolic status and coronary anatomical structure, SPECT-CT enables comprehensive evaluation of myocardial ischemia, injury and its etiology, thereby providing comprehensive imaging evidence for diagnosis, treatment decision-making and prognosis assessment.

In the diagnosis and treatment of coronary heart disease, SPECT-CT adopts myocardial perfusion tracers such as ^{99m}Tc-Methoxyisobutylisonitrile (^{99m}Tc-MIBI) and Technetium [^{99m}Tc] Tetrofosmin (^{99m}Tc-Tetrofosmin) to comparatively analyze myocardial blood flow distribution at rest and under stress, so as to assess the location, scope and severity of myocardial ischemia [11]. Relevant studies have shown that CT attenuationcorrected SPECT-CT myocardial perfusion imaging has a diagnostic sensitivity of approximately 90%–95% and specificity of 85%–90% for coronary heart disease, and possesses high clinical application value especially in suspected patients with ambiguous results of electrocardiography or echocardiography.

For patients with ischemic cardiomyopathy, combined SPECT-CT, CT and CMR can evaluate the status of viable myocardium, so as to differentiate hibernating myocardium, stunned myocardium and necrotic myocardium. Among them, hibernating myocardium is usually characterized by reduced perfusion with relatively preserved glucose metabolism. This type of myocardium has the potential for functional recovery after revascularization, providing a crucial decision-making basis for performing procedures such as coronary artery bypass grafting and stent implantation [12].

3.3. Application of SPECT-CT imaging in tumor imaging

The core value of SPECT-CT in the field of oncology lies in the integration of tumor metabolic functional information with precise anatomical localization. It effectively compensates for the limitations of standalone SPECT in spatial resolution and localization capability, as well as the insufficient sensitivity of conventional CT in differentiating benign and malignant lesions. Meanwhile, a tumor dosimetry method based on hybrid planar SPECT images and semi-automatic segmentation has been developed, providing full-process imaging support for tumor screening, staging and therapeutic effect evaluation [13].

In the screening of bone metastases from common malignant tumors such as lung cancer, prostate cancer and breast cancer, tumor-related or receptor-specific tracers including Technetium Methylene Diphosphonate (99mTc-MDP) and Indium Octreotide (111In-Octreotide) can reflect the metabolic activity, receptor expression and proliferation status of tumor tissues [14]. SPECT-CT is applied for lymphatic localization; combined with non-invasive injection techniques, it is used to observe lymphatic drainage of Oropharyngeal Squamous Cell Carcinoma (OPSCC), so as to evaluate contralateral lymphatic drainage in lateralized oropharyngeal cancer [15]. In general, malignant tumors manifest high uptake of radiotracers due to vigorous metabolism, while benign lesions mostly show low uptake or no obvious uptake, enabling accurate differentiation between benign and malignant lesions.

For the screening of bone metastatic tumors, 99mTc-MDP bone imaging combined with CT localization has become a commonly used and effective clinical imaging protocol. This technique can detect tiny bone metastatic lesions at an early stage before obvious structural changes appear on X-ray or conventional CT. It can also distinguish osteolytic lesions (inhomogeneous or decreased radionuclide uptake) from osteoblastic lesions (diffusely increased radionuclide uptake) according to the characteristics of radionuclide uptake [16].

Studies have shown that in the detection of bone metastases from breast cancer and prostate cancer, Whole-Body technetium methylene diphosphonate SPECT (WB-SPECT) achieves a detection sensitivity of 90% and a specificity of 95% by patient-based analysis; by lesion-based analysis, WB-SPECT yields a detection sensitivity of 63% and a specificity of 97% [17].

In addition, for postoperative follow-up of patients with differentiated thyroid carcinoma, iodine-131 single photon emission computed tomography-computed tomography (^{131}I-SPECT-CT) can accurately evaluate the iodine uptake function of residual thyroid tissue or distant metastatic lesions, providing objective evidence for the necessity of further ^{131}I internal radiotherapy [18].

3.4. Application of SPECT-CT imaging in intrahepatic biliary diseases

SPECT-CT, leveraging the advantage of integrating functional imaging with precise anatomical localization, has become an important supplementary modality in the diagnosis and treatment of intrahepatic biliary tract diseases. Breaking through the limitation of traditional morphological examinations such as ultrasound, CT and MRI that emphasize structure while neglecting function, this technology enables quantitative or semi-quantitative evaluation of key functional indicators including bile production and excretion as well as hepatic parenchymal metabolism [19].

In patients with Primary Sclerosing Cholangitis (PSC), conventional imaging examinations can only demonstrate morphological changes such as bile duct wall thickening and luminal stenosis, and fail to objectively reflect the degree of biliary dysfunction. Through dynamic imaging with hepatobiliary-specific tracers such as Technetium-99m Diethylacetanilide Iminodiacetic Acid (^{99m}Tc-EHIDA), SPECT-CT can completely track the processes of bile uptake, transport and excretion. Combined with parameters such as hepatic uptake rate and biliary excretion half-emptying time, it can objectively assess the lesion involvement range and disease activity, providing quantitative evidence for therapeutic regimen adjustment and curative effect monitoring [20].

For patients with intrahepatic bile duct stones complicated with biliary obstruction, although ultrasound and Magnetic Resonance Cholangiopancreatography (MRCP) can clearly display the stone location and bile duct dilatation, they are limited in distinguishing mechanical obstruction from functional obstruction, and show insufficient sensitivity in identifying postoperative tiny residual obstruction or anastomotic stenosis. In contrast, SPECT-CT can functionally differentiate different types of obstruction according to the retention characteristics and excretion delay degree of tracers in the biliary tract. Moreover, it can detect biliary dysfunction at an early stage during postoperative follow-up, allowing timely intervention to reduce the risk of recurrent cholangitis and progressive liver fibrosis.

3.5. Application of SPECT-CT in musculoskeletal system disease imaging

In the imaging evaluation of musculoskeletal system diseases, the core advantage of SPECT-CT lies in its capability to early detect functional and metabolic abnormalities of bones and joints and achieve precise anatomical localization. It is particularly applicable to regions with complex anatomical structures or difficult conventional imaging diagnosis, such as the spine and foot.

In terms of spinal diseases, for ankylosing spondylitis, the tracer 99mTc-MDP can reveal increased blood perfusion and active bone metabolism of the sacroiliac joints at the early stage of the disease. Combined with articular surface erosion and osteosclerosis changes displayed by thin-slice CT scanning, early diagnosis and disease activity evaluation can be realized. It can detect lesions approximately 6–12 months earlier than conventional X-ray examination [21].

For foot lesions, stress fractures of the metatarsals and phalanges, which are common in athletes and long-term weight-bearing populations, often lack specific manifestations on conventional X-rays in the early stage. In contrast, SPECT-CT can achieve early diagnosis by identifying localized increased blood perfusion and hypermetabolism, as well as accurately localizing the fracture site and evaluating the healing status [22].

4. Conclusion of SPECT-CT imaging technology

To sum up, Combining the dual-modal merits of functional metabolic imaging of SPECT and anatomical imaging of CT, SPECT-CT overcomes the limitation of single imaging modality which only focuses on either morphological or functional information. It enables simultaneous acquisition of metabolic activity, blood perfusion and precise anatomical localization of lesions, and has established a mature clinical application system covering five major disease categories: neurological, cardiovascular, oncological, intrahepatic biliary and musculoskeletal disorders. In neurology, this technique facilitates early functional detection and accurate localization of lesions related to Parkinson's disease, Alzheimer's disease and epileptogenic foci. For cardiovascular disorders, it accurately evaluates the scope of myocardial ischemia and viable myocardium to support individualized treatment planning of coronary heart disease. In oncology, it is widely used for screening tumor bone metastasis, postoperative follow-up of thyroid carcinoma and differential diagnosis between benign and malignant lesions. For hepatobiliary diseases, it quantifies bile production and excretion to distinguish mechanical from functional biliary obstruction. In musculoskeletal imaging, it identifies early metabolic lesions such as ankylosing spondylitis and occult stress fractures that are hardly detected by conventional imaging modalities.

Nevertheless, its extensive popularization at primary medical institutions is restricted by several existing drawbacks, including high equipment cost, immature quantitative image analysis as well as inconsistent standards for radiation dose management and clinical diagnosis.

With the continuous development of detector technology, image reconstruction algorithms and targeted tracers, as well as the integration of artificial intelligence and big data analysis, SPECT-CT is expected to further improve imaging quality and diagnostic specificity while reducing radiation exposure and equipment cost. It will promote its development toward precision, intelligence and popularization, and is expected to play a greater role in personalized diagnosis and treatment, early disease warning and health management in the future.

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