**LORYŚ, Laura, KLIMCZAK, Klaudia, BUDZYŃSKA, Kamila, NARLOCH, Marcin, KASPRZAK, Stanisław, KASPRZAK, Karolina, KAMIŃSKI, Jakub and KANDEFER, Norbert. Comparison of first- and second-line imaging diagnostics (ultrasound + scintigraphy and PET + 4DCT) in visualizing parathyroid glands in primary hyperparathyroidism including ectopic foci. Journal of Education, Health and Sport. 2025;82:60366. eISSN 2391-8306.**
**https://doi.org/10.12775/JEHS.2025.82.60366**
**https://apcz.umk.pl/JEHS/article/view/60366**

The journal has had 40 points in Minister of Science and Higher Education of Poland parametric evaluation. Annex to the announcement of the Minister of Education and Science of 05.01.2024 No. 32318. Has a Journal's Unique Identifier: 201159. Scientific disciplines assigned: Physical culture sciences (Field of medical and health sciences); Health Sciences (Field of medical and health sciences).
Punkty Ministerialne 40 punktów. Załącznik do komunikatu Ministra Nauki i Szkolnictwa Wyższego z dnia 05.01.2024 Lp. 32318. Posiada Unikatowy Identyfikator Czasopisma: 201159. Przypisane dyscypliny naukowe: Nauki o kulturze fizycznej (Dziedzina nauk medycznych i nauk o zdrowiu); Nauki o zdrowiu (Dziedzina nauk medycznych i nauk o zdrowiu). 
The authors declare that there is no conflict of interests regarding the publication of this paper.
Received: 17.04.2025. Revised: 25.04.2025. Accepted: 11.06.2025. Published: 13.06.2025.

# COMPARISON OF FIRST- AND SECOND-LINE IMAGING DIAGNOSTICS (ULTRASOUND + SCINTIGRAPHY AND PET + 4DCT) IN VISUALIZING PARATHYROID GLANDS IN PRIMARY HYPERPARATHYROIDISM INCLUDING ECTOPIC FOCI

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**Abstract**

**Introduction:**

Primary hyperparathyroidism is an endocrine disorder that causes disturbances in calcium and phosphorus metabolism in the human body. The most effective permanent treatment is surgery, which involves the removal of the affected gland. To locate such small glands, various imaging diagnostic methods, including nuclear medicine, are currently used. This study aims to review current imaging protocols for hyperparathyroid glands and compare first- and second-line methods, particularly in cases of ectopic foci.

**Material and methods:**

This review was prepared based on articles available on PubMed. The literature review was conducted using the following keywords: primary hyperparathyroidism, primary hyperparathyroidism imaging, primary hyperparathyroidism US, primary hyperparathyroidism MIBI, primary hyperparathyroidism PET/CT, primary hyperparathyroidism 4DCT, ectopic hyperparathyroidism imaging.

**The current state of knowledge:**

Primary hyperparathyroidism is a condition that can go unnoticed for an extended period. The diagnosis of the disease is based on laboratory tests, followed by the crucial step of locating the gland responsible for progressively causing damage to the body over time. Identifying the hyperactive gland is essential for performing a successful surgery and curing the patient. However, this often poses a significant challenge, due to the potential for ectopic gland locations.

**Summary:**

It is hard to unequivocally state the superiority of one imaging line over the other, as each has specific pros and cons in specific cases. However, in the case of ectopic foci, the 2nd imaging line shows promising results.

**Keywords:** primary hyperparathyroidism imaging, hyperparathyroidism MIBI, hyperparathyroidism PET/CT, hyperparathyroidism 4DCT, hyperparathyroidism ultrasound, ectopic primary hyperparathyroidism

## Introduction:

Primary hyperparathyroidism (PHPT) is an endocrine disorder affecting the small parathyroid glands located behind the thyroid gland. These glands are tiny, measuring approximately 6 mm by 4 mm (about the size of an apple seed) and weighing around 0.5 g [1, 2]. Parathyroid glands are typically located posterior to the thyroid, at its upper and lower poles, and anterior to other neck structures. Humans usually have four parathyroid glands, although studies have shown that their number can increase to as many as 12. Embryologically, the superior glands develop from the fourth pharyngeal pouch near the thyroid, while the inferior glands migrate along with the thymus from the third pharyngeal pouch [3].

PHPT is more common in women than men, with a ratio of approximately 2:1. It affects about 2 in 1000 women and 1 in 1000 men and most commonly occurs in the sixth decade of life [1, 4, 5].

PHPT disrupts calcium and phosphate metabolism in the body by elevating serum parathyroid hormone (PTH) levels above the physiological range [1]. The pathogenesis of PHPT involves calcium-sensing receptors (CaSR) located on parathyroid cells, which detect changes in extracellular calcium levels [4]. These receptors enable the glands to respond appropriately to the body's needs. However, clonal proliferation of these cells and reduced reactivity of CaSR can lead to the development of PHPT [4].

The causes of PHPT can include hyperplasia, adenoma, atypical adenoma, or parathyroid carcinoma [6]. Most commonly, this condition presents as an adenoma (80–85%), followed by hyperplasia (15%), while carcinoma and atypical adenoma are the rarest (<5%) [1, 6]. Atypical adenoma is of particular interest, as it exhibits features of both adenoma and carcinoma. It is characterized by a thick capsule, the presence of fibrotic trabeculation, atypical cellular nuclei, and mitotic activity, but lacks invasive growth, metastases, vascular invasion, or infiltration of surrounding tissues [5, 6].

Ectopic parathyroid glands, located outside their standard anatomical position, can pose significant diagnostic challenges and must be considered in all cases of hyperparathyroidism [7]. Such atypical localization may involve one of the standard four glands or an additional, supernumerary gland [8].

Ectopic parathyroid glands are a common cause of recurrent PHPT, accounting for approximately 16% of PHPT cases and about 14% of secondary hyperparathyroidism cases [8, 9]. To prevent recurrence and ensure effective surgical treatment, identifying the location of ectopic glands and implementing appropriate diagnostic measures is crucial [10].

This study aims to compare imaging diagnostic methods used in the first and second lines of PHPT diagnostics, with particular attention to ectopic parathyroid glands, which present diagnostic challenges. Accurate localization of hyperfunctioning glands enables successful surgery and therapeutic outcomes.

## Materials and methods:

This review was prepared based on articles available on PubMed that contained the issues of imaging parathyroid glands including ectopic lesions. Original articles, review articles, case reports and guidelines were used for this review. The literature review was conducted using the following keywords: primary hyperparathyroidism, primary hyperparathyroidism imaging, primary hyperparathyroidism US, primary hyperparathyroidism MIBI, primary hyperparathyroidism PET/CT, primary hyperparathyroidism 4DCT, ectopic hyperparathyroidism imaging.

### Symptoms

PHPT can present in three clinical forms: symptomatic, asymptomatic, and normocalcemic. The symptomatic form was the first to be described, while the normocalcemic form was the last to be identified in patients [11]. PHPT disrupts calcium metabolism, which plays a critical role in maintaining homeostasis, thereby impacting the body's overall function. However, this disease often remains asymptomatic. The asymptomatic form is the most common presentation in most developed countries [2, 11].

Symptoms associated with PHPT include:

- Osteoporosis and osteopenia,
- Kidney dysfunction and urinary tract stones,
- Cognitive impairments and cardiovascular disease,
- Peptic ulcer symptoms,
- Psychiatric symptoms such as depression, anxiety, and restlessness,
- Generalized weakness, decreased muscle strength, and muscle or joint pain [1, 2, 5, 12].

Interestingly, the symptomatic form is more commonly observed in men than women within the affected population [13]. It has also been noted that African Americans tend to have higher serum calcium and PTH levels, yet paradoxically show less severe bone symptoms on densitometry (DXA) scans [14]. The most common initial symptoms are kidney stones and bone weakening [1]. Historically, PHPT was diagnosed in individuals experiencing recurrent episodes of these two symptoms [2, 4]. The risk of developing either of these symptoms is similar in both normocalcemic and hypercalcemic forms of the disease [15]. In the normocalcemic form, symptoms may be subclinical or entirely absent [16].

It is worth emphasizing that symptoms of PHPT may already be present but go unnoticed by the patient. Changes in the body are often identified during additional diagnostic tests, such as bone densitometry (DXA) [11, 16].

**Diagnostics**

The diagnosis of PHPT is based on laboratory test results, which include elevated calcium and PTH levels in the blood [1, 11, 16]. Diagnosing PHPT is crucial because of the long-term effects it can have on the body. After laboratory confirmation, the initial imaging modalities typically include ultrasonography (USG) and scintigraphy, followed by [18F]F-Choline PET/CT and 4D-CT [17]. Unfortunately, only about 70% of patients undergo adequate preoperative imaging diagnostics, highlighting the need for optimizing patient management in cases of PHPT [18].

A thorough differential diagnosis is essential during the diagnostic process. A detailed patient history can help rule out other causes of elevated calcium levels. Particular attention should be paid to medications or supplements taken by the patient, including thiazide diuretics, lithium, and vitamin D3, as well as existing conditions such as hyperthyroidism, malignancies, prolonged immobilization, granulomatous diseases, or adrenal insufficiency, all of which can contribute to hypercalcemia [1,16,19,20].

Additionally, conditions that result in elevated PTH levels should be considered, such as familial hyperparathyroidism, familial hypocalciuric hypercalcemia, tumors causing increased PTH levels, lithium usage, and tertiary hyperparathyroidism [20]. PHPT may also be part of genetic syndromes such as MEN1, MEN2A, and MEN4 [4].

Effective differentiation and imaging diagnostics are crucial for accurately identifying the source of PHPT and ensuring successful treatment.

**Imaging Diagnostics**

Imaging diagnostics play a critical role in the management of patients with PHPT as incomplete diagnostic workup can lead to unfavorable outcomes and the progression of symptoms. Unfortunately, this disease is often underdiagnosed, leading to delays in initiating treatment. According to studies conducted in the United States, 43.7% of patients with elevated calcium and PTH levels (>= 50 pg/ml) remained undiagnosed [21]. Therefore, precise imaging diagnostics are crucial to localize the hyperactive parathyroid tissue, which is often challenging due to the possibility of the gland being located outside its usual anatomical position [9, 17]. Hyperparathyroidism can also be associated with the presence of additional parathyroid glands [9].

Due to the difficulties in imaging this small gland, imaging diagnostic methods have evolved over time [22]. Accurate localization of hyperactive parathyroid tissue is essential for determining whether the patient is a candidate for surgical treatment, which is the only definitive cure [9,22]. In particular, when ectopic parathyroid tissue is present, preoperative imaging is of great significance as it allows for minimally invasive parathyroidectomy (MIP), which is safer for the patient compared to the previously used bilateral open neck exploration [23].

For preoperative imaging, ultrasound and scintigraphy/SPECT are typically used as the first-line methods. When these do not provide sufficient information, second-line imaging methods, such as 18F-fluorocholine PET/CT and 4D-CT, are employed [9, 17]. Accurate and thorough imaging is essential to plan and execute effective and minimally invasive surgery, improving the safety and success of the treatment.

**Imaging Diagnostics and Surgery in Primary Hyperparathyroidism**

Parathyroid surgery has undergone significant changes over the past few decades. Traditional parathyroidectomy has been largely replaced by MIP techniques, which have led to reductions in operation time, hospital stay, and postoperative complications, assuming that most patients suffer from single gland disease (SGD) [24, 25, 26]. The financial aspect also plays a role in this shift. Studies have shown that bilateral neck exploration is more expensive (9578 USD) and has a slightly lower success rate (97.3%) compared to MIP using SPECT imaging, where the cost is lower (8197 USD) and the success rate is higher (98.6%) [22]. Thus, the development of multidimensional imaging techniques offers many advantages. Moreover, imaging is an essential tool for the successful implementation of MIP and for the correct classification of patients for the appropriate procedure [27].

In cases of ectopic parathyroid glands, during bilateral open neck exploration, caution is advised. For upper glands, the procedure should include careful examination of the posterior surface of the upper pole, followed by investigation along the tracheoesophageal groove, pre-esophageal space, and pyriform sinus. When searching for glands in the vicinity of the lower poles of the thyroid, the procedure should include the path leading to the thymus (anterior mediastinum), after which the carotid sheath may be assessed and, if necessary, dissected [28].

**Ultrasonography in Primary Hyperparathyroidism**

USG is commonly the first imaging modality used in the diagnosis of PHPT. It is widely employed, often in combination with scintigraphy, which provides more reliable results when both tests are consistent [9]. USG involves the assessment of glandular structure and appearance, allowing for the detection of gland enlargement, hypoechogenicity, the presence of fluid collections or cysts [22, 23]. When combined with scintigraphy using [99mTc]Tc-MIBI, the sensitivity ranges from 81% to 95%, although scintigraphy plays a larger role in the diagnostic process [8].

The advantages of USG include its low cost and safety for the patient since there is no radiation exposure [8, 22]. However, limitations include operator-dependent errors, difficulty performing the procedure in patients with high BMI (increased neck circumference can hinder a proper examination), restricted ability to image only superficial structures of the neck, and low sensitivity in detecting ectopic parathyroid glands or multi-gland disease (MGD) [9, 22, 23]. Negative preoperative MIBI scintigraphy or USG results are considered prognostic indicators of MGD [29]. That said, when conducted by an experienced practitioner, this method is sensitive and accurate [23, 30].

USG can also be used in performing fine-needle aspiration (FNA) biopsies, which helps in precisely obtaining tissue samples for cytological analysis, especially in challenging cases [9, 23]. Intraoperative USG can also aid surgeons by allowing precise localization of parathyroid glands, which can then improve surgical outcomes [22, 31].

USG also plays a role in minimally invasive procedures, such as ablation, used to treat patients with hyperplastic parathyroid glands who are not candidates for surgery or who decline surgical treatment [32].

In summary, USG has extensive applications in PHPT diagnosis and management, from initial disease screening to identifying complications, aiding further diagnostics, and even in some treatment approaches. However, when it comes to detecting ectopic parathyroid glands, USG has relatively low sensitivity, ranging from 57% to 76%, due to difficulties in identifying these glands, especially when they are deeply situated within neck tissues. For first-line imaging, 99mTc-sestamibi scintigraphy is far superior to USG for detecting ectopic parathyroid glands [9, 33].

**Scintigraphy with Tc-99m-MIBI in Primary Hyperparathyroidism**

Currently, most medical facilities use scintigraphy with radiotracers such as technetium-99m-methoxyisobutylisonitrile (Tc-99m-MIBI) alongside USG as a first-line diagnostic method for PHPT [8, 24, 34]. Additionally, the integration of single-photon emission computed tomography (SPECT) with computed tomography (CT), through a two-phase protocol, has enabled clinicians to obtain three-dimensional views of the affected organ, significantly enhancing the accuracy and sensitivity of diagnostics [8, 24]. These tests complement each other: USG provides anatomical details, while nuclear medicine reveals functional imaging

[27]. Moreover, Tc-MIBI has an advantage over USG in detecting ectopic and deeply located parathyroid lesions [10].

Among the numerous radiopharmaceuticals used for locating parathyroid glands, Tc-MIBI is one of the most commonly employed. The lipophilic cationic complex of Tc-MIBI accumulates in hyperactive parathyroid tissue due to the increased number of mitochondria in oxyphil cells. The uptake and retention of Tc-MIBI are influenced by various factors, including the phase of the cell cycle, blood flow to the tissue, calcium levels, and vascular permeability [8, 27].

In clinical practice, specialists employ different imaging protocols depending on factors such as the availability of certain tests, time constraints (two-phase MIBI imaging), the use of multiple radiotracers (dual-isotope subtraction), and the type of acquisition methods (flat-panel CT, SPECT). This variability makes it challenging to definitively assess the diagnostic accuracy of each protocol [22, 27].

Scintigraphy is a nuclear medicine technique in which the radiopharmaceutical Tc-MIBI is administered intravenously, and images are captured using a gamma camera equipped with a collimator [27, 35, 36]. During the procedure, images of the neck and chest are obtained from both anteroposterior (AP) and posteroanterior (PA) projections. The scintigrams show the distribution of the radioisotope in tissues that contain a high density of mitochondria, such as parathyroid and thyroid tissues, certain tumors, and cardiac muscle cells [35].

## Single-Photon Emission Computed Tomography (SPECT) in Primary Hyperparathyroidism

SPECT (Single-Photon Emission Computed Tomography) uses radiopharmaceuticals that emit gamma radiation, which is utilized in diagnosing conditions like strokes, seizures, bone diseases, and infections [37]. In the context of PHPT, SPECT can be used before MIP to detect parathyroid glands with the lowest uptake, facilitating preservation or partial transplantation of the gland tissue [10]. This imaging technique enables the creation of three-dimensional images through a rotating detector that circles the examined object. Importantly, SPECT does not involve increased exposure to ionizing radiation, though it requires additional time for acquiring three-dimensional images of a single anatomical area [27, 36, 37].

During scintigraphy or SPECT imaging, two methods can be employed: the two-phase method and dual-isotope subtraction, both of which are explained below [27].

In the two-phase imaging method, two time points are used: an early phase (10-30 minutes) and a late phase (90-150 minutes) following the injection of the radiopharmaceutical. The radiotracer accumulates not only in the parathyroid glands but also in the thyroid. However, their washout rates differ, which is leveraged in this imaging technique. On delayed images, the parathyroid glands are more distinctly visible [10, 27].

The dual-isotope subtraction method involves injecting two radioisotopes: Iodine 123 or technetium-99m-pertechnetate and MIBI. The first two radioisotopes are selectively taken up by the thyroid cells. During the procedure, two different images are obtained and subtracted from each other. The areas that show persistent uptake correspond to abnormal parathyroid glands. This method, however, involves an additional dose of radiation [8, 10, 27]. Moreover, this single-phase dual-isotope technique shows increased sensitivity in detecting multi-gland disease (MGD) compared to single-isotope two-phase scans [10].

A review of 24 studies over 11 years, utilizing different protocols with 99m Tc-sestamibi, showed that the estimated sensitivity for SPECT/CT is 86%, while for SPECT, it is only 74%, and 70% for planar techniques (scintigraphy) [22]. However, the sensitivity of these tests is dependent on lesion size and the level of PTH in the serum. A retrospective study of PHPT patients hospitalized between 2011 and 2015 at the Department of Endocrinology and Metabolism in Shanghai, China, by Minting Zhu et al., demonstrated that sensitivity for USG and SPECT/CT decreases for lesions ≤1.3 cm. Additionally, lower sensitivity for SPECT/CT was observed with PTH levels ≤252 pg/ml [38].

It’s important to note that while SPECT/CT provides valuable diagnostic information, it also carries an increased radiation dose, necessitating careful consideration and the use of the lowest possible radiation dose during CT scans [8, 37].

**Tc-MIBI SPECT/CT in Identifying Ectopic Parathyroid Lesions**

Tc-MIBI SPECT/CT is essential for identifying the location of ectopic parathyroid nodules [10, 16, 39]. In the previously mentioned retrospective study by Chinese researchers, it was found that SPECT/CT accurately detected all ectopic lesions [38]. However, it is important to note that the sensitivity or diagnostic accuracy reported in various studies can differ, influenced by factors such as the level of expert knowledge and patient population variability [22].

False positive results can occur for a variety of reasons. Commonly mentioned causes include thyroid nodules, where tracer washout is prolonged, leading to imaging similar to parathyroid pathology. Additionally, similar effects can be seen in paragangliomas producing PTH or lymph node metastases [10, 34]. Tc-MIBI scans, however, tend to have lower sensitivity, with false negative results particularly in cases of multi-gland disease (MGD), hyperplasia, or very small adenomas [2, 16, 34].

Ectopic parathyroid glands, as noted earlier, also pose challenges for localization and may contribute to surgical treatment failure. A rare example of this is the intrathyroidal parathyroid adenoma (ITPA) [22]. The diagnostic accuracy of USG, MIBI-SPECT scintigraphy, and their combination in locating ITPA was 89.3%, 64.3%, and 89.3%, respectively, although it is important to mention that the USG was always performed by an experienced specialist [30].

In summary, Tc-MIBI SPECT/CT has many advantages, including image acquisition availability and a lower radiation dose compared to 4DCT. Furthermore, it is crucial for detecting ectopic and deep lesions that may be missed by USG. It is especially preferred for patients with iodine contrast allergies or renal insufficiency. Disadvantages include longer scan times due to the need for waiting between time points and higher costs compared to USG or 4D-CT. Additionally, as mentioned, false results can occur due to unusual tracer washout patterns or the presence of thyroid nodules [27].

**PET and PET/CT in Parathyroid Imaging**

Positron Emission Tomography (PET) is a nuclear medicine imaging technique that serves as a second-line diagnostic tool in patients with PHPT. While no specific guidelines exist for the radiotracers used in PET imaging for PHPT, the most commonly employed radiopharmaceutical is [18F]-fluorocholine. This marker demonstrates better localization of hyperactive parathyroid glands compared to another radiotracer, 11C-methionine, also used in parathyroid imaging [8, 40].

Choline, a component of cell membrane phospholipids, is in high demand in proliferating tissues. [18F]-fluorocholine, a radioactive labeled form of choline, is absorbed by overactive parathyroid cells, emitting radiation detected by a gamma camera [17]. PET can be conducted as a standalone procedure or combined with low-dose CT (PET/CT) to improve results and limit radiation exposure [17]. PET and CT complement each other, but it is essential to analyze

the images both before and after attenuation correction to improve diagnostic accuracy and reduce the potential for artifacts in the CT portion of the scan [8].

PET is particularly beneficial when neck ultrasound and scintigraphy results are inconsistent, ambiguous, or fail to detect lesions [9]. PET/CT offers superior spatial resolution, providing faster results and greater patient comfort, all while exposing the patient to a lower dose of radiation compared to methods like MIBI [41, 42]. PET imaging's ability to assess whole-body choline metabolism is especially advantageous when dealing with ectopic parathyroid glands [17].

PET/CT proves extremely useful for detecting ectopic parathyroid glands. Even when an ultrasound identifies overactive parathyroid glands, PET may provide additional benefits by locating ectopic or additional glands that were missed on ultrasound [8]. Similarly, when scintigraphy with MIBI is positive, PET with choline can reveal the presence of additional parathyroid glands not detected in the MIBI scan [43].

**Challenges in PET Imaging and the Role of PET/CT in Parathyroid Disease**

In the context of PET imaging, certain factors can complicate result interpretation. Thyroid conditions such as inflammation, Graves' disease, and thyroid nodules may accumulate the tracer and mimic hyperactive parathyroid glands. Similarly, reactive lymph nodes can also absorb [18F]FCH, potentially leading to false-positive results indicating ectopic parathyroid glands. In these cases, additional imaging methods such as CT or MRI may be useful to reduce the risk of false diagnoses [8].

Another major drawback of PET is its high cost and less widespread availability compared to other imaging methods [41, 42].

In a 2021 study by Zhu et al., PET/CT with choline was conducted on patients suspected of having malignant changes with metastases. This approach demonstrated a 100% sensitivity for locating areas of hyperactive parathyroid tissue [38]. In a 2022 study by Boudousq et al., 72 patients with negative results from ultrasound and scintigraphy underwent PET, which succeeded in identifying hyperactive parathyroid glands in 70 cases. Regarding specificity, MIBI scintigraphy showed one more true negative result than PET with choline, but in terms of sensitivity and accuracy, PET outperformed MIBI and ultrasound (sensitivity: 99.3%, specificity: 97%, accuracy: 98%) [42].

Among the patients analyzed by Boudousq et al., five had ectopic parathyroid glands, and all these cases were successfully identified by PET with choline, whereas scintigraphy detected only one of five [42]. Furthermore, only one case yielded a false negative result in PET, which aligns with the findings of another study by Noltes et al. [18, 42]. The authors of the studies suggest that PET/CT with choline may be the best diagnostic tool for detecting ectopic parathyroid glands and should potentially be considered a first-line test [42]. This conclusion has been reinforced by subsequent studies showing 100% detectability of ectopic parathyroid glands and greater accuracy in detecting small adenomas, hyperplasia, and MGD [36, 44].

In conclusion, the advantages of PET/CT over other imaging methods lie in its superior sensitivity, accuracy, and the high recognition of ectopic hyperactive parathyroid glands. Additionally, PET/CT requires less reliance on the operator's skills and experience compared to other imaging modalities [42, 45].

**4DCT in Parathyroid Imaging**

Multiphasic dynamic contrast-enhanced CT (4DCT) was first introduced in 2006. This method allows for the visualization of parathyroid tissue morphology both in a standard CT scan without contrast and after contrast administration. Imaging is done in three or four phases: pre-contrast, arterial phase (25-30 seconds after contrast injection), venous phase (30 seconds post-injection), and optionally a delayed venous phase (around 60 seconds) [22]. The characteristic changes seen in hyperactive parathyroid glands after contrast administration include significant contrast accumulation and rapid washout [17].

Like PET/CT, 4DCT is generally used as a second-line imaging technique when first-line methods fail, after unsuccessful surgery, or in cases involving anatomical distortions in the neck [22, 46]. Sensitivity of 4DCT after negative first-line imaging results has been reported as 89%, with a positive predictive value (PPV) of 74% [9].

However, 4DCT has notable drawbacks. It exposes patients to a much higher dose of radiation, up to 57 times greater than 99mTc-sestamibi scintigraphy. Additionally, iodine-based contrast agents can pose risks to individuals with kidney dysfunction, allergic reactions, or hyperthyroidism [9, 17, 22]. To reduce radiation exposure, it is possible to decrease the number of contrast phases (e.g., two-phase CT), but this could lower the sensitivity of the examination [17, 22]. Furthermore, the examination requires precise evaluation by an experienced physician to be effective [9]. Another limitation is the detection of hyperactive parathyroid glands only

within the scanned area, making it difficult to visualize small or peripheral ectopic lesions, especially in the presence of thyroid nodules or lesions smaller than 10 mm [9, 22].

Despite these challenges, 4DCT offers advantages such as high anatomical accuracy and spatial resolution, which, when combined with tissue contrast, allows for improved sensitivity in differentiating tissues [17, 41]. Additionally, 4DCT is useful in distinguishing benign from malignant lesions by assessing how parathyroid tissue contrasts with surrounding structures [41]. Another benefit is that this method is widely available and increasingly accessible globally [17].

Regarding ectopic parathyroid glands, 4DCT is helpful in their localization, especially due to its anatomical precision. However, since it is not a whole-body imaging technique, it will miss ectopic sites located outside of the imaged area, which can limit its usefulness for certain cases [22, 41]. Nevertheless, a case report highlights the utility of 4DCT in a patient with recurrent hyperparathyroidism, where 4DCT was the only imaging modality that identified ectopic parathyroid glands. This was confirmed by selective venous sampling for PTH, enabling precise surgical intervention [47].

Overall, while 4DCT has limitations, its high anatomical accuracy and resolution, coupled with its growing availability, make it a valuable tool in specific clinical situations, particularly for imaging recurrent or ectopic hyperactive parathyroid glands.

## Conclusions

Despite advances in imaging technology, there is still no optimal imaging algorithm for preoperative diagnosis of PHPT. In clinical practice, a variety of methods are used, which means these algorithms may differ depending on the center and patient. Currently, the most commonly used combination in diagnosing PHPT is USG and MIBI, mainly due to their low cost, availability, and widespread use. In recent years, however, there has been growing popularity of using 4DCT and PET/CT with choline, marking progress in diagnosis, especially for detecting ectopic parathyroid glands.

The decision on the appropriate imaging method depends on various factors, such as the preferences of the diagnostic team, the availability of equipment, the cost of the tests, and the patient's health condition. Second-line methods, such as PET/CT, show higher sensitivity and accuracy in diagnosing hyperparathyroidism, particularly in detecting ectopic parathyroid

glands, and may be considered as a first-line choice in the future. Specifically, PET/CT with choline has shown promising results in locating ectopic hyperparathyroid lesions, but further research is needed. MIBI-SPECT/CT still remains a competitive second-line method, particularly for areas that may go undetected in other studies.

Each of the mentioned methods has its strengths, but also limitations depending on the specific case and clinical conditions of the patient. Therefore, an individualized approach to each case is necessary to select the best imaging method tailored to the specific situation. It is worth noting that the advancement of imaging technology may still influence improvements in diagnostic results and the accuracy of parathyroid lesion localization.

**Article information and deceleration:**

**Author contributions**

Conceptualization: LL, KK and MN; methodology: SK, KK and NK; software: JK; check: SK, KK and JK; formal analysis: LL, KK and KB; investigation: LL, KK, SK and KB; resources: JK, SK; data curation: JK, SK and NK; writing - rough preparation: LL, KK, MN; writing - review and editing: KB, LL and KK; visualization: LL; supervision: KK; project administration: SK, KK;

All authors have read and agreed with the published version of the manuscript.

**Funding statement:**
No funding was received.

**Statement of institutional review board:**
Not applicable.

**Statement of informed consent:**
Not applicable.

**Data availability statement:**
Not applicable.

**Conflict of interest statement:**
The authors report no conflicts of interest.

List of abbreviations:

USG – ultrasonography

Tc-99m-(MIBI) – technetium-99m-(methoxyisobutylisonitrile)

PET – positron emission tomography

4DCT – four dimensional computed tomography

PHPT – primary hyperparathyroidism

CaSR – calcium - sensing receptors

DXA – Dual-energy X-ray Absorptiometry

PTH – parathyroid hormone

MEN1 – multiple endocrine neoplasia type 1

MEN2A – multiple endocrine neoplasia type 2A

MEN4 – multiple endocrine neoplasia type 4

CT – computed tomography

SPECT – single-photon emission computed tomography

MIP – minimally invasive parathyroidectomy

SGD – single gland disease

BMI – body mass index

MGD – multi gland disease

FNA – fine-needle aspiration

AP – anteroposterior

PA – posteroanterior

ITPA – intrathyroidal parathyroid adenoma

PPV – positive predictive value

References:

1. Kowalski GJ, Buła G, Żądło D, Gawrychowska A, Gawrychowski J. Primary hyperparathyroidism. Endokrynol Pol. 2020;71(3):260-270. PMID: 32797471. https://doi.org/10.5603/EP.a2020.0028

2. Pokhrel B, Leslie SW, Levine SN. Primary Hyperparathyroidism. 2024 Mar 1. In: StatPearls. Treasure Island (FL): StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK441895/ (access: 19.10.2024)

3. Georgakopoulos B, Al Khalili Y. Anatomy, Head and Neck, Parathyroid, Ectopic Glands. 2023 Jul 17. In: StatPearls. Treasure Island (FL): StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK540972/ (access: 29.11.2024)

4. Minisola S, Arnold A, Belaya Z, Brandi ML, Clarke BL, Hannan FM, Hofbauer LC, Insogna KL, Lacroix A, Liberman U, Palermo A, Pepe J, Rizzoli R, Wermers R, Thakker RV. Epidemiology, Pathophysiology, and Genetics of Primary Hyperparathyroidism. J Bone Miner Res. 2022 Nov;37(11):2315-2329. Epub 2022 Oct 17. PMID: 36245271; PMCID: PMC10092691. https://doi.org/10.1002/jbmr.4665

5. Galani A, Morandi R, Dimko M, Molfino S, Baronchelli C, Lai S, Gheza F, Cappelli C, Casella C. Atypical parathyroid adenoma: clinical and anatomical pathologic features. World J Surg Oncol. 2021 Jan 20;19(1):19. PMID: 33472651; PMCID: PMC7818751. https://doi.org/10.1186/s12957-021-02123-7

6. Guilmette J, Sadow PM. Parathyroid Pathology. Surg Pathol Clin. 2019 Dec;12(4):1007-1019. Epub 2019 Sep 27. PMID: 31672291; PMCID: PMC7395581. https://doi.org/10.1016/j.path.2019.08.006

7. Boccalatte LA, Gómez NL, Olivera López S, Yanzon A, Abuawad CY, Smith DE, Mazzaro EL, Figari MF. Hiperparatiroidismo ectópico. Detección de la localización mediastinal [Ectopic hyperparathyroidism. Detection of mediastinal localization]. Medicina (B Aires). 2020;80(1):39-47. Spanish. PMID: 32044740.

8. Petranović Ovčariček P, Giovanella L, Carrió Gasset I, Hindié E, Huellner MW, Luster M, Piccardo A, Weber T, Talbot JN, Verburg FA. The EANM practice guidelines for parathyroid imaging. Eur J Nucl Med Mol Imaging. 2021 Aug;48(9):2801-2822. Epub 2021 Apr 10. PMID: 33839893; PMCID: PMC8263421. https://doi.org/10.1007/s00259-021-05334-y

9. Hindié E, Schwartz P, Avram AM, Imperiale A, Sebag F, Taïeb D. Primary Hyperparathyroidism: Defining the Appropriate Preoperative Imaging Algorithm. J Nucl Med. 2021 Jul;62(Suppl 2):3S-12S. PMID: 34230072. https://doi.org/10.2967/jnumed.120.245993

10. Chakrabarty N, Mahajan A, Basu S, D'Cruz AK. Imaging Recommendations for Diagnosis and Management of Primary Parathyroid Pathologies: A Comprehensive Review. Cancers (Basel). 2024 Jul 19;16(14):2593. PMID: 39061231; PMCID: PMC11274996. https://doi.org/10.3390/cancers16142593

11. Walker MD, Bilezikian JP. Primary Hyperparathyroidism. [Updated 2021 Apr 19]. In: Feingold KR, Anawalt B, Blackman MR, et al., editors. Endotext. https://www.ncbi.nlm.nih.gov/books/NBK278923/ (access: 21.10.2024)

12. Pappachan JM, Lahart IM, Viswanath AK, Borumandi F, Sodi R, Metzendorf MI, Bongaerts B. Parathyroidectomy for adults with primary hyperparathyroidism. Cochrane Database Syst Rev. 2023 Mar 8;3(3):CD013035. PMID: 36883976; PMCID: PMC9995748. https://doi.org/10.1002/14651858.CD013035.pub2

13. Weber T, Hillenbrand A, Peth S, Hummel R. Symptoms of Primary Hyperparathyroidism in Men and Women: The Same but Different? Visc Med. 2020 Feb;36(1):41-47. Epub 2020 Jan 22. PMID: 32110656; PMCID: PMC7036559. https://doi.org/10.1159/000505497

14. Fieber J, Goodsell K, Kelz RR, Ermer JP, Wirtalla C, Fraker DL, Wachtel H. Racial Disparities in Primary Hyperparathyroidism. World J Surg. 2021 Jan;45(1):180-187. Epub 2020 Sep 25. PMID: 32978665; PMCID: PMC7906108. https://doi.org/10.1007/s00268-020-05791-w

15. Leslie SW, Levine SN. Normocalcemic Hyperparathyroidism. [Updated 2024 Mar 4]. In: StatPearls. Treasure Island (FL): StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK555967/ (access: 23.10.2024)

16. Kochman M. Primary hyperparathyroidism: clinical manifestations, diagnosis and evaluation according to the Fifth International Workshop guidelines. Reumatologia. 2023;61(4):256-263. Epub 2023 Aug 31. PMID: 37745146; PMCID: PMC10515122. https://doi.org/10.5114/reum/170705

17. Fiz F, Bottoni G, Massollo M, Trimboli P, Catrambone U, Bacigalupo L, Righi S, Treglia G, Imperiale A, Piccardo A. [18F]F-Choline PET/CT and 4D-CT in the evaluation of primary

hyperparathyroidism: rivals or allies? Q J Nucl Med Mol Imaging. 2023 Jun;67(2):130-137. PMID: 37232932. https://doi.org/10.23736/S1824-4785.23.03514-8

18. Noltes ME, Cottrell J, Madani A, Rotstein L, Gomez-Hernandez K, Devon K, Boggild MK, Goldstein DP, Wong EM, Brouwers AH, Kruijff S, Eskander A, Monteiro E, Pasternak JD. Quality Indicators for the Diagnosis and Management of Primary Hyperparathyroidism. JAMA Otolaryngol Head Neck Surg. 2022 Mar 1;148(3):209-219. PMID: 34989783; PMCID: PMC8739767. https://doi.org/10.1001/jamaoto.2021.3858

19. Mifsud S, Montanaro G, Craus S, Mifsud EL, Gruppetta M. Thiazide diuretics and primary hyperparathyroidism. Br J Hosp Med (Lond). 2023 Dec 2;84(12):1-8. Epub 2023 Dec
20. PMID: 38153014. https://doi.org/10.12968/hmed.2023.0228

20. Sell J, Ramirez S, Partin M. Parathyroid Disorders. Am Fam Physician. 2022 Mar 1;105(3):289-298. PMID: 35289573.

21. Lorenz FJ, Beauchamp-Perez F, Manni A, Chung T, Goldenberg D, Goyal N. Analysis of Time to Diagnosis and Outcomes Among Adults With Primary Hyperparathyroidism. JAMA Netw Open. 2022 Dec 1;5(12):e2248332. PMID: 36574247; PMCID: PMC9857508. https://doi.org/10.1001/jamanetworkopen.2022.48332

22. Morris MA, Saboury B, Ahlman M, Malayeri AA, Jones EC, Chen CC, Millo C. Parathyroid Imaging: Past, Present, and Future. Front Endocrinol (Lausanne). 2022 Feb 25;12:760419. PMID: 35283807; PMCID: PMC8914059. https://doi.org/10.3389/fendo.2021.760419

23. Karunaratne D, Karunaratne N, Vasanthan R, Ojofeitimi O, Owens E, Sathiskumar P, Till D, Kirkland P, Howlett D. Primary Hyperparathyroidism: Outcomes of Repeated Imaging After Initial Negative Radiological Localization. Cureus. 2023 Aug 3;15(8):e42889. PMID: 37664265; PMCID: PMC10474611. https://doi.org/10.7759/cureus.42889

24. Salhi H, Bouziane T, Maaroufi M, Alaoui NI, El Ouahabi H. Primary hyperparathyroidism: Correlation between cervical ultrasound and MIBI scan. Ann Afr Med. 2022 Apr-

Jun;21(2):161-164. PMID: 35848650; PMCID: PMC9383011. https://doi.org/10.4103/aam.aam_73_20

25. Kim WW, Lee YM, Sung TY, Chung KW, Hong SJ. Selection of parathyroidectomy methods for primary hyperparathyroidism according to concordance between ultrasonography and MIBI scan results. Gland Surg. 2021 Jan;10(1):298-306. PMID: 33633986; PMCID: PMC7882318. https://doi.org/10.21037/gs-20-611

26. Quak E, Lasne-Cardon A, Cavarec M, Lireux B, Bastit V, Roudaut N, Salaun PY, Keromnes N, Potard G, Vaduva P, Esvant A, Jegoux F, de Crouy-Chanel O, Devillers A, Guery C, Lasnon C, Ciappuccini R, Legrand B, Estienne A, Christy F, Grellard JM, Bardet S, Clarisse B. F18-Choline PET/CT or MIBI SPECT/CT in the Surgical Management of Primary Hyperparathyroidism: A Diagnostic Randomized Clinical Trial. JAMA Otolaryngol Head Neck Surg. 2024 Aug 1;150(8):658-665. PMID: 38900416; PMCID: PMC11190825. https://doi.org/10.1001/jamaoto.2024.1421

27. Tay D, Das JP, Yeh R. Preoperative Localization for Primary Hyperparathyroidism: A Clinical Review. Biomedicines. 2021 Apr 6;9(4):390. PMID: 33917470; PMCID: PMC8067482. https://doi.org/10.3390/biomedicines9040390

28. Poh BR, Nagadia RH, Tay GC. Ectopic parathyroid gland within carotid sheath. Clin Case Rep. 2020 Nov 22;9(1):578-579. PMID: 33505697; PMCID: PMC7813128. https://doi.org/10.1002/ccr3.3476

29. Zajíčková K, Včelák J, Lešková Z, Grega M, Goltzman D, Zogala D. Multiglandular Parathyroid Disease in Primary Hyperparathyroidism With Inconclusive Conventional Imaging. Physiol Res. 2022 Apr 30;71(2):233-240. Epub 2022 Apr 11. PMID: 35275696; PMCID: PMC9150553. https://doi.org/10.33549/physiolres.934851

30. Haciyanli SG, Karaisli S, Erdogan N, Turgut B, Gur EO, Haciyanli M. Intrathyroidal Parathyroid Adenomas in Primary Hyperparathyroidism: Clinical and Imaging Findings. Sisli Etfal Hastan Tip Bul. 2022 Jun 28;56(2):256-261. PMID: 35990304; PMCID: PMC9350060. https://doi.org/10.14744/SEMB.2022.82584

31. Lala M. Management of Primary Hyperparathyroidism. Indian J Surg Oncol. 2022 Mar;13(1):143-151. Epub 2021 Apr 27. PMID: 35462664; PMCID: PMC8986895. https://doi.org/10.1007/s13193-021-01319-3

32. Chen Z, Cheng L, Zhang W, He W. Ultrasound-guided thermal ablation for hyperparathyroidism: current status and prospects. Int J Hyperthermia. 2022;39(1):466-474. PMID: 35271788. https://doi.org/10.1080/02656736.2022.2028907

33. Liu Y, Dang Y, Huo L, Hu Y, Wang O, Liu H, Chang X, Liu Y, Xing X, Li F, Liao Q, Hacker M, Li X, Kreissl MC. Preoperative Localization of Adenomas in Primary Hyperparathyroidism: The Value of 11C-Choline PET/CT in Patients with Negative or Discordant Findings on Ultrasonography and 99mTc-Sestamibi SPECT/CT. J Nucl Med. 2020 Apr;61(4):584-589. Epub 2019 Oct 10. PMID: 31601698. https://doi.org/10.2967/jnumed.119.233213

34. Hargitai L, Schefner M, Traub-Weidinger T, Haug A, Arikan M, Scheuba C, Riss P. Accessing the influence of 99mTc-Sesta-MIBI-positive thyroid nodules on preoperative localisation studies in patients with primary hyperparathyroidism. Langenbecks Arch Surg. 2022 May;407(3):1183-1191. Epub 2022 Jan 21. PMID: 35061094; PMCID: PMC9151570. https://doi.org/10.1007/s00423-022-02442-7

35. Gladić Nenadić V, Šiško Markoš I, Punda M, Blažeković I, Franceschi M, Fröbe A, Jukić T. 99mTc-MIBI SPECT/CT SCINTIGRAPHY AND ULTRASOUND OF THE ANTERIOR NECK REGION IN DIAGNOSING PARATHYROID GLAND PATHOLOGY IN PATIENTS WITH THYROID NODULES. Acta Clin Croat. 2022 Feb;60(3):423-428. PMID: 35282495; PMCID: PMC8907962. https://doi.org/10.20471/acc.2021.60.03.12

36. Manyalich-Blasi M, Domínguez-Garijo P, Saavedra-Pérez D, Sánchez-Izquierdo N, Casanueva Eliceiry S, Perissinotti A, Mora Porta M, de Hollanda A, Hanzu FA, López-Boado Serrat MA, Rull Ortuño AR, Ardid J, Vidal-Sicart S, Vidal Pérez Ò. Comparison of [18F]fluorocholine PET/CT with [99mTc]sestamibi and ultrasonography to detect parathyroid lesions in primary hyperparathyroidism: a prospective study. Gland Surg. 2022 Nov;11(11):1764-1771. PMID: 36518798; PMCID: PMC9742049. https://doi.org/10.21037/gs-22-198

37. Crișan G, Moldovean-Cioroianu NS, Timaru DG, Andrieș G, Căinap C, Chiș V. Radiopharmaceuticals for PET and SPECT Imaging: A Literature Review over the Last Decade. Int J Mol Sci. 2022 Apr 30;23(9):5023. PMID: 35563414; PMCID: PMC9103893. https://doi.org/10.3390/ijms23095023

38. Zhu M, He Y, Liu T, Tao B, Zhan W, Zhang Y, Xie J, Chen X, Zhao H, Sun L, Liu J. Factors That Affect the Sensitivity of Imaging Modalities in Primary Hyperparathyroidism. Int J Endocrinol. 2021 Feb 20;2021:3108395. PMID: 34840566; PMCID: PMC8616673. https://doi.org/10.1155/2021/3108395

39. Battistella E, Pomba L, Toniato R, Burei M, Gregianin M, Watutantrige Fernando S, Toniato A. Evolution of the Diagnosis and Treatment of Primary Hyperparathyroidism. J Clin Med. 2023 Mar 6;12(5):2057. PMID: 36902844; PMCID: PMC10004239. https://doi.org/10.3390/jcm12052057

40. Mathey C, Keyzer C, Blocklet D, Van Simaeys G, Trotta N, Lacroix S, Corvilain B, Goldman S, Moreno-Reyes R. 18F-Fluorocholine PET/CT Is More Sensitive Than 11C-Methionine PET/CT for the Localization of Hyperfunctioning Parathyroid Tissue in Primary Hyperparathyroidism. J Nucl Med. 2022 May;63(5):785-791. Epub 2021 Aug 19. PMID: 34413141. https://doi.org/10.2967/jnumed.121.262395

41. Evangelista L, Ravelli I, Magnani F, Iacobone M, Giraudo C, Camozzi V, Spimpolo A, Cecchin D. 18F-choline PET/CT and PET/MRI in primary and recurrent hyperparathyroidism: a systematic review of the literature. Ann Nucl Med. 2020 Sep;34(9):601-619. Epub 2020 Aug 7. PMID: 32767248; PMCID: PMC7438295. https://doi.org/10.1007/s12149-020-01507-1

42. Boudousq V, Guignard N, Gilly O, Chambert B, Mamou A, Moranne O, Zemmour M, Sharara H, Lallemant B. Diagnostic Performance of Cervical Ultrasound, 99mTc-Sestamibi Scintigraphy, and Contrast-Enhanced 18F-Fluorocholine PET in Primary Hyperparathyroidism. J Nucl Med. 2022 Jul;63(7):1081-1086. Epub 2021 Dec 2. PMID: 34857659. https://doi.org/10.2967/jnumed.121.261900

43. Aphale R, Dharmashaktu Y, Damle NA, Singareddy CR, Behera A, Wakankar R, Kumar P, Bal C, Khadgawat R, Chumber S. Odd Sites of Parathyroid Adenomas: 18F-fluorocholine PET/CT Pointing to the Right Place. Indian J Nucl Med. 2024 Mar-Apr;39(2):123-125. Epub 2024 May 29. PMID: 38989306; PMCID: PMC11232731. https://doi.org/10.4103/ijnm.ijnm_13_23

44. Imperiale A, Bani J, Bottoni G, Latgé A, Heimburger C, Catrambone U, Vix M, Treglia G, Piccardo A. Does 18F-Fluorocholine PET/CT add value to positive parathyroid scintigraphy in the presurgical assessment of primary hyperparathyroidism? Front Med (Lausanne). 2023 Apr 27;10:1148287. PMID: 37181366; PMCID: PMC10172498. https://doi.org/10.3389/fmed.2023.1148287

45. Uslu-Beşli L, Sonmezoglu K, Teksoz S, Akgun E, Karayel E, Pehlivanoglu H, Khosroshahi BR, Ocak M, Kabasakal L, Sager S, Bukey Y. Performance of F-18 Fluorocholine PET/CT for Detection of Hyperfunctioning Parathyroid Tissue in Patients with Elevated Parathyroid Hormone Levels and Negative or Discrepant Results in conventional Imaging. Korean J Radiol. 2020 Feb;21(2):236-247. PMID: 31997599; PMCID: PMC6992441. https://doi.org/10.3348/kjr.2019.0268

46. Latge A, Riehm S, Vix M, Bani J, Ignat M, Pretet V, Helali M, Treglia G, Imperiale A. 18F-Fluorocholine PET and 4D-CT in Patients with Persistent and Recurrent Primary Hyperparathyroidism. Diagnostics (Basel). 2021 Dec 17;11(12):2384. PMID: 34943620; PMCID: PMC8700343. https://doi.org/10.3390/diagnostics11122384

47. Suntornlohanakul O, Leelawattana R. A case report of successful identification of ectopic parathyroid adenomas with a sequence of selective parathyroid venous sampling and 4D-computed tomography in a patient with recurrent hyperparathyroidism. Int J Surg Case Rep. 2020;71:183-186. Epub 2020 May 7. PMID: 32464540; PMCID: PMC7256430. https://doi.org/10.1016/j.ijscr.2020.04.021