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BREAST THERMOGRAPHY AS A POTENTIAL NON-CONTACT METHOD IN THE EARLY DETECTION OF CANCER: A REVIEW

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This review paper discusses recent research achievements in medical thermography with concerns about the possibility of early breast cancer detection. With the advancements in infrared (IR) technology, image processing methods, and the pathophysiological-based knowledge of thermograms, IR screening is sufficiently mature to be utilized as a first-line complement to both health managing and clinical prognosis. In addition, it explains the performance and environmental conditions in identifying thermography for breast tumor imaging under strict indoor controlled environmental circumstances. An irregular thermogram is indicated as a significant biological risk marker for the presence or growth of breast tumors. Breast thermography is completely non-contact, with no form of radiation and compression. It is useful for all women of all ages, for pregnant and breastfeeding women, for women with implants, for women with dense or fibrocystic breasts, for women on hormone replacement therapy, and for pre or post menopausal women.

Breast thermography is specifically worthwhile during the early stages of fast tumor growth, which is not yet recognizable by mammography as thermography is a physiological test while mammography is an anatomical one. Often, physiological changes precede anatomical changes. This early detection of irregular tissue liveliness gives breast thermography the potential to be greatly useful and economical as an imaging program and provides the opportunity to apply non-invasive treatment to reform breast tissue activity. The non-radiating nature of thermography also permits repeated images. Thus, changes can be compared over time and the results of protective approaches can be observed to ensure utmost care of breast cells.

Keywords: Breast thermography; contactless; early detection; cancer; asymmetric hot spots.

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1. Introduction

The first recorded use of thermobiological diagnostics can be traced back to in the writings of Hippocrates at around 480 BC.[1] Sludge applied all over a patient was observed for regions that would dry first and was assumed to show underlying organ pathology. Since then, it has been clarified that specific temperatures corresponding to parts of the human body were absolutely demonstrative of normal and abnormal physiologic processes by continued study and clinical investigation. Military investigation into infrared (IR) managing arrangements for night-time armed forces activity was conducted in a new generation of thermal diagnostics in the 1950s. In 1957, the first application of diagnostic thermography was initialized when Lawson realized that the skin temperature over a cancer in the breast was higher than that of healthy tissue.[2] Moreover, he demonstrated that venous blood draining the cancer is usually warmer than its arterial supply. In 1972, the Department of Health Education and Welfare released a position paper in which Thomas Tiernery, the director, issued that, "...medical consultants indicate that thermography, in its existing state of improvement, is beyond the experimental state as a diagnostic procedure in the following 4 areas: (1) Pathology of the female breast. (2) ..." On January 29, 1982, the Food and Drug Administration (FDA) published its confirmation and classification of thermography as a complementary diagnostic imaging procedure for the detection of breast cancer. Many medical centers and independent health services have utilized thermography for different diagnostic goals since the late 1970s.[3]

Thermography, alternatively accepted as digital IR imaging (DII), is dependent on an accurate analysis of skin and tissue temperatures. It is a diagnostic procedure that allows practitioners to identify the locations of abnormal chemical and blood vessel activity in body tissue. It is a non-invasive approach by applying the technology of the IR camera and state-of-the-art software. With each scan, an image is composed, which is interpreted for signs of possible sickness or abnormality. Sufficient research and investigation performed at distinguished medical teaching universities such as John Hopkins University Medical School have created normal values for the distribution of heat in each part of the body.[4] Variations from these normal values are measured and correlated with suspected illness or damage in the same way a blood or urine laboratory investigation is defined over 30 years of scientific use, and more than 8,000 peer-reviewed studies in the medical literature have established thermography as a harmless and effective means to test the human body.[5,6] FDA approval has been obtained in the United States since 1982 and has been applied there and in Europe for more than 30 years. To the IACT (International Academy of Clinical Thermology),[7] breast thermography is a demonstrative method that images the breasts to help in early detection of breast cancer. It relies on the standard that chemical and blood vessel liveliness in both pre-cancerous tissue and the region surrounding an expanding breast cancer is commonly higher than that in healthy breast tissue. Because pre-cancerous and cancerous masses are highly metabolic tissues, they require a generous amount of nutrients to manage their expansion and this can increase the surface temperature of the breast.

Advanced breast thermography utilizes ultra-sensitive IR cameras and advanced computers to detect, interpret, and provide accurate demonstrative images of these temperature and vascular distortions. By carefully examining changes in the temperature and blood vessels of the breast, signs of possible cancer or pre-cancerous cell expansion may be recognized up to 10 years earlier to being found applying any other method.[8] This accommodates for the most primarily achievable observation of pre-cancerous and cancerous circumstances.[9] Thermography identifies abnormal physiological changes in the breasts that may be cancerous. Mammography, a type of X-ray, identifies specific structures in the breast that can conceivably be cancer. With both mammography and thermography, absolute diagnosis is done by other strategies such as a biopsy or lumpectomy. Since mammograms detect anatomical changes, a lump or mass of a size recognizable on X-ray already exists in breast tissue by the time a problem is found. The next step is another inspection by ultrasound and/or biopsy to identify the nature of the lump or mass, and to make therapy decisions. By then, it is usually too late to carry out preventive procedures alone and medical action or therapy is the norm. In comparison, breast thermography recognizes functional changes in breast tissue before the birth of tumors and when the tumors are too small to be identified with X-rays. Breast thermography is completely non-contact, with no form of radiation and compression. It is useful for all women of all ages, for pregnant and breastfeeding women, for women with implants, for women with dense or fibrocystic breasts, for women on hormone replacement therapy, and for pre- or postmenopausal women. It has the potential to detect problems five to eight years earlier than the irregularities that can be found with mammograms.[8] This prompt detection of typical tissue movement enables breast thermography to be a helpful and cost-effective imaging method and allows the convenience to apply safe therapies to promote breast tissue function. The non-invasive nature of thermography also allows repeating images. This upgrades the possibility to compare changes over time and manage the results of preventative methods to defend breast tissue. Since we have not been able to interrupt breast cancer as of yet, there is an agreement among specialists that more lives will be rescued with earlier detection. Since both physical and mammographic tests cannot identify all cancers, specifically smaller tumors in younger cases and cases with dense breast tissue, there is presently much interest in identifying new ways to promote techniques for early detection. Although some hopeful novel methods have appeared, such as MRI, Doppler ultrasound, and scinti-mammography, most are designed to be applied in selected cases where physical and mammographic tests have already identified irregularities. Various screening methods for breast cancer that have obtained FDA approval are outlined in Table 1. These examinations are not restricted to joint physical tests and mammography in front-line detection. There have been too many patients who have gone through these two screening strategies

Table 1. Imaging modalities for breast cancer detection approved by the FDA.[10]

Imaging modalities for breast cancer detection	Year
Film-screen mammography	1976
Full-field digital mammography	1997
Computer-aided detection	1980's
Ultrasound	Late 70s
Magnetic resonance imaging (MRI)	Late 80s
Positron emission tomography (PET)	Mid 90s
Thermography	1982
Electrical impedance imaging	1984

Source: Institute of Medicine, *Mammography and Beyond: Developing Technologies for the Early Detection of Breast Cancer*, National Academy Press, 2001.

and still depart with unrecognizable breast cancer. Specialists therefore have determined that no modality or technique of imaging is completely able for breast cancer recognition.[10]

2. Infrared Imaging in Medicine

The first recorded application of IR imaging in medicine was in 1956, when breast cancer cases were investigated for asymmetric hot spots and vascularity in IR images of the breasts. Many investigational findings have been issued since then[11–13] and the 1960s announced the first increase of medical application of the IR method,[14] with breast cancer detection as the basic trial. Regardless, IR screening is not recognized worldwide in medicine even till today, mostly because of the immature usefulness of the method, the lack of in-depth knowledge of IR images, and its inadequate presentation into breast cancer detection in the 1970s.[15] Recently, developments in some corresponding fields have forced a series of forward movements to reconsider the performance of IR imaging in medicine.[15–20]

2.1. *Worldwide use of infrared imaging in medicine*

2.1.1. *The United States and Canada*

New IR technology, new image processing techniques, significant high-speed computers, and the presence of numerous studies have brought IR imaging into reconsideration in the United States. This was witnessed by the increasing number of studies available in the open literature and national databases such as "Index Medicus" and "Medline."[3] Presently, academic institutions with research initiatives in IR imaging are the National Institutes of Health (NIH), John Hopkins University, the University of Houston, and the University of Texas. The NIH in particular has various ongoing activities: vascular disorders (diabetes, deep venous thrombosis); monitoring angiogenesis activity in Kaposi sarcoma; pain–reflex sympathetic dystrophy; monitoring the efficacy of radiation therapy; organ transplant perfusion; and multispectral imaging. John Hopkins University delves into microcirculation; monitoring projects in Kaposi sarcoma and breast imaging; and laparoscopic IR images in renal disease. The University of Houston has recently developed an IR imaging laboratory to examine the facial thermal characteristics for applications such as lie detection, fatigue, anxiety, and fear.[3] There are multimodality medical centers working on breast cancer projects that apply IR routinely as part of their premier detection system. They also perform mammography and clinical examinations. Two of these centers are the EHH Breast Cancer and Treatment Center in Baton Rouge, Los Angeles, USA and the Ville Marie Oncology Research Center in Montreal, Canada. These centers are impressively furnished with advanced imaging equipment, and members of the community are for the improvement of a "knowledge-based" database of thermal features of the breast with "ground-truth" approval. Dr. William Cockburn has been authorized in clinical thermology since 1987 and is now a Fellow of the International Academy of Clinical Thermology. Since 1975, he has taken care of a thermal imaging center in Los Angeles and has been licensed to proceed. He has written many articles and given numerous presentations with regards to the breast.[21,22] In addition, there are current new study activities being completed in collaborative medical centers.[3]

2.1.2. *China*

China has approved IR imaging in medicine for many years. More recently, the new approach of thermal texture maps (TTM) has gained attention due to the increased specificity in static imaging. This approach has been considerably applied in this country,[23] and it is a goal for TTM to be realized as a possible and efficient technique by the international society. The outcome envisioned through this approach should be written in open findings of medical journals and international conference proceedings. In spite of the shortage of the availability of such publications, presentations of TTM have been given to the NIH. Of late, they are favorably employing this approach with its camera in recognition and therapy in Kaposi sarcoma (correlated with AIDS patients). After further argumentation, its application in the field of breast cancer (i.e., in the discovery of angiogenesis) has been heavily proposed.[3]

2.1.3. *Japan*

IR imaging is validated nationwide in Japan by the administration and the medical association. More than 1,500 health services and clinics employ IR imaging consistently. The administration establishes the standards and retrieves clinical examinations. Their focus is in the following fields: blood perfusion, breast cancer, dermatology, pain, neurology, ophthalmology, surgery (open-heart, orthopedic, dental, cosmetic), sports medicine, and oriental medicine. The main work is accomplished at the following institutions: the University of Tokyo (organ transplant); Tokyo Medical and Dental University (skin temperature characterization and thermal properties); Toho University (neurological operation); and the Cancer Institute Hospital (breast cancer).[3] In a project for dry eye detection, Kamao *et al.* used the newly established ocular surface thermographer (TOMEY Corp., Japan) for dry eye screening.[24] In addition, approximately 40 other medical associations are applying IR for breast cancer imaging.

2.1.4. *The United Kingdom*

The University of Glamorgan is the heart of IR screening; its School of Computing has a thermal physiology research room that focuses on the following fields: medical IR projects, standardization, educating (university diploma), and the "SPORTI" Project launched by the European Union (EU). The aim of this attempt was to develop a reference database of normal thermal features from healthy subjects. The Royal National Hospital of Rheumatic Diseases practices in rheumatic irregularities, vocational health (Raynaud's sickness, carpal tunnel syndrome, and sports medicine), and the Royal Free University College Medical School Hospital performs investigations on vascular irregularities (diabetes, DVT, etc.) to upgrade IR imaging methods and Raynaud's abnormality.[3]

2.1.5. *Iran*

Studies concerning breast thermography have started since 2006. Color segmentation,[25] symmetry analysis,[26,27] and feature extraction[28–30] of breast thermal images are among these studies.

2.1.6. *Germany*

The University of Leipzig utilizes IR for open-heart surgery, perfusion, and microcirculation. There are several public health centers and other clinics that employ IR imaging for assorted purposes. Evo Bus-Daimler Chrysler utilizes IR imaging for screening all their members in their routine checkup. Infra Medic, AG, guides breast cancer screening of women from 20 to 85 years old for the administration with a two-year award.[3]

2.1.7. *Austria*

The Ludwig Boltzmann Research Institute for Physical Diagnostics has been doing projects in IR for many decades and has established *Thermology International* (a quarterly journal of IR clinical research and instrumentation). This journal contains articles from many thermology communities. A recent issue incorporates the results of a review of 2,003 international articles addressed in thermology. The General Hospital, University of Vienna, conducts projects mainly in angiology (study of blood and lymph vessels) and diabetic foot (pedobarography).[3]

2.1.8. *Poland*

In Poland, the growth of utilizing IR imaging for clinical purposes is more rapid than the acceleration of the demand for IR cameras in the Polish market. There are currently more than 50 cameras being employed in the following clinical places: Warsaw University, the Technical University of Gdansk, Poznan University, Lodz University, Katowice University, and the Military Clinical Hospital. The investigation movements emphasize on the following fields: active IR screening, open-heart surgery, quantitative evaluation of skin burns, ophthalmology, dentistry, allergic illness, neurological sickness, plastic surgery, IR image database for normal and pathological subjects, and multispectral screening (IR, visual, X-ray, ultrasound, etc.).[3] In 1986, the Eurotherm Committee was established by associates of the European community to increase participation in thermal researches by associating experts and investigators in the field of thermology. This constitution is concerned with thermography and regularly holds conferences and seminars.[3]

2.1.9. *Italy*

A great deal of the medical application of IR screening is accomplished under the community health system, in conjunction with private medical centers. The advanced medical achievements are in the following fields: dermatology (melanoma), neurology, rheumatology, anesthesiology, reproductive medicine, and sports medicine. The University of G. d'Annunzio, Chieti, has a screening testing room entirely dedicated to the investigation of IR functions. It forms collaborations with other institutions (all over Italy) on these projects.[31]

2.1.10. *Singapore*

A new method was introduced by Tan *et al.* to measure tear evaporation and monitor its variation with respect to time.[32] Furthermore, several advantages of thermography in the field of ophthalmology were explained by Tan *et al.*[33] In another research, the application of IR for the investigation of facial skin and aural temperature was elaborated by Ng *et al.*[34] In addition, Ng *et al.* demonstrated a review of remote-sensing IR thermography for indoor mass blind fever screening in containing an epidemic.[35] Ng also wrote a review of thermography as a potential safe detection procedure for breast tumors.[36] Besides, Ng *et al.* proposed an algorithm as a basis for an intelligent diagnostic system based on thermography for the detection of tumors in breasts.[37] Also, they presented the analysis of thermograms by applying artificial neural networks (ANN) and biostatistical approaches, including regression and receiver operating characteristics (ROC).[38] In 2009, Ng *et al.* figured out the potential of application of the thermography diagnostic system in computing sexual function in subjects with erectile dysfunction.[39]

Other countries such as Australia, Norway, Brazil, South America, and the Russian Federation have shown various advancements in the research of IR as well.

3. History of Infrared Imaging for Breast Cancer

Numerous investigations have been conducted on the application of IR imaging in breast cancer imaging since the late 1950s. More than 800 articles can be found in the indexed medical literary works, with more than 300,000 women cooperating as project subjects in this database. The numbers of participants in these respective projects are considerable, ranging from 10,000 to 85,000. Subjects have been observed for up to 12 years in some of these projects in order to consider and organize the unique ability of this method as a risk marker. IR screening of the breast has attained an average sensitivity and specificity of 90% with authoritarian standardized interpretation protocols that have been constituted for more than 15 years.[36] A constant irregular thermogram carries a risk 22 times higher than its regular counterpart and is 10 times more noticeable than a first-order family history of the illness as a future risk signal for breast cancer. Studies have indicated that an irregular IR image is probably the single most crucial risk marker for the presence of or future growth of breast cancer. In 1965, Gershon-Cohen, a radiologist and researcher from the Albert Einstein Medical Center, raised the potential of IR imaging to the United States.[14] He documented the cases of 4,000 subjects with a sensitivity of 94% and a false-positive rate of 6% by applying a Barnes thermograph. This data was recorded in *A Cancer Journal for Physicians* in 1968 in California. In another investigation, Hoffman[5] first recorded a thermogram in gynecologic practice. He diagnosed 23 carcinomas in 1,924 subjects (a detection rate of 12.5 per 1,000), with an 8.4% false-negative rate (91.6% sensitivity) and a 7.4% false-positive (92.6% specificity) rate. Stark and Way provided images of 4,621 asymptomatic subjects, 35% of whom were under 35 years of age, and identified 24 cancers (detection rate of 7.6 per 1,000), with a sensitivity and specificity of 98.3 and 93.5%, respectively.[40] Amalric *et al.* worked on IR imaging with 25,000 subjects imaged, resulting in 1,878 histologically confirmed breast cancers. From this series, false-negative and false-positive rates of 9% (91% sensitivity and specificity) were discovered.[41] In a mobile unit trial in rural Wisconsin, Hobbins[42,43] imaged 37,506 subjects using thermography. He recorded a recognition rate of 5.7 cancers per 1,000 subjects imaged with 12% false-negative and 14% false-positive rates. His investigations were in agreement with others in that thermography is the absolute initial sign in 10% of breast cancers.[44] Isard *et al.*[42,43] obtained a number of considerable notions including the extraordinary thermal and vascular stabilities of the IR image from year to year in a normal subject and the significance of detecting any considerable change by recording his radiology division's knowledge with 10,000 thermographic projects accomplished resultantly with mammography over a three-year term. They determined that there had been 4,393 abnormal cases in their group by IR imaging, while a mammographic test would have been limited to only 1,028 cases with abnormal IR imaging. This would have achieved a cancer identification rate of 24.1 per 1,000 by incorporating both IR and mammographic tests as compared to the expected seven per 1,000 by mammographic test alone. He claimed that since IR imaging is a safe test, it could be applied to women with abnormal breasts who should be examined more frequently. They also attributed the same to mammography and other breast screening methods — IR imaging does not detect cancer, but only shows the existence of an irregularity. Spitalier *et al.*[45] examined 61,000 cases using thermography for a period of more than 10 years. They obtained 11% (89% sensitivity and specificity) for the false-negative and false-positive rates. They also could identify 91% of the non-palpable cancers which are Grade T0 or tumors smaller than 1 cm in size. They reported that thermography alone had the potential to identify the first signs of tumor growth in 60% of the cancer cases.[45]

Moskowitz[12] and Threatt[13] studied the sensitivity and accuracy of IR imaging with two small groups of 150 and 515 cases, respectively. Unidentified specialists analyzed the breast IR images in both groups. While Moskowitz eliminated incomprehensible images, data from Threatt's project showed that less than 30% of the images provided were acceptable, the rest being lower than set standards. Both of these projects did not produce any worthwhile findings, though this could be resulted from the lack of standard screening approaches and protocols. Haberman *et al.*[16] utilized thermography and a physical test in a unique project incorporating 39,802 subjects imaged over a three-year term. They recorded 85% sensitivity and 70% specificity for thermography. They cautioned that their determination of thermographic specificity may not be reliable as it is common knowledge that a long period of observation (eight to 10 years or more) is required to obtain a true false-positive rate. Gros and Gautherie conducted a large-scale project with 85,000 subjects imaged. They demonstrated 90% sensitivity and 88% specificity for thermography.[46,47] Jones[19] performed a large-scale multicenter review using almost 70,000 subjects, and recorded false-negative and false-positive rates of 13% (87% sensitivity) and 15% (85% sensitivity), respectively, for thermography. In 1986, Usuki[17] accomplished a project on the role of thermographic observation in breast cancer recognition. He recorded 88% sensitivity for thermography in the detection of breast cancers. Parisky *et al.*[48] documented a four-year project utilizing IR imaging to determine mammographically questionable cases. They studied 875 biopsied cases — 187 malignant and 688 benign.[48] In a study, Nyirjesy *et al.*[20] made a comparison between physical examination, mammography, and thermography for identifying breast cancer. They worked with three groups: 4,716 cases with proven carcinoma, 3,305 cases with histologically identified benign breast disease, and 8,757 normal cases. They also compared between physical examination and mammography to other famous works including the National Cancer Institute (NCI)-sponsored Breast Cancer Detection and Demonstration Projects (BCDDPs). Here, physical examination had an average sensitivity of 75% for identifying all kind of tumors and 50% in cancers smaller than 2 cm in size. This rate is particularly good when analyzing other studies with sensitivity between 35% and 66%. Mammography was observed to achieve an average of 80% sensitivity and 73% specificity. Thermography had an average sensitivity of 88% (85% in tumors smaller than 1 cm in size) and specificity of 85%. An irregular thermogram was discovered to have a

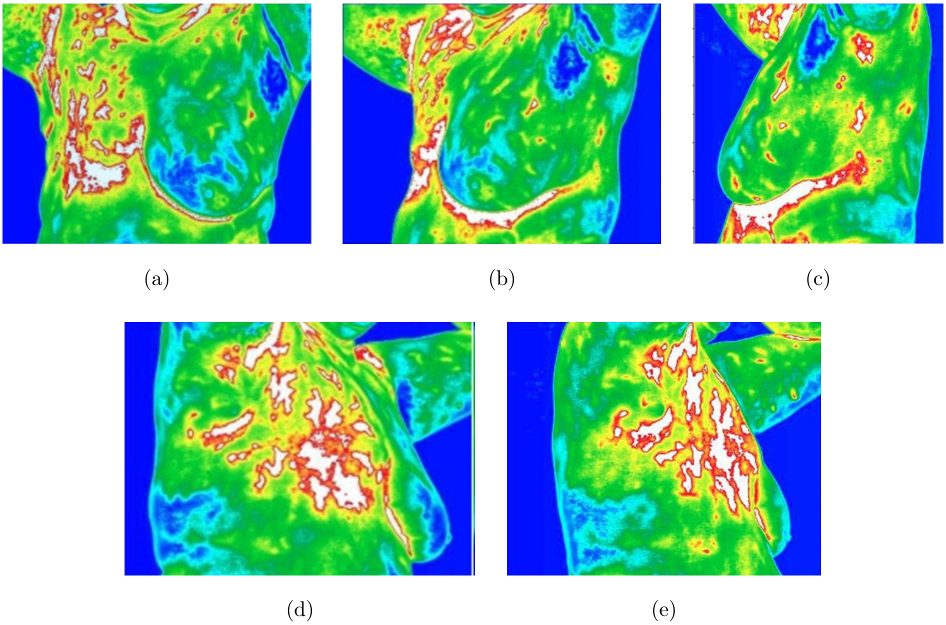
94% predictive value. They concluded that none of the methods available for imaging of breast carcinoma and cases with breast-related symptoms are adequately accurate to be applied alone. Utilizing a multimodal approach has had the best outcomes. In a group of 4,000 approved breast cancer patients, Thomassin *et al.*[49] observed 130 carcinoma cases ranging in diameters of 3 to 5 mm. Both mammography and thermography were utilized alone and in combination with 130 cancers — 10% of the cases were identified by mammography, 50% by thermography, and 40% by both methods. In other words, there was a thermal sign in 90% of the cases and it was the only sign in 50% of the cases. From 1967 to 1998, in an examination over 15 large-scale projects, IR imaging of the breast has indicated an average sensitivity and specificity of 90%. In the past decade with advanced technology in IR imaging, some works are indicating even higher sensitivity and specificity rates.[3]

4. Principles of Infrared Imaging

All objects with a temperature above absolute zero (-273 K) emit IR radiation from their surface. More details on the basics of infrared principles are provided in Ref. 3. Human skin emits IR radiation essentially in the range of 2–20-μm wavelengths and with an average peak at 9–10 μm. The skin is the most substantial part of the human body and helps to manage the core body temperature. Both the physiological processes and thermal properties of skin are acted upon a variety of factors.[50,51] The work on the heat exchange processes of the body from the deep tissues to the skin and afterwards to the surroundings may reveal information on pathology.[52–57] Heat transport activity of the skin and physiology of thermal features have been investigated.[58–60] The application of thermography for different prospects in conjunction with its advantages as a recognition method are explained in Refs. 61–65. Nevertheless, several variables can disrupt IR imaging precision, and are elaborated in Refs. 61, 64, and 66. Disease, alcohol consumption, regular cigarette smoking, heavy powdering on the chest, hormone replacement therapy (HRT), pregnancy and menstruation, and some other factors can also influence breast surface temperature (discussed in Refs. 62, 67–75). There are several projects with regards to the pathological understanding of IR screening.[77–83] Generally, proper protocols involving equipment considerations, preparation of the patient, examination environment, and standardization of the thermal imager system are important factors.[80,84–89] In addition, image capture protocol (ICP) is included in Refs. 90 and 91.

5. Imaging Protocol

The real process of imaging is recognized with the purpose to adequately identify IR emissions from the relevant surface regions of the breasts. A minimum set of images is required in order to attain a satisfactory scope with mammography. The set of breast IR images consists of five images: one front view, two side views, and two oblique views, which capture the whole chest, underarms, and lymph region. The bilateral frontal view acts as a scout image to give a standard representation of the



(a) (b) (c) (d) (e)

Fig. 1. Breast infrared imaging in the Seied Shohada Hospital in Isfahan (one mastectomy case). (a) Frontal view, (b) oblique view (left breast), (c) side view (left breast), (d) oblique view (right breast), and (e) side view (right breast).

two breasts. The subject sets "proceeding" to "screening," facilitating adjustment to the surface regions to help imaging. Then, she is positioned in a seated or standing manner at the time of the adjustment. In the seated position, the subject puts her arms on the arm rests, away from the body to allow for the required adjustment. When the subject positions herself in frontal of the camera, a swivel chair may be utilized or she may be on her feet for certain aspects. For example, images of one mastectomy case, which are provided from the Seied Shohada Hospital in Isfahan, are shown in Figs. 1(a)–1(e).

6. Image Interpretation

The Marseille System of classification provides standard criteria for rating breast thermography images. The images are recorded on a scale of TH-1 to TH-5.[92] Sample images are shown in Figs. 2(a)–2(e). The scale of TH-1 to TH-5 are explained as follows:

(1) TH-1: Normal regular nonvascular,
(2) TH-2: Normal regular vascular,
(3) TH-3: Watchful tissue function with higher heat spots,
(4) TH-4: Abnormal tissue function, and
(5) TH-5: Severely abnormal tissue function.

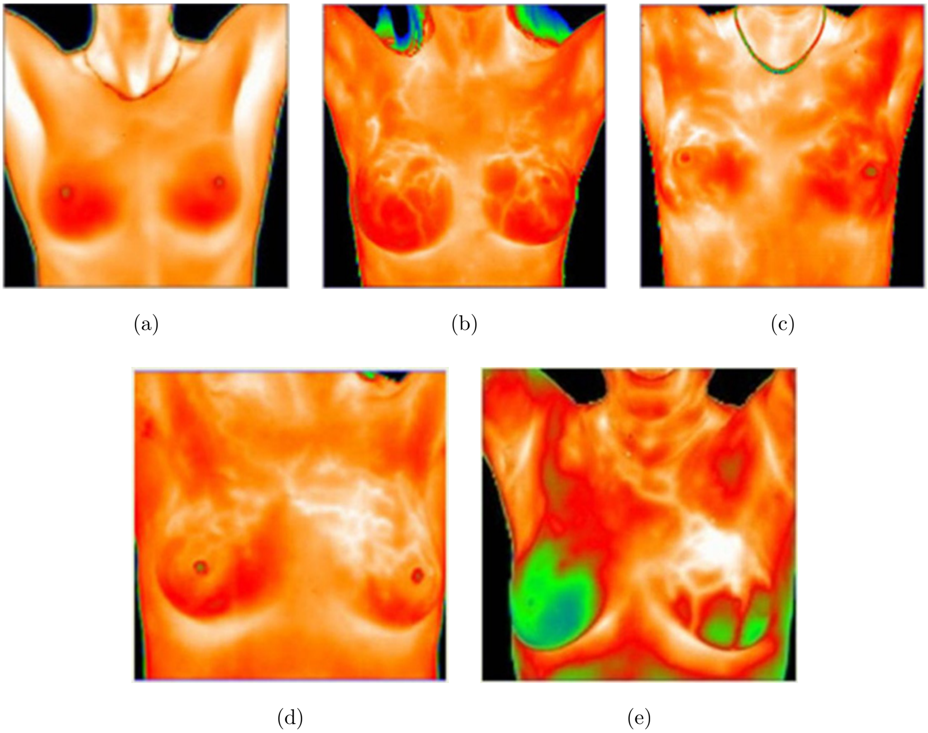


Fig. 2. Different samples for the scale of TH-1 to TH-5. (a) TH-1, (b) TH-2, (c) TH-3, (d) TH-4, and (e) TH-5.[92]

7. Intelligent Image Processing Approaches to Infrared Images

Computer-aided diagnosis (CAD) has been playing an important role in the analysis of IR images for many years. Nevertheless, in CAD, human analysis of images is often affected by various factors such as lethargy, absent-mindedness, and carelessness. The accuracy of detection is also restricted by the limitations of the human visual system. In addition, a shortage of trained radiologists perpetuates the error rate of CAD approaches. Recently however, studies on intelligent image processing approaches on IR images enhance the detection accuracy in three areas: intelligent image enhancement and restoration techniques, asymmetry interpretation of the images, and feature extraction and classification.

7.1. *Intelligent image enhancement and restoration algorithms*

The lack of high resolution in thermograms as a result of blurriness accumulated by a great amount of noise is one of the challenges of IR imaging. An algorithm has been proposed by Snyder *et al.*[68] to enhance the efficient resolution of thermograms by a 2:1 ratio, and at the same time, removing noise and holding boundaries in the image.

This algorithm allows techniques of blur, noise, and image correlations to attain an optimal estimate of the disregarded pixels, which is depended on a minimization approach, termed mean field annealing. The enhancement of resolution of IR images has been attempted through another method by an MIT researcher. IR light was connected with an intravenously injected dye and a special computer software to provide a clear, high-contrast image that could help doctors to identify breast lesions and diagnose if tumors are benign or malignant. This was applied by the minimally invasive optical biopsy system created at MIT. Kakuta *et al.*[70] fashioned a "human thermal model" such that IR images provided under various requirements can be analyzed through the normalization of the skin surface temperature to eliminate the result of different thermal surrounding requirements. The model was dependent on a numerical calculation of bio-heat transfer equations and a 16-cylinder-segment model functioned as the geometry of the human body. The application of active dynamic thermography (ADT) for additional improvements of the image condition was introduced by Kaczmarek and Nowakowski. Their ADT analyzed thermal transients after the application of external thermal excitation.[72] Some primary outcomes have indicated the promise of that method. Dynamic thermography is another approach recently introduced to better appreciate IR images. As a consequence of the interference from complex vascular architecture and the presence of tumors, in breast cancer identification, investigators have proposed to observe the thermal recovery process after the presentation of cold stress by consecutive thermography or by digital subtraction thermography. In addition, Ng *et al.*[37] presented a method to segment breast thermograms and extract useful regions from the background. Studies have shown an increase in the sensitivity of breast imaging.

7.2. *Asymmetry interpretation*

Radiologists routinely compare two contralateral images. Small asymmetries may demonstrate a watchful region when the images are nearly symmetrical. Adversely, these small unbalances may not be easy to identify and hence, it is valuable to design an automatic method to eliminate human factors. There have been a few articles discussing the techniques for the asymmetry interpretation of mammograms. The asymmetric anomalies in IR images have been evaluated by Head *et al.*[18] First, the image is segmented by an operator, then breast quadrants are derived automatically depending on the unique point of reference, or the chin, the lowest, rightmost, and leftmost points of the breast. An automatic method by Qi *et al.*[85] was presented for the asymmetry interpretation of IR images. In this method, an automatic segmentation and pattern classification are involved. The four feature curves that can singularly partition the left and the right breasts are derived by utilizing Hough transform. The feature curves consist of the left and the right body edges curves, and the two parabolic curves showing the lower edges of the breasts. A computerized thermographic system, which provides images of the allocation of temperature differences between the impressed side and the contralateral normal side was presented by Mabuchi *et al.*[93] The system shows the body surface temperature of each pixel in the impressed region, and that subtracted from the body-surface temperature of the correlated pixel in the symmetrically located contralateral normal region to produce the difference in images through the absence of any absolute skin surface temperatures. Comparison of the thermal profiles of two contralateral breasts was achieved by Etehadtavakol *et al.*[26] They computed mutual information of two breasts and showed that the more similar the thermal image of right breast to the thermal image of left breast, the closer the normalized mutual information value is to one. The mutual information is a good measure of nonlinear correlation. In this study, they used nonparametric windows which incorporated an interpolation model that enhanced the resolution to a highly over sampled image.

7.3. *Feature extraction and classification*

On top of segmentations, various features can be derived from the sections. According to updated pattern recognition approaches, irregularities can then be identified. Therefore, feature extraction is greatly crucial to the application of CAD. Kuruganti and Qi[94] demonstrated that high-order statistics (e.g., variance, skewness, and kurtosis) and joint entropy are essential features to recognize irregularities, and low-order statistics (e.g., mean) and entropy are not as useful in irregularities identification. Furthermore, the significance of employing statistical parameters (1st and 2nd orders) in deriving thermal signatures for asymmetry interpretation were discussed by Jakubowska *et al.*[95] A new model shift that was introduced by Szu *et al.*[81] employs at least two dual-band (mid and long) IR imaging cameras operating together on the patient. A smart brain-like neural network algorithm, the Lagrange constrained neural network (LCNN), was used to achieve sub-millimeter scaling of the close-up breast imaging for the vascular, angiogenic, as well as stage-zero detection of ductal carcinoma *in situ*.

The transition of automatic target recognition (ATR) algorithms from military application to medicine is crucial in this area, and was given the term "from tanks to tumors."[96] The rich collection of ATR algorithms that the military has provided has greatly advanced the progress of CAD. Moreover, an upgraded approach, which is a multipronged method consisting of linear regression (LR), radial basis function network (RBFN), and receiver operating characteristics (ROC) was introduced by Ng *et al.*[97] It is a new and combinatorial method which can be applied to determine elaborated and large numerical data.

Color segmentation of IR thermal images is a critical aspect in identifying tumor regions. The cancerous cell with angiogenesis and inflammation emits temperature architecture different from a normal cell. Two color segmentation methods, K-means and fuzzy c-means for color segmentation of IR breast images were modeled and compared by Etehadtavakol *et al.*[25] As a result of the fuzzy nature of the IR images, the fuzzy c-means method provides more precise outcomes to segment IR images. Cancer is usually described as a chaotic, imperfectly regulated process. Etehadtavakol *et al.*[28] applied fractal dimension to determine the possible difference between malignant and benign architectures in breast IR images. Their numerical experimental findings validated theoretical concepts and showed a considerable difference in the fractal dimensions between malignant and benign cases, with the fractal dimensions for benign cases close to 1, while those for malignant cases considerably greater. Furthermore, Etehadtavakol *et al.*[29] introduced a novel approach using the nonlinear chaotic dynamical system theory to estimate Lyapunov exponents to identify the possible differences between malignant and benign patterns.

8. Conclusion

In the medical fieldm, IR imaging is not a new technique. The potential of this technology has been favorably recognized and acknowledged since 1959, but the undeveloped technology of the IR camera was inadequate, which caused some early researches to be derided. The improvement of the quality of camera over the years is responsible for the increased usage of IR imaging as a tool for recognition that provides images of skin temperatures. The skin surface temperature is however mostly dependent on both skin blood perfusion and surrounding conditions. There is also a requirement for IR images to be applied in an unchangeable environment with minimal environmental conflict to provide accurate results.

This review paper evaluates the clinical fulfillment of IR for breast imaging and its determining operating requirements such as the minimization of surrounding IR conflicts and being free of draft and direct airflow. Breast thermography has attained an average sensitivity and specificity of 90% from the last 15 years of satisfying the standardized thermographic interpretation protocols by proper IR trained personnel as recorded in the literature. An irregular thermogram is regarded as a considerable biological risk marker for the presence or as a promoter of the growth of breast tumors.

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