Basal cell carcinoma (BCC) is a form of skin cancer originating from the basal cell layer of the epidermis and associated follicular structures. It is the most common human cancer, accounting for 25% of all cancer cases and 75% of skin malignant neoplasms diagnosed in the United States.1 More than 2 million new nonmelanoma skin cancers are estimated to have been diagnosed in United States in 2014.2 Basal cell carcinomas are diagnosed primarily by clinical evaluation. Furthermore, an increasing number of clinicians are being trained in the art of dermoscopy to aid in the diagnosis of early tumors. The definitive diagnosis has always been provided by a skin biopsy followed by sample preparation and histopathologic examination.

Advances in optical imaging and spectroscopy technologies raise the possibility of performing rapid and noninvasive light-based histopathologic examination, a pain-free process that would be appreciated by patients and reduce the time from consultation to treatment. Therefore, technologies such as conventional optical coherence tomography (OCT),3,4 high-definition OCT (HD-OCT),5-7 reflectance confocal microscopy (RCM),8-15 multiphoton microscopy (MPM),16,17 fluorescence lifetime microscopy (FLIM),13,18 and multimodal spectral approaches19 have been investigated for their applicability for diagnosis of skin cancer, including BCC. Each of these techniques has strengths and limitations that at present make them complementary.

Both OCT and HD-OCT have the benefit of deeper penetration (several hundreds of microns) compared with the microscopy techniques. However, although HD-OCT offers improved resolution compared with conventional OCT, it still proves insufficient in the assessment of the cellular morphologic characteristics in tumor nests, which is important for accurate diagnosis of BCC. The microscopy laser-scanning tech-
In vivo multiphoton microscopy of basal cell carcinoma

Multiphoton microscopy selectively visualizes the cellular and extracellular matrix based on 2-photon excited fluorescence (TPEF) from NADH, FAD, melanin, keratin, and elastin fibers and on second-harmonic generation (SHG) from collagen fibers. Although the resolutions of RCM and MPM are comparable, MPM’s contrast mechanism seems to favor visualization of certain cellular tissue structures. The cellular structures inside the BCC tumor are of interest and particularly discussed in this study. Multiphoton microscopy has been used in pilot studies on ex vivo and recently on in vivo imaging of BCC, but the BCC tumor nests were either not shown as being imaged or their cellular structure was not resolved.

In this study, we sought to assess the ability of the MPM to visualize the BCC tumor nests and their cellular structure. Compared with the previous pilot study, this work was facilitated by using a recently developed clinical multiphoton tomograph (MPTflex; JenLab GmbH). This is the successor model of JenLab’s DermalInspect system. It is a portable instrument with an articulated arm, which allowed us to image lesions on different parts of the body rather than being limited to lesions on the extremities.

Methods

Patients
This study included 10 BCC lesions imaged in 9 patients, the diagnoses of which were subsequently confirmed by standard histologic examination. Lesions that were hyperkeratotic, crusted, or ulcerated and those that had previously been biopsied were excluded. The topographic location and pathologic characteristics of each case are summarized in the Table. All in vivo measurements were conducted according to an approved institutional review board protocol of the University of California–Irvine (HS No. 2011-8494) with written informed consent obtained from all patients. Patients were compensated for their participation.

MPM-Based Clinical Tomograph MPTflex
Multiphoton microscopy is a laser-scanning microscopic technique that relies on nonlinear light-matter interactions, such as TPEF and SHG to achieve 3-dimensional submicron resolution images. The histopathologic characteristics of BCC are related to the presence in the dermis or at the dermoeidermal junction of islands of basaloid cells, often showing palisading in the peripheral cell layer. The BCC tumor islands are referred to as “dark tumor islands,” “phantom islands” or “dark silhouettes” in RCM imaging. This has been shown to lead to misdiagnosis of BCC by RCM. Correct diagnosis of BCC requires an accurate assessment of both cellular morphologic characteristics inside the tumor nests as well as a low-power view of the nests overall.

Multiphoton microscopy selectively visualizes the cellular and extracellular matrix based on 2-photon excited fluorescence—RCM, MPM, and FLIM—have the ability to produce submicron resolution images. They are based on different contrast mechanisms, which is reflected in their capability to distinguish particular molecular compounds in the images. Among these techniques, FLIM, the contrast mechanism of which is based on differences in the fluorescence lifetime of different biomolecules in tissue, is the most efficient in distinguishing different endogenous fluorophores, such as bound and free components of nicotinamide adenine dinucleotide (NADH) and flavin adenine dinucleotide (FAD), keratin, melanin, porphyrin, elastin, and collagen. Distinguishing bound from free NADH-FAD is key in studying potential disease biomarkers related to cellular metabolism. To date, this technique has been explored only in ex vivo imaging of BCC in human skin. Unlike FLIM, RCM is not able to distinguish different tissue fluorophores because its contrast mechanism is based on variation of tissue refractive index. In this technique, the light focused and raster-scanned on the skin surface is reflected and, on detection, reconstructed into a gray-scale image. Stacks of images are acquired at progressive depths in skin by adjustment of focus. This is a simple and efficient technique for obtaining 3-dimensional submicron resolution images of skin, but it has the disadvantage of not distinguishing among different tissue fluorophores. Generally, gray-scale images are sufficient for the overall assessment of the tissue structure, but in some cases, owing to its contrast mechanism, certain cellular structures, such as those inside the BCC tumor nests, are difficult to distinguish by RCM, and other criteria are usually introduced for BCC diagnosis.

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Table. Location of the Lesions, Pathologic Diagnosis, and MPM Morphologic Features of BCC

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Location</th>
<th>Pathological Diagnosis</th>
<th>Morphologic Features</th>
<th>Parallel Collagen and Elastin Bundles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Nests of Basaloid Cells</td>
<td>Elongated Tumor Cells</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>in the Papillary and/or Upper Dermis</td>
<td>Aligned in 1 Direction</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Thigh</td>
<td>SBCC</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>Shoulder</td>
<td>SBCC + NBCC</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>Arm</td>
<td>SBCC</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>Shoulder</td>
<td>SBCC</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>Back</td>
<td>SBCC</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>6</td>
<td>Back</td>
<td>NBCC</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>7</td>
<td>Face</td>
<td>MNBCC + NBCC</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>8</td>
<td>Leg</td>
<td>SBCC</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>9</td>
<td>Arm</td>
<td>SBCC + NBCC</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>10</td>
<td>Arm</td>
<td>SBCC</td>
<td>+</td>
<td>–</td>
</tr>
</tbody>
</table>

Abbreviations: BCC, basal cell carcinomas; MNBCC, micronodular BCC; MPM, multiphoton microscopy; NBCC, nodular BCC; SBCC, superficial BCC; +, present; –, absent.
In MPM, TPEF derives its signal from various sources, including NADH, FAD, keratin, melanin, and elastin fibers, whereas SHG is used to visualize collagen fibers. It is important to note that these contrast mechanisms rely on the intrinsic optical properties of endogenous tissue biomolecules without using specific fluorescent labels.

In this study, we used an MPM-based clinical tomograph (MPTflex) for imaging of BCC lesions in human skin. This system, as shown in Figure 1, consists of a compact, turn-key femtosecond (fs) laser (MaiTai Ti:Sapphire oscillator, sub-100 fs, 80 MHz, tunable 690-1020 nm; Spectra Physics), an articulated arm with near-infrared optics, and beam-scanning module. The imaging head includes 2 photomultiplier tube (PMT) detectors used for parallel acquisition of TPEF and SHG signals. Owing to the high sensitivity of the detectors, the images were acquired in a darkened room. A customized metallic ring taped on the patient’s skin attaches magnetically to the objective holder in the articulated arm, minimizing motion artifacts. The excitation wavelength used for this study was 790 nm. The TPEF signal was detected over the spectral range of 410 to 650 nm, whereas the SHG signal was detected over a narrow spectral bandwidth (385-405 nm) through emission filters placed in the TPEF and SHG detection channels, respectively. We used a Zeiss objective (40×, 1.3 numerical aperture, oil immersion) for focusing into the tissue. The laser power used was 5 mW at the surface of the skin and up to 30 mW in deeper skin layers. The articulated arm of the clinical tomograph allows imaging of almost any part of the body. However, some areas in proximity of the eyes, nose, or ears are still difficult to image.

**Study Design**

We acquired the MPM images using 2 scanning modalities: The first modality was x-y scanning, resulting in z-stacks of horizontal images from the stratum corneum to the dermis. The z-stacks were obtained by moving the objective in the z-direction, thus scanning at different depths in the skin. The field of view for each optical section was about 200 × 200 μm². Typically, we set a step of 5 μm between the optical sections. Because the optical section is limited to a small scan field, the overall investigation of the lesion required the acquisition of several image stacks of different skin sites. We acquired about 3 image stacks for each lesion. The second modality was x-z scanning, resulting in cross-sectional, “histology-like” images from the stratum corneum to superficial dermis.

The x-y sections were 512 × 512-pixel images acquired at approximately 6 seconds per frame. The x-z sections were 1024 × 1024-pixel images acquired at approximately 30 seconds per frame. Owing to time constraints, we did not acquire x-z sections for all the lesions. This did not influence the results, however, because, the MPM features were clearly identified in the horizontal sections. For the same reason, we did not acquire images of normal skin adjacent to the lesion. Certainly, this would be necessary if the lesion margins are assessed, but this was not the purpose of our study.

Multiphoton microscopy imaging was performed in vivo prior to biopsy. All lesions suspected to be BCC through clinical dermatologic assessment were biopsied and diagnosed using standard hematoxylin-eosin histopathologic protocol.

**Results**

Nine patients with a total of 10 BCCs underwent imaging shortly before excisional surgery. The histopathologic features of these lesions are listed in the Table and included superficial, nodular, and micronodular BCCs. The main histopathologic findings were nests of basaloid cells extending along the dermoeidermal junction into the papillary dermis (superficial BCC) and various-sized nests invading the reticular dermis (nodular and micronodular BCC). The main MPM features associated with these lesions included (1) nests of basaloid cells present in the papillary and upper reticular dermis, some of which showed palisading in the peripheral cell layer; (2) elongated tumor cells in epidermis aligned in 1 direction; and (3) parallel collagen and elastin bundles surrounding the tumors. A summary of the MPM features found in each lesion is presented in the Table. The morphologic MPM features and the routine histologic findings corresponding to 3 of the 10 lesions are illustrated in Figures 2, 3, and 4). In addition, MPM images and histologic findings corresponding to a micronodular BCC lesion are presented in the eFigure in the Supplement.
Representative MPM images corresponding to 1 of the lesions are shown in Figure 2. A nest of basaloid cells can be seen in both horizontal sections (x-y scan) and the corresponding cross-sectional (x-z scan) images. Particularly in this lesion, the mucinous stroma adjacent to tumor was visualized with MPM. In the standard hematoxylin-eosin–stained histologic appearance, the stroma frequently shows retraction from the tumor islands because mucin shrinks during the process of fixation and dehydration of the specimen, so that the tumor islands appear partially or completely detached from the surrounding dermis. The arrowheads in the images of Figure 2 indicate the mucin adjacent to tumor in the MPM images and its appearance as retraction from tumor islands in the histologic section. Histologic examination revealed palisading in the peripheral cell layer. This image represents a z-projection of 3 consecutive images (3-μm step) for an increase in the depth of field and better visualization. E, MPM image of the same nest in a deeper layer (arrowheads) (z = 130 μm). F, Hematoxylin-eosin–stained histologic section of the lesion; original magnification ×40. Both the MPM and the histologic images show a mucinous stroma adjacent to the tumor mass (case 2). B-D, Arrowheads indicate mucinous stroma.
logic section. The MPM images of this lesion show tumor elongated cells aligned in 1 direction (Figure 3B). Palisading of the peripheral layer was present in the MPM images of the BCC nests of this lesion (Figure 3D).

Figure 4 shows the MPM images and the routine histologic findings corresponding to another lesion. The MPM images show the third feature we observed in this study: parallel bundles of collagen surrounding tumor masses, along with palisading of the peripheral cell layer, and tumor cells aligned in 1 direction. The bright cells in Figure 4D and E are most likely melanophages.

Discussion

In this study, we evaluated the potential of MPM to be used as a noninvasive in vivo imaging tool for the immediate and rapid diagnosis of BCC.

The main feature identified in all lesions by MPM imaging was the presence of nested groups of basaloid cells in the papillary and upper reticular dermis. Some of these nests showed palisading at the peripheral cell layer. This feature correlated well with the standard hematoxylin-eosin–stained histologic appearance of near-matching locations. Basal cell carcinoma tumor nests have been previously imaged with various optical imaging techniques.3–7,9,13–18 The morphologic structures inside the tumor nests were clearly observed only in 2 reported studies13,18 on ex vivo imaging of BCC in human skin using FLIM. Our study shows that in vivo MPM imaging can resolve the cellular structure inside the tumor nests corresponding to BCC lesions that include superficial components. This is important because the presence of nests of basaloid cells at the dermoeidermal junction and/or in the dermis is the main histopathologic criterion for BCC diagnosis.20 Therefore, this feature can be potentially used as a criterion for BCC diagnosis with MPM imaging. It still remains challenging to resolve the cellular structure of deeper nests, such as ones found in micronodular BCC (eFigure in the Supplement), but this needs to be investigated in an extended study to include a larger number of nodular and micronodular BCC lesions.

Elongated cells, oriented in 1 direction in the epidermis, have been previously identified in BCC lesions by in vivo RCM8,10,11,13,14 and ex vivo MPM imaging,13,16 although in the latter study16 this was present in only 1 of 6 tumors. This feature has traditionally been considered an RCM criterion for in vivo diagnosis of BCC because it was identified with high sensitivity and specificity in these lesions.10 While in some studies the elongated cells, oriented in 1 direction are regarded as BCC tumoral cells8,13 or BCC tumoral palisading,10 in others, they were referred to as keratinocytes and most likely regarded as epidermal response to underlying BCC.13,16 In this study, we imaged elongated cells oriented in 1 direction in 4 of 10 lesions. All these lesions were superficial BCCs or nodular BCCs with superficial components. We believe that the presence of elongated cells oriented in a single direction can be explained as appearing only in those BCCs that are superficial enough to be imaged in the epidermis and not, as previously stated,13,16 to be a specific (pathognomonic) feature present in the overlying epidermis of underlying BCCs. If present, elongated cells are related to the palisading of the peripheral cell layer in the intraepidermal BCC nests of basaloid cells. Nevertheless, in 1 of the 4 lesions, the elongated cells oriented in a single direction were present in very superficial layers of the epidermis (Figure 3B). The standard hematoxylin-eosin–stained histologic appearance corresponding to this lesion did not show the presence of this feature in the upper epidermal layers. However, the sampling of heterogeneous tumor will inevitably be somewhat imprecise when attempting to correlate with standard histologic appearance. Horizontal rather
than vertical hematoxylin-eosin-stained sections might be more effective in correlating this phenomenon provided by MPM imaging with histologic appearance.

It is well established that islands of tumor are surrounded by a proliferating connective tissue stroma, which is arranged in parallel bundles surrounding the tumor masses so that a relationship seems to exist between the tumor and its stroma. We found this interesting feature in 5 of the 10 BCC lesions imaged. Parallel bundles of collagen and elastin around the tumor masses have been previously noted in an RCM imaging study of BCC lesions. In a previous study, the tumor-induced stroma of BCC was associated with the superficial subtype of this tumor. However, in our study, this feature did not indicate a predilection for a particular subtype. Stroma morphologic characteristics of BCC lesions should be further investigated in future studies with larger number of patients.

In this study, we demonstrate that MPM is capable of imaging in vivo tumor nests in BCC lesions of superficial and nodular types along with other features that may be specific to BCC. The MPM imaging was able to visualize the cellular structure inside the tumor nests of BCC lesions that included superficial components. These results provide the groundwork for a future study with a larger number of patients that would assess MPM imaging sensitivity and specificity for in vivo noninvasive BCC diagnosis. One might foresee 2 major technical limitations in performing such a study. In this early stage of MPM clinical translation, limited field of view (about 250 \( \times \) 250 \( \mu \)m\(^2\)) and penetration depth (about 200-300 \( \mu \)m) are the main technical challenges. High penetration depth is important for imaging tumor nests that are far from the dermoeipidermal junction in the dermis, as is often the case for nodular BCC. One way to increase penetration depth is implementing dispersion compensation to decrease the laser pulse duration, but the gain would be limited. Nevertheless, MPM imaging of tumor nests in several nodular BCC included in this work shows great promise. Scanning large areas of the lesions is important to avoid false-negative diagnoses because lesions are often nonuniform, presenting focal dysplasia and/or malignant neoplasm. The field of view can be increased by implementing a mosaic feature (acquisition of adjacent fields of view) or by redesign of the optical components. This technical limitation is being addressed, and implementation has been initiated in a newly developed instrument.

Conclusions

This study demonstrates, in a limited patient population, that noninvasive in vivo MPM imaging can provide label-free contrast that reveals several characteristic features of BCC lesions. Future studies are needed to validate the technique and correlate MPM performance with histopathologic findings.


NOTABLE NOTES

Remembering Dr Walter Burgdorf

Leonard J. Hoenig, MD

And therefore never send to know for whom the bell tolls; it tolls for thee. John Donne

Dermatology has suffered a great loss, as did all of us, with the passing of Dr Walter H. C. Burgdorf (1943-2015). He was a pioneer in dermatopathology and one of medicine’s finest teachers. Dr Burgdorf published numerous articles on dermatology and edited the English editions of Braun-Falco’s Dermatology and Pantheon of Dermatology, among other books.

His professional accomplishments are simply too impressive to cover in this short tribute. Rather, I will share with you some personal reflections about this most remarkable physician. For the past 3 years, it has been my privilege and honor to coauthor, with Dr Burgdorf, nearly 40 Notable Notes for JAMA Dermatology. This collection of essays is Dr Burgdorf’s special gift to dermatology, as it features his brilliant insights as a master teacher of the specialty. In these Notes, you will find Dr Burgdorf’s wisdom and charm as he covers all aspects of dermatology as they relate to the humanities.

Dr Burgdorf published articles at a frenetic pace. Every time we submitted a Notable Note, I thought I could relax, only to have Dr Burgdorf email me the next day with another proposed topic to develop. So it was back to work for both of us, but I enjoyed every minute of it.

Dr Burgdorf and I became online friends who developed a great respect for one another. When Pantheon of Dermatology was published, Dr Burgdorf wished to send me a copy, but the book was heavy and costly to ship from Germany. So Dr Burgdorf, on his next trip to the United States, carried the book with him and mailed it to me on his arrival. That was Wally! A good friend with a big heart.

What impressed me about Dr Burgdorf was his dedication to writing about and honoring the great teachers of dermatology who have inspired us and pioneered the profession. It is most fitting that we now honor Dr Burgdorf for the same reasons.

Dr Burgdorf taught and lectured about the Holocaust and he, more than anyone else, documented the fate of German Jewish dermatologists during World War II. His final article, to be published in Clinics in Dermatology, will tell the story of Hungarian Jewish dermatologists during the Nazi era.

Yes, dermatology has suffered a great loss with the passing of Dr Burgdorf. But at the same time we are grateful for all that he has left us. Future students of dermatology will continue to learn from his many publications. And perchance, when they come across the Notable Notes that bear his name, they will appreciate what a wonderful person Dr Burgdorf truly was: a man who exemplified what it means to be a good physician who is first and foremost a good human being.

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