

Hybrid Convolution Kernel: Optimized CT of the Head, Neck, and Spine

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OBJECTIVE. Conventional CT requires generation of separate images utilizing different convolution kernels to optimize lesion detection. Our goal was to develop and test a hybrid CT algorithm to simultaneously optimize bone and soft-tissue characterization, potentially halving the number of images that need to be stored, transmitted, and reviewed.

MATERIALS AND METHODS. CT images generated with separate high-pass (bone) and low-pass (soft tissue) kernels were retrospectively combined so that low-pass algorithm pixels less than –150 HU or greater than 150 HU are substituted with corresponding high-pass kernel reconstructed pixels. A total of 38 CT examinations were reviewed using the hybrid technique, including 20 head, eight spine, and 10 head and neck scans. Three neuroradiologists independently reviewed all 38 hybrid cases, comparing them to both standard low-pass and high-pass kernel convolved images for characterization of anatomy and pathologic abnormalities. The conspicuity of bone, soft tissue, and related anatomy were compared for each CT reconstruction technique.

RESULTS. For the depiction of bone, in all 38 cases, the three neuroradiologists scored the hybrid images as being equivalent to high-pass kernel reconstructions but superior to the low-pass kernel. For depiction of extracranial soft tissues and brain, the hybrid kernel was rated equivalent to the low-pass kernel but superior to that of the high-pass kernel.

CONCLUSION. The hybrid convolution kernel is a promising technique affording optimized bone and soft tissue evaluation while potentially halving the number of images needed to be transmitted, stored, and reviewed.

Selection of a CT convolution kernel determines the trade-off between image sharpness and pixel noise [1]. High-pass filter algorithms used in commercially available “sharp” convolution kernels—such as GE Healthcare’s proprietary bone or lung kernels, Siemens Healthcare’s proprietary higher numbered kernels (e.g., B70), or Philips Healthcare’s EC kernel—preserve higher spatial frequencies at the expense of greater noise and typically work best for tissues with inherently high CT contrast. Conversely, low-pass algorithms used in “smooth” convolution kernels—such as GE Healthcare’s standard kernel, Siemens Healthcare’s lower numbered kernels (e.g., B40), or Philips Healthcare’s B kernel—reduce the higher frequency contribution, decreasing noise and spatial resolution, and work best for tissues with inherently lower contrast, such as the brain or liver [2, 3]. Consequently, because most clinical examinations include tissues with both high and low

inherent contrast, it is often desirable to create at least two separate data sets utilizing different convolution kernels. Unfortunately, this increases the number of images needed to be generated, transmitted, stored, and reviewed by a corresponding factor of 2 or more. To address this problem, Schaller et al. [1] described a spatial domain-filtering algorithm for fast modification of the image sharpness–pixel noise trade-off. Although this algorithm provides the ad hoc ability to reduce the noise and spatial resolution of images generated with a high-pass convolution kernel, trade-offs exist, and the resultant images only approximate those prospectively created with routine low-pass convolution kernels.

Rather than develop a distinct algorithm to approximate routine clinical convolution kernels, we chose to combine well-established kernels in such a fashion as to directly duplicate within a single hybrid image the established tissue contrast that had been individually optimized for soft tissues or bone.

In so doing, we hoped to halve the number of images to be archived and reviewed without compromising or altering clinically established CT tissue contrast, thereby obviating a learning curve and facilitating comparison with conventional single-kernel images.

Materials and Methods

Subjects

Institutional review board approval with waived consent was obtained to retrospectively review de-identified shelf data and to test the proposed investigational algorithm. Subjects were not stratified by ethnicity, age, or sex. Selection was based solely on the presence of both high- and low-pass convolution kernels obtained at a similar slice location and plane thickness from retrospective clinical CT studies performed from September 14, 2006, through February 25, 2007. During this period, the vast majority of studies were reconstructed using only one kernel, and if two kernels were performed, the slice thickness was usually different. A total of 38 CT examinations were retrospectively reviewed using the hybrid technique, including 20 head, eight spine, and 10 head and neck (two orbit, two paranasal sinus, four posterior fossa, and two temporal bone protocols) cases.

Image Acquisition

CT examinations were performed on a 16-MDCT scanner (LightSpeed Pro, GE Healthcare) or 8-MDCT scanner (LightSpeed Ultra, GE Healthcare) with standard unenhanced clinical protocols. Images were generated with separate high-pass ("bone") and low-pass ("standard") kernels from the same slice locations and with the same slice thickness, typically 2.5 mm.

Image Processing

Corresponding images generated with high- and low-pass kernels were retrospectively combined so that low-pass algorithm pixels less than -150 HU or greater than 150 HU are substituted with corresponding high-pass convolution pixels. The resultant hybrid convolution kernel was generated in Matlab (Math Works) using the code below:

```
clear all;
serieID = dicomuid;
dirname = pwd;
imageNumber = input('Image number:','s');
imageNumber = str2num(imageNumber);
for i = 0:(imageNumber-1)
filehighpass = sprintf('%s%s%s%s',dirname,'\
HP_',num2str(i),'.dcm');
filelowpass = sprintf('%s%s%s%s',dirname,'\
LP_',num2str(i),'.dcm');
fileHCK = sprintf('%s%s%s%s',dirname,'\
HCK_',num2str(i),'.dcm');
```

```
dataHP = dicomread(filehighpass);
dataLP = dicomread(filelowpass);
n = find(dataLP > 874 & dataLP < 1174); %[-150
HU to 150 HU]
dataHCK = dataHP;
dataHCK(n) = dataLP(n);
figure(i+1),imshow(dataHCK,[]);
info = dicominfo(filehighpass);
info.SeriesInstanceUID = serieID;
info.SeriesNumber = 401;
info.SeriesDescription = 'Hybrid Convolution
Kernel';
dicomwrite(dataHCK, fileHCK, info);
end.
```

The reconstructed hybrid images were subsequently reimported into an eFilm Workstation 2.0 (Merge Technologies). Patient identification (name, medical record number, and birth date) and study acquisition data (date and time of study and kernel type) were removed from each image set, and a three-digit identifier was randomly assigned.

Analysis

Three blinded neuroradiologists with 24, 20, and 1 years of experience, respectively, independently reviewed all 38 cases (12 normal and 26 abnormal according to clinical dictation) on the eFilm workstation, comparing the three kernels (low-pass, high-pass, and hybrid convolution kernel) generated for each series. Using the autoalign by image location function, corresponding image sections were simultaneously viewed (paged through) in the manufacturer preset window settings for bone (width, 2,500 HU; level, 480 HU), head and neck (width, 350 HU; level, 90 HU), and brain (width, 80 HU; level, 40 HU) and with independently adjusted window and level settings. An additional intermediate setting (width, 800 HU; level, 200 HU) for spine cases was reviewed. The relative conspicuity of bone and soft-tissue anatomy and pathology was separately compared across the three kernels. Each kernel was subjectively rated against the other two, and its score against each was added (superior, score 1; equivalent, score 0; and inferior, score -1).

Results

For the depiction of bone, in all 38 cases, the three neuroradiologists scored the hybrid images as being equivalent to the high-pass (bone) kernel reconstructions (mean hybrid convolution kernel = mean high-pass kernel = 1.00 ± 0.00) but superior to the low-pass (standard) kernel (mean low-pass kernel = -2.00 ± 0.00). For depiction of extracranial soft tissues and brain, the hybrid kernel was rated equivalent to the low-pass kernel (mean hybrid convolution kernel = mean low-pass kernel =

1.00 ± 0.00) but superior to that of the high-pass kernel (mean high-pass kernel = -2.00 ± 0.00). Figures 1, 2, and 3 illustrate the dual optimized bone and soft-tissue depiction afforded by the hybrid kernel technique (middle column) in CT scans of the head, paranasal sinuses, and spine, respectively.

Discussion

Although the three raters were nominally blinded to the convolution kernel type, on the basis of typical imaging features, particularly noise versus spatial resolution, it was fairly obvious to the raters which convolution kernel was which as they paged through each case on the workstation at different window settings (Figs. 1–3). Consequently, related scoring bias cannot be excluded or readily mitigated.

The aforementioned hybrid technique is easily implemented, requiring only a few lines of code, and may have broader utility than shown in this investigation. For example, by substituting the high-pass (lung) convolution kernel for the high-pass (bone) kernel, the technique has recently shown promise for chest CT [4].

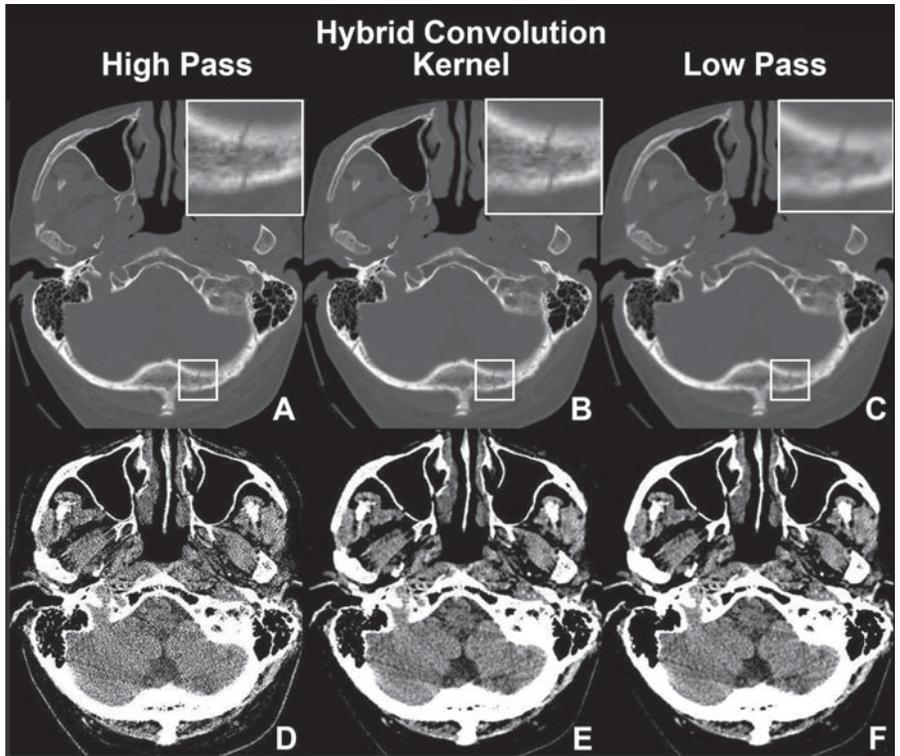
Although the algorithm was performed retrospectively off-line for this investigation, if manufacturers of CT scanners desire and if regulatory clearance is obtained, it could become an online processing option, allowing routine essentially real-time creation of such hybrid data sets without the need for single convolution kernel image generation. As such, radiologists would not have to choose between convolution kernels to limit image creation and storage.

An intermediate window setting for hybrid kernel display (e.g., spine: width, 800 HU; level, 200 HU) might permit simultaneous review of both bone and soft-tissue anatomy or pathologic abnormalities in a single image (Fig. 3), potentially halving the number of images to analyze while retaining the ability to apply more focused window adjustments where desired (e.g., toggling between intermediate, bone, and soft-tissue window settings).

The choice of convolution kernel can affect lesion conspicuity as well as measured Hounsfield units [2–7]. With the technique described, hybrid kernel tissues containing Hounsfield unit measurements between -150 and 150 HU should behave similarly to those generated with the low-pass standard algorithm, and tissues above or below this range should behave similarly to those generated with the high-pass bone algorithm. The conspicuity of lesions that overlap the boundaries of -150 or 150 HU, so that both low-pass and high-pass

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Fig. 1—From left to right, axial 2.5-mm section from unenhanced head CT scan generated with bone (high pass), hybrid (hybrid convolution kernel), and standard (low pass) convolution kernels and displayed with preset bone (top row: width, 2,500 HU; level, 480 HU) and brain (bottom row: width, 80 HU; level, 40 HU) window settings. For depiction of bone, raters judged **A** and **B** equivalent but superior to **C**. Note trabeculae and nondisplaced fracture of left occipital bone (square box with magnified inset) are less distinct in **C**. For depiction of soft tissue, raters judged **E** and **F** equivalent but superior to **D**. Note increased noise within brain and extracranial soft tissue (**D** vs **E** and **F**).



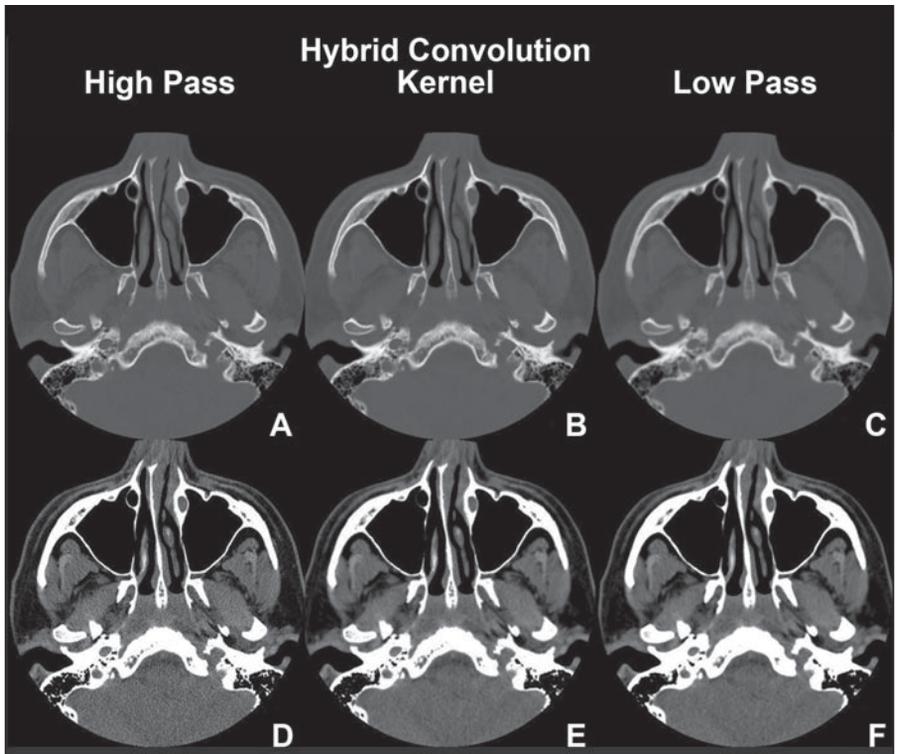
kernels will be applied to a single lesion, is less clear and may deserve further study.

When using the hybrid convolution kernel, a fine (single pixel) speckled rim can often be appreciated outlining the edges of

bone on magnified images viewed with narrow window settings (Fig. 3B), related to the higher spatial resolution and increased noise provided by the high-pass kernel incorporated in the hybrid algorithm. This

phenomenon is limited to bone edges and air interfaces. Although it is subtle and not evident in the subjective scorings of the three raters, it may be distracting to radiologists who are not familiar with this phenomenon. Con-

Fig. 2—From left to right, axial 2.5-mm section from unenhanced paranasal sinus CT scan generated with bone (high pass), hybrid (hybrid convolution kernel), and standard (low pass) convolution kernels and displayed with preset bone (top row: width, 2,500 HU; level, 480 HU) and soft-tissue (bottom row: width, 350 HU; level, 90 HU) window settings. For depiction of bone, raters judged **A** and **B** equivalent but superior to **C**. Note trabeculae are less distinct in **C**. For depiction of soft tissue, raters judged **E** and **F** equivalent but superior to **D**. Note increased noise within brain and extracranial soft tissue (**D** vs **E** and **F**).



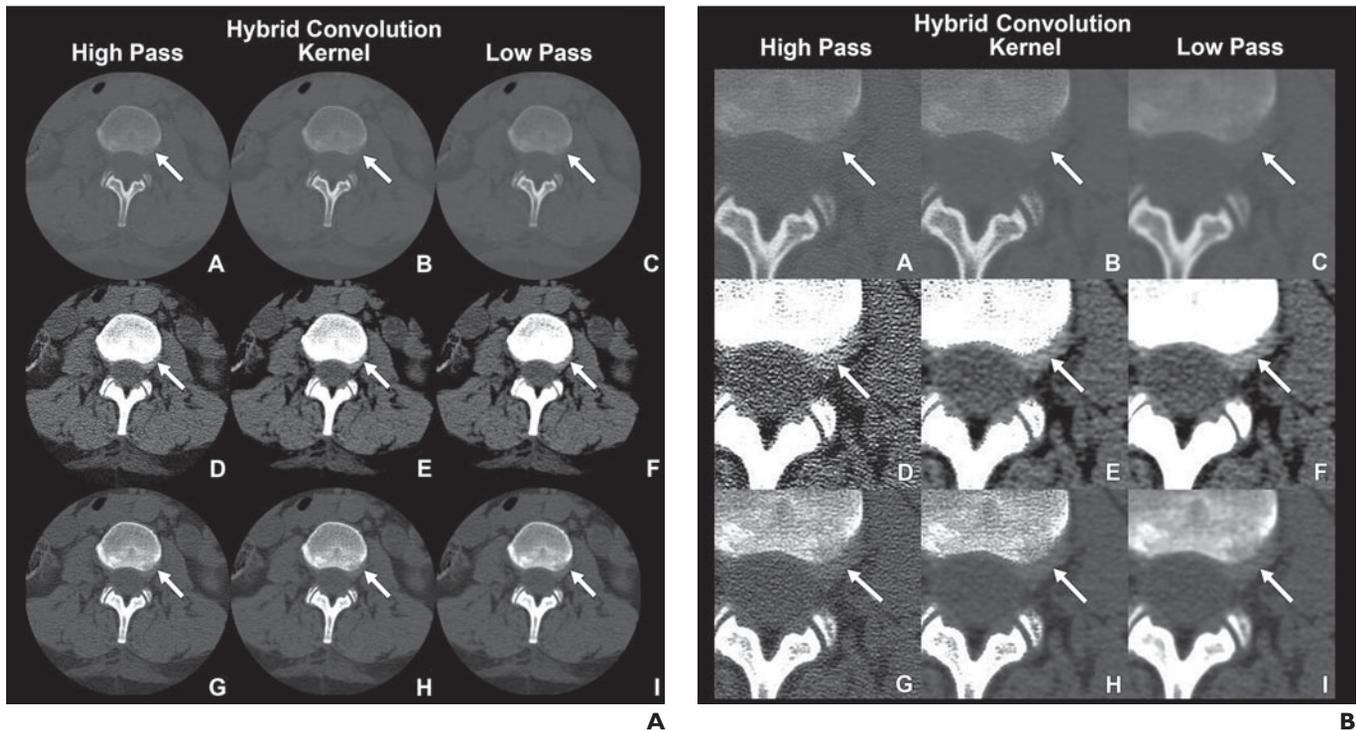


Fig. 3—From left to right, images at 100% magnification (**A**) and 300% magnification (**B**) of axial 2.5-mm section from unenhanced lumbar spine CT scan generated with bone (high pass), hybrid (hybrid convolution kernel), and standard (low pass) convolution kernels and displayed with preset bone (top row: width, 2,500 HU; level, 480 HU), soft-tissue (middle row: width, 350 HU; level, 90 HU), and intermediate (bottom row: width, 800 HU; level, 200 HU) window settings. For depiction of bone, raters judged high-pass and hybrid kernels equivalent but superior to low-pass kernels. For depiction of soft tissue, raters judged low-pass and hybrid kernels equivalent but superior to high-pass kernels. Note left foraminal disk herniation (*arrows*) and other soft-tissue structures appear noisier with high-pass kernel, whereas vertebral cortex and trabeculae are less distinct with low-pass kernel. In bottom row, where bone and soft tissue can be simultaneously assessed with intermediate window settings, hybrid convolution kernel image (**H**) was favored over high-pass kernel (**G**) because of less soft-tissue noise and was favored over low-pass kernel (**I**) because of greater trabeculae conspicuity. As best appreciated on magnified hybrid convolution kernel image displayed with soft-tissue window settings (**E**), fine (single pixel) speckled rim may be noted along bone edges but is not evident on low-pass kernel (**F**). This rim, however, was not thought to compromise soft-tissue evaluation.

versely, in certain cases where delineation between bone and soft tissue may otherwise be unclear, the speckled outline might potentially aid interpretation.

It should be noted that the hybrid convolution kernel algorithm was developed and tested in this study using two proprietary convolution kernels (bone and standard) from a single manufacturer (GE Healthcare). As such, results may not necessarily generalize across the scores of proprietary kernels offered by the various CT scanner vendors. High-pass kernels, for example, which incorporate an edge enhancement algorithm, might well accentuate the aforementioned speckled rim phenomena when incorporated in a hybrid kernel and viewed with narrow window settings. Consequently, further investigation with inclusion of various proprietary kernels from other manufacturers is warranted and encouraged by the authors.

More testing is also required to assess the technique's performance over a wider range of scans, particularly those obtained with IV administration of contrast medium. Because administration of iodine-based contrast agents increases soft-tissue attenuation,

when contrast agent is given, it might prove helpful to increase the algorithm's 150-HU upper limit for the soft-tissue (standard) low-pass convolution kernel. In addition, although the initial hybrid algorithm was designed to combine only two kernels (high and low pass), subsequent versions allow combining three (high, intermediate, and low pass) or more convolution kernels, if desired. Typically, only one or two kernels are conventionally generated for clinical examinations and the large raw data sets are subsequently erased; thus, a prospective study would need to be performed to assess the optimal combination of convolution kernels to be hybridized.

In conclusion, hybrid convolution kernel is a promising technique affording optimized bone and soft-tissue evaluation while potentially halving the number of images needed to be transmitted, stored, and reviewed. Further investigation is warranted.

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