

Application of trained Deep BCD-Net to iterative low-count PET image reconstruction

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Formulation of emission tomography

- Measurement follows Poisson statistical model:

$$Y_i \sim \text{Poisson}(\bar{y}_i(\mathbf{x}_{\text{true}})), \quad i = 1, \dots, n_d$$

where $\bar{y}_i(\mathbf{x}_{\text{true}}) = [\mathbf{A}\mathbf{x}_{\text{true}}]_i + \bar{r}_i$

- (Negative) Poisson log-likelihood function $f(\mathbf{x})$:

$$f(\mathbf{x}) \stackrel{c}{=} \sum_{i=1}^{n_d} \bar{y}_i(\mathbf{x}) - y_i \log(\bar{y}_i(\mathbf{x}))$$

- Goal of conventional emission tomography:

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x}} f(\mathbf{x})$$

subject to $\mathbf{x} \geq 0$

SNR in positron emission tomography (PET)

- Signal to Noise Ratio (SNR) \propto square root of the noise equivalent count rate (NEC)¹:

$$\text{SNR} = c \cdot \sqrt{\text{NEC}} = c \cdot \left[\frac{T^2}{(T + S + \gamma R)} \right]^{1/2}$$

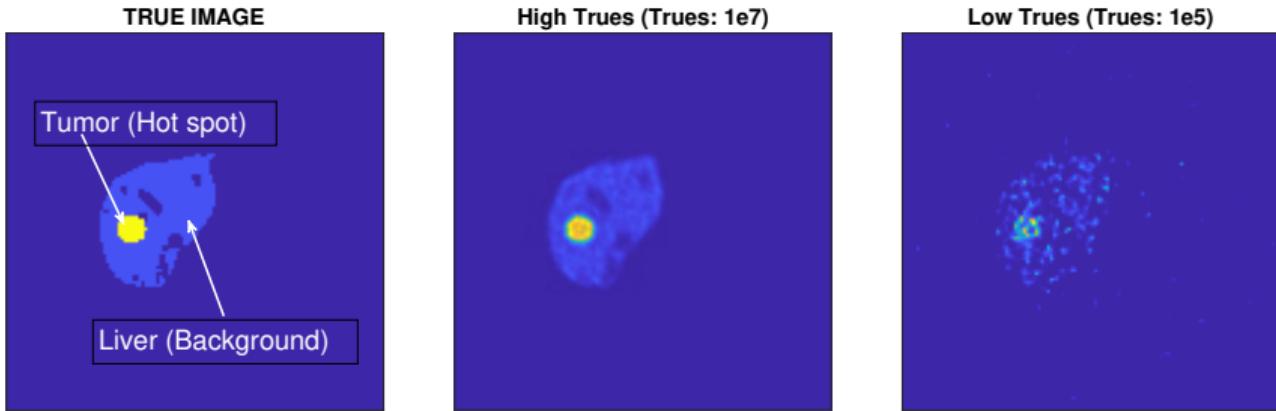
where c is a constant, T is total trues, S and R are total scatters and randoms, and γ is 1 or 2 depending on randoms estimation method.

→ SNR in PET is proportional to trues and disproportionate to randoms and scatters.

¹Strother, S. C., M. E. Casey, and E. J. Hoffman. "Measuring PET scanner sensitivity: relating count rates to image signal-to-noise ratios using noise equivalents counts." IEEE transactions on nuclear science 37.2 (1990): 783-788.

Impact of total trues on image quality

Figure: True and estimated images with EM (100 iterations)



- Simulation with XCAT phantom
- Random fraction is high in both cases

Approaches to low-count imaging

- Post-reconstruction filtering (used in clinic):
Clinical choice is 3D 5-8mm FWHM Gaussian filter².

- Add regularization term to cost function:

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x} \geq 0} f(\mathbf{x}) + R(\mathbf{x}),$$

where $R(\mathbf{x})$ is a regularization term.

- Two families of $R(\mathbf{x})$:
 - ① Mathematically designed regularizer
 - ② Learned (trained) regularizer

²Carlier, Thomas, et al. "90YPET imaging: Exploring limitations and accuracy under conditions of low counts and high random fraction." Medical physics 42.7 (2015): 4295-4309.

BCD-Net problem formulation

- BCD-Net³ is inspired by following **sparsity**-based regularization with **trained convolutional** filters:

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x}} \min_{\mathbf{z}} f(\mathbf{x}) + R(\mathbf{x}, \mathbf{z}) = \arg \min_{\mathbf{x}} \min_{\mathbf{z}} f(\mathbf{x}) + \sum_{k=1}^K \|\mathbf{c}_k * \mathbf{x} - \mathbf{z}_k\|_2^2 + \alpha_k \|\mathbf{z}_k\|_1,$$

- Block Coordinate Descent (BCD) algorithm alternatively updates $\{\mathbf{z}_k : \mathbf{z}_1, \dots, \mathbf{z}_K\}$ and \mathbf{x} :

$$\{\mathbf{z}_k^{(n+1)}\} = \arg \min_{\{\mathbf{z}_k\}} \|\mathbf{c}_k * \mathbf{x}^{(n)} - \mathbf{z}_k\|_2^2 + \alpha_k \|\mathbf{z}_k\|_1 = \mathcal{T}(\mathbf{c}_k * \mathbf{x}^{(n)}, \alpha_k)$$

$$\mathbf{x}^{(n+1)} = \arg \min_{\mathbf{x}} f(\mathbf{x}) + \beta \left(\sum_{k=1}^K \|\mathbf{c}_k * \mathbf{x} - \mathbf{z}_k^{(n+1)}\|_2^2 \right)$$

where $\mathcal{T}(\cdot, \cdot)$ is the element-wise soft thresholding operator:

$$[\mathcal{T}(\mathbf{t}, q)]_j = \begin{cases} t_j - q \cdot \text{sign}(t_j), & |t_j| > q \\ 0, & |t_j| \leq q \end{cases}.$$

³Chun & Fessler. (2018). "Deep BCD-Net Using Identical Encoding-Decoding CNN Structures for Iterative Image Recovery." 1-5.
10.1109/IVMSPW.2018.8448694.

BCD-Net problem formulation

- Previous formulation becomes following equivalent updates with one condition:

$$\{\mathbf{z}_k^{(n+1)}\} = \mathcal{T}(\mathbf{c}_k * \mathbf{x}^{(n)}, \alpha_k)$$

$$\mathbf{x}^{(n+1)} = \arg \min_{\mathbf{x}} f(\mathbf{x}) + \beta \left(\sum_{k=1}^K \|\mathbf{c}_k * \mathbf{x} - \mathbf{z}_k^{(n+1)}\|_2^2 \right)$$

$$\Updownarrow \quad \mathbf{C}^T \mathbf{C} = \mathbf{I}$$

$$\mathbf{u}^{(n+1)} = \sum_{k=1}^K \tilde{\mathbf{c}}_k * \left(\mathcal{T}(\mathbf{c}_k * \mathbf{x}^{(n)}, \alpha_k) \right)$$

$$\mathbf{x}^{(n+1)} = \arg \min_{\mathbf{x}} f(\mathbf{x}) + \beta \|\mathbf{x} - \mathbf{u}^{(n+1)}\|_2^2,$$

where $\mathbf{C} = [\mathbf{C}_1; \mathbf{C}_2; \dots; \mathbf{C}_K]$, $\mathbf{C}_k \mathbf{x} = \mathbf{c}_k * \mathbf{x}$ and $\tilde{\mathbf{c}}_k$ is flipped version of \mathbf{c}_k .

BCD-Net problem formulation

- K set of $\{\mathbf{c}_k\}, \{\alpha_k\}$ are trained at each iteration to map a noisy image into high quality (true, if possible) image:

$$\{\hat{\mathbf{c}}_1^{(n+1)}, \dots, \hat{\mathbf{c}}_K^{(n+1)}\}, \{\hat{\alpha}_1^{(n+1)}, \dots, \hat{\alpha}_K^{(n+1)}\} = \underset{\{\mathbf{c}_k\}, \{\alpha_k\}}{\arg \min} \frac{1}{J_{\text{FOV}}} \left\| \mathbf{x}_{\text{true}} - \sum_{k=1}^K \tilde{\mathbf{c}}_k * \left(\mathcal{T}(\mathbf{c}_k * \mathbf{x}^{(n)}, \alpha_k) \right) \right\|_2^2.$$

- In this work, we train separate decoding convolutional filters $\{\mathbf{d}_k\}$ instead of using $\{\tilde{\mathbf{c}}_k\}$
- With trained convolutional filters and soft-thresholding value, each variable update will be:

$$\begin{aligned} \mathbf{u}^{(n+1)} &= \sum_{k=1}^K \mathbf{d}_k^{(n+1)} * \left(\mathcal{T}(\mathbf{c}_k^{(n+1)} * \mathbf{x}^{(n)}, \alpha_k^{(n+1)}) \right) \\ \mathbf{x}^{(n+1)} &= \underset{\mathbf{x}}{\arg \min} f(\mathbf{x}) + \beta \|\mathbf{x} - \mathbf{u}^{(n+1)}\|_2^2. \end{aligned}$$

Details on x -update

- To solve following update image step:

$$\mathbf{x}^{(n+1)} = \arg \min_{\mathbf{x} \geq \mathbf{0}} f(\mathbf{x}) + \beta \|\mathbf{x} - \mathbf{u}^{(n+1)}\|_2^2,$$

- we use EM-surrogate for $f(\mathbf{x})$:

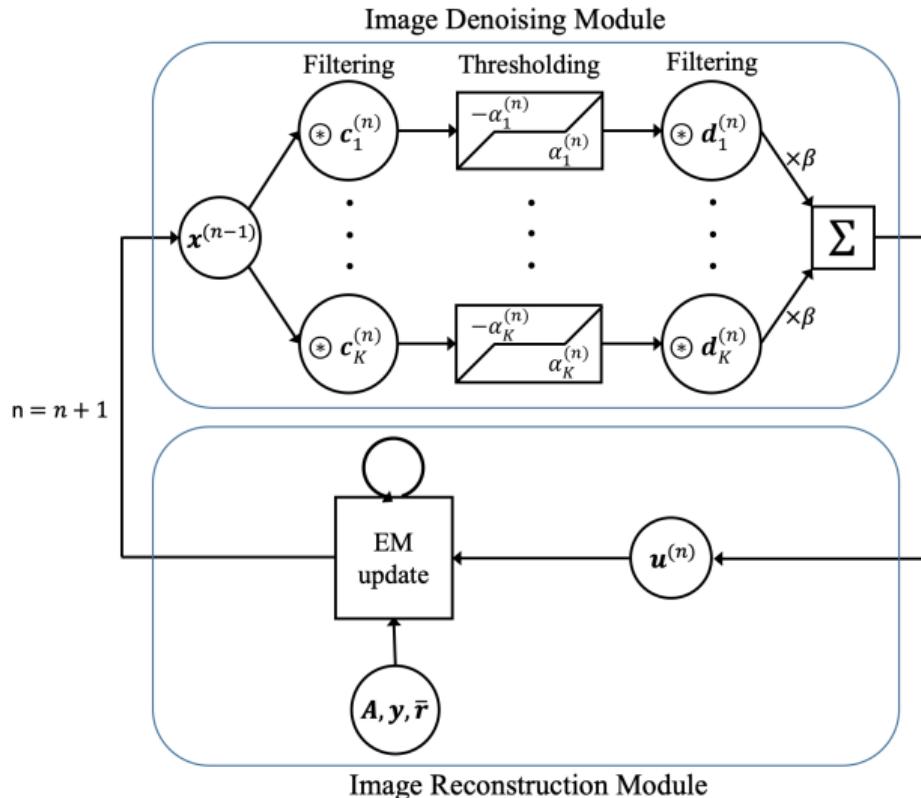
$$\begin{aligned} f(\mathbf{x}) + \beta \|\mathbf{x} - \mathbf{u}^{(n+1)}\|_2^2 &= \sum_i [\mathbf{Ax}]_i + \bar{r}_i - y_i \log([\mathbf{Ax}]_i + \bar{r}_i) + \beta \sum_j (x_j - u_j^{(n+1)})^2 \\ &\leq \sum_j a_j x_j - e_j(\mathbf{x}^{(n')})(x_j^{(n')}) \log(x_j) + \beta (x_j - u_j^{(n+1)})^2 \\ &= \sum_j Q_j(x_j), \end{aligned}$$

where $e_j(\mathbf{x}^{(n')}) = \sum_i a_{ij} \frac{y_i}{\bar{y}_i(\mathbf{x}^{(n')})}$ and n' is n 'th iteration in x -update.

- Equating $\frac{\partial Q_j(x_j)}{\partial x_j}$ to zero is equivalent to finding the root of the following formula:

$$2\beta x_j^2 + (a_j - 2\beta z_j^{(n+1)})x_j - e_j(\mathbf{x}^{(n')})(x_j^{(n')}) = 0.$$

Architecture of BCD-Net



Conventional non-trained regularizers

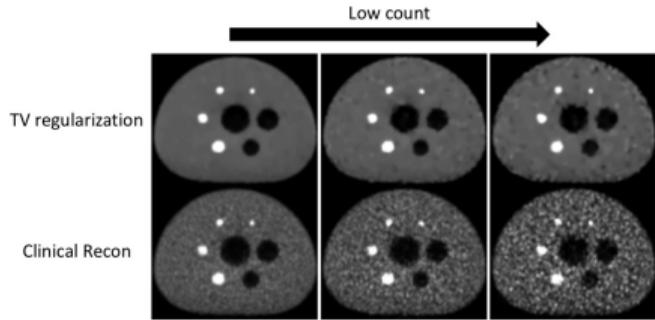
- Total-variation (TV) regularization
- Non-local means (NLM) regularization

TV regularization

- TV regularization solves following formulation:

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x} \geq 0} f(\mathbf{x}) + R(\mathbf{x}) = \arg \min_{\mathbf{x} \geq 0} f(\mathbf{x}) + \beta \|\mathbf{Cx}\|_1.$$

- Recent work⁴ demonstrated that TV regularized reconstruction gives better qualitative & quantitative result than clinical reconstruction for low-count data sets (w.r.t. contrast recovery, variability)



⁴Zhang, Zheng, et al. "Optimization-Based Image Reconstruction from Low-Count, List-Mode TOF-PET Data." IEEE Transactions on Biomedical Engineering (2018).

Algorithm for TV regularization

- Primal-Dual Hybrid Gradient (PDHG)⁵ solves TV-constrained problem by reformulating the primal problem as the saddle point optimization problem. Then PDHG approaches to the saddle point by using proximal mapping of each function:

$$\min_x \{F(\mathbf{Kx}) + G(x)\}$$

$$\Updownarrow \mathbf{y} = \mathbf{Kx}$$

$$\min_x \max_y \{\langle \mathbf{Kx}, \mathbf{y} \rangle + G(x) - F^*(\mathbf{y})\}$$

↓ solve via proximal-point method

$$\mathbf{y}^{(n+1)} = \text{prox}_{\sigma}[F^*](\mathbf{y}^{(n)} + \sigma \mathbf{K}\bar{\mathbf{x}}^{(n)})$$

$$\mathbf{x}^{(n+1)} = \text{prox}_{\tau}[G](\mathbf{x}^{(n)} - \tau \mathbf{K}^T \mathbf{y}^{(n+1)})$$

$$\bar{\mathbf{x}}^{(n+1)} = \mathbf{x}^{(n+1)} + \theta(\mathbf{x}^{(n+1)} - \mathbf{x}^{(n)})$$

⁵Chambolle, Antonin, and Thomas Pock. "A first-order primal-dual algorithm for convex problems with applications to imaging." Journal of mathematical imaging and vision 40.1 (2011): 120-145.

Conventional non-trained regularizers

- Total-variation (TV) regularization
- Non-local means (NLM) regularization

NLM regularization

- NLM⁶ regularization⁷ solves following formulation:

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x} \geq 0} f(\mathbf{x}) + R(\mathbf{x}) = \arg \min_{\mathbf{x} \geq 0} f(\mathbf{x}) + \beta \sum_{i,j \in S_i} p(||\mathbf{N}_i \mathbf{x} - \mathbf{N}_j \mathbf{x}||_2^2).$$

where $p(t)$ is a potential function of a scalar variable t ,

S_i is the search neighborhood around the i th voxel, and

$\mathbf{N}_i \mathbf{x}$ is a vector of image intensities of all voxels within a fixed distance from the i th voxel.

⁶Buades, A., Coll, B., Morel, J. M. (2005). A review of image denoising algorithms, with a new one. *Multiscale Modeling Simulation*, 4(2), 490-530.

⁷Lou, Yifei, et al. "Image recovery via nonlocal operators." *Journal of Scientific Computing* 42.2 (2010): 185-197.

Algorithm for NLM regularization

- For the acceleration of convergence, we use variable splitting method and solve the problem via ADMM⁸ with adaptive penalty parameter (ρ) selection method⁹:

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x} \geq \mathbf{0}} f(\mathbf{x}) + R(\mathbf{x})$$

⇓

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x} \geq \mathbf{0}} \min_{\mathbf{z}} \mathbb{1}^T (\mathbf{A}\mathbf{z} + \bar{\mathbf{r}}) - \mathbf{y}^T \log(\mathbf{A}\mathbf{z} + \bar{\mathbf{r}}) + R(\mathbf{x}), \quad \text{s.t. } \mathbf{z} = \mathbf{x}$$

⇓ solve via ADMM

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x} \geq \mathbf{0}} \min_{\mathbf{z}} \max_{\mathbf{u}} \mathbb{1}^T (\mathbf{A}\mathbf{z} + \bar{\mathbf{r}}) - \mathbf{y}^T \log(\mathbf{A}\mathbf{z} + \bar{\mathbf{r}}) + R(\mathbf{x}) + \frac{\rho}{2} \|\mathbf{x} - \mathbf{z} + \mathbf{u}\|_2^2 - \frac{\rho}{2} \|\mathbf{u}\|_2^2$$

⁸Chun, Se Young et al. "ADMM for tomography with nonlocal regularizers." IEEE TMI 33.10 (2014): 1960-1968.

⁹Boyd, Stephen, et al. "Distributed optimization and statistical learning via the ADMM." Foundations and Trends in Machine learning 3.1 (2011): 1-122.

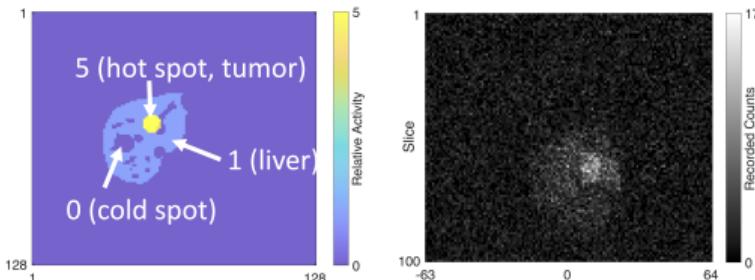
Experimental setting

- Simulating Y-90 Radioembolization

	Patient A	Patient B
Y-90 Injection (GBq)	3.9	0.9
True Prompts	675K	97K
Random Prompts	3.3M	1.7M
Total Prompts	3.9M	1.8M
Random Fraction (%)	83	95

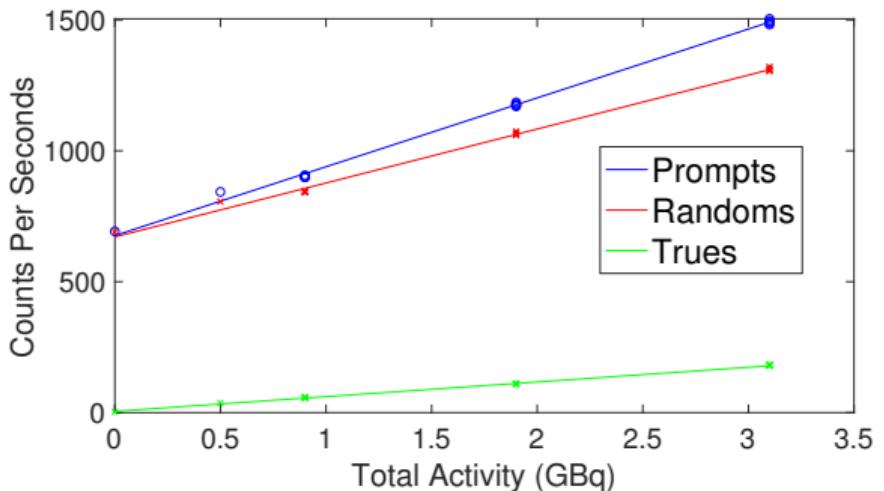
* Random Fraction = (Random prompts / Total prompts) × 100

- Digital phantom and projection



Particulars about Y-90 imaging

- Y-90: Radioisotope for radioembolization
 - ▷ Almost pure beta emitter
 - ▷ Very low probability of positron emission : 3.2×10^{-5}
 - ▷ ^{176}Lu and Bremsstrahlung photons contribute to random coincidences
 - Low true coincidence counts & very high random fraction



BCD-Net training details

- x_{Train} : 6 set of 3-D XCAT ($128 \times 128 \times 100$) with a voxel size $4 \times 4 \times 4$ (mm^3),
1:5 activity ratio between healthy liver and lesion.
- $x^{(0)}$: An image estimated with EM algorithm using 20 iterations
- 10 layers ($n = 10$)
- 3D Filters and soft-thresholding values are trained using back-propagation algorithm:
 - Pytorch deep-learning library
 - ADAM optimization with epoch number: 200, mini-batch size: 1 ($128 \times 128 \times 100 \times 1$)
 - Learning rate: Encoding($1e-3$), Decoding($1e-3$), Thresholding($1e-1$)
 - Learning rate decay method is used ($lr = lr \times 0.9$ every 10 epoch)
 - Initialization of thresholding value needs to be carefully chosen
 - $(n_p \times 0.1)$ -th largest value of sorted $x^{(0)}$, where n_p is number of voxels in image x
 - Filter size: $3 \times 3 \times 3$, Filter number (K): 200
- Testing 1 set of 3-D XCAT ($128 \times 128 \times 100$): changed location of lesion and cold spot.

Evaluation metrics

- Activity Recovery (AR):

$$AR = \frac{\text{Estimated } C_{VOI}}{\text{True } C_{VOI}} \times 100(\%),$$

where C_{VOI} is mean counts in the volume of interest (VOI)

- Contrast to Noise Ratio (CNR):

$$CNR = \frac{C_{hotspot} - C_{bkg}}{STD_{bkg}}.$$

- Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{\sum_j (\mathbf{x}_{true}[j] - \hat{\mathbf{x}}[j])^2}{J_{FOV}}} \times 100(\%),$$

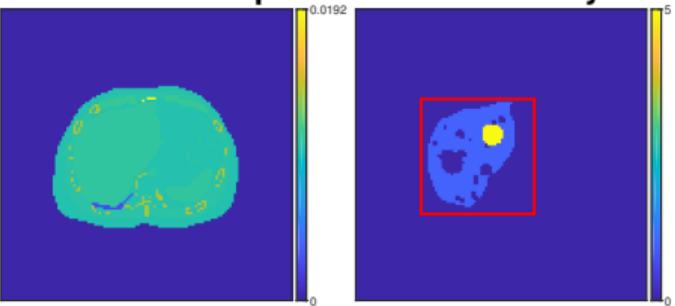
where J_{FOV} is the total number of voxels in field of view (FOV).

Choosing regularization parameter for each method

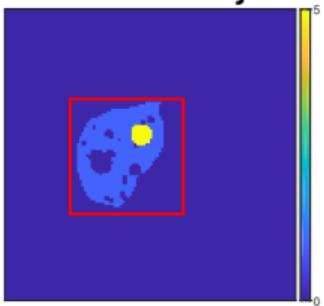
- β value test range:
 - ▷ TV regularization: 2^{-4} - 2^4
 - ▷ NLM regularization: 2^{-20} - 2^{-7}
 - ▷ BCD-Net regularization: 2^4 - 2^{-4}
- Parameter value to obtain the highest contrast to noise ratio (CNR) and lowest RMSE:
 - ▷ $\beta_{\text{TV}} = 2^{-2}$
 - ▷ $\beta_{\text{NLM}} = 2^{-10}$
 - ▷ $\beta_{\text{BCD-Net}} = 2^2$

Reconstructed images

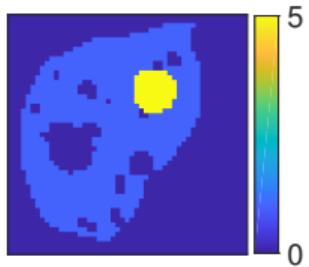
Attenuation Map



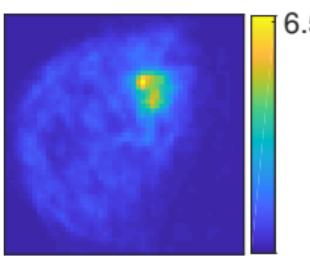
True Activity



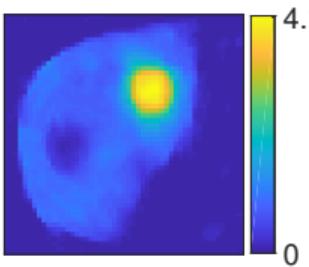
TRUE



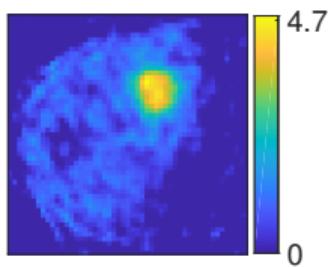
EM



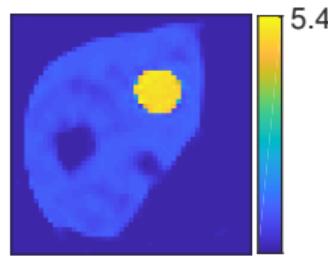
PDHG-TV



ADMM-NLM



BCD-Net

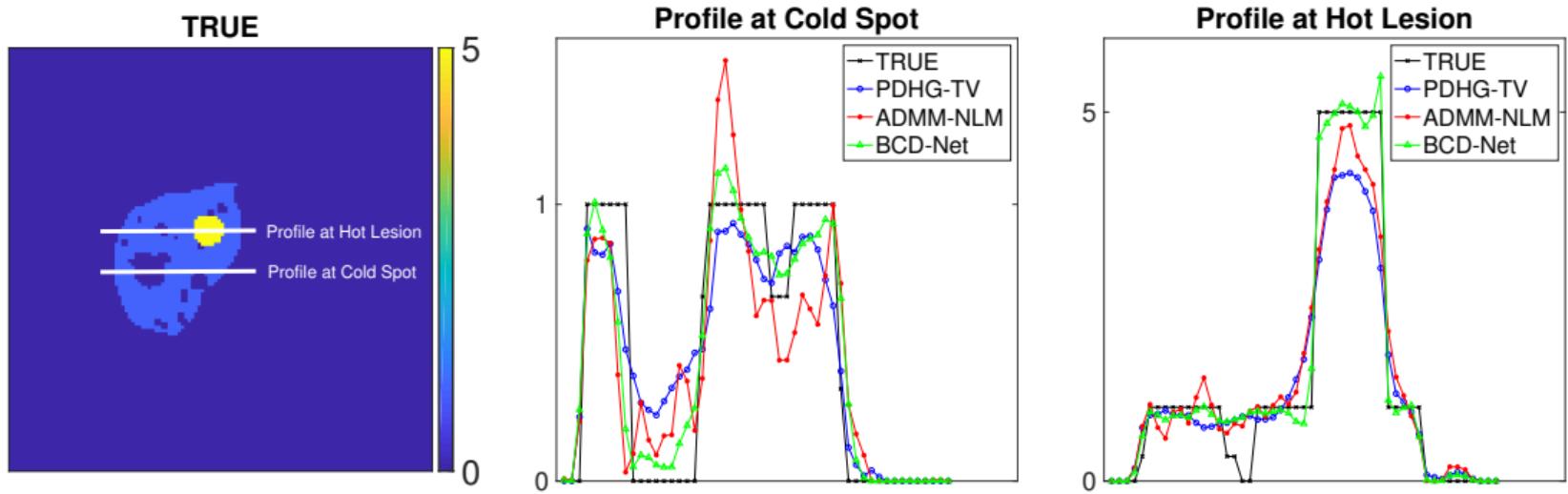


Quantitative evaluation results

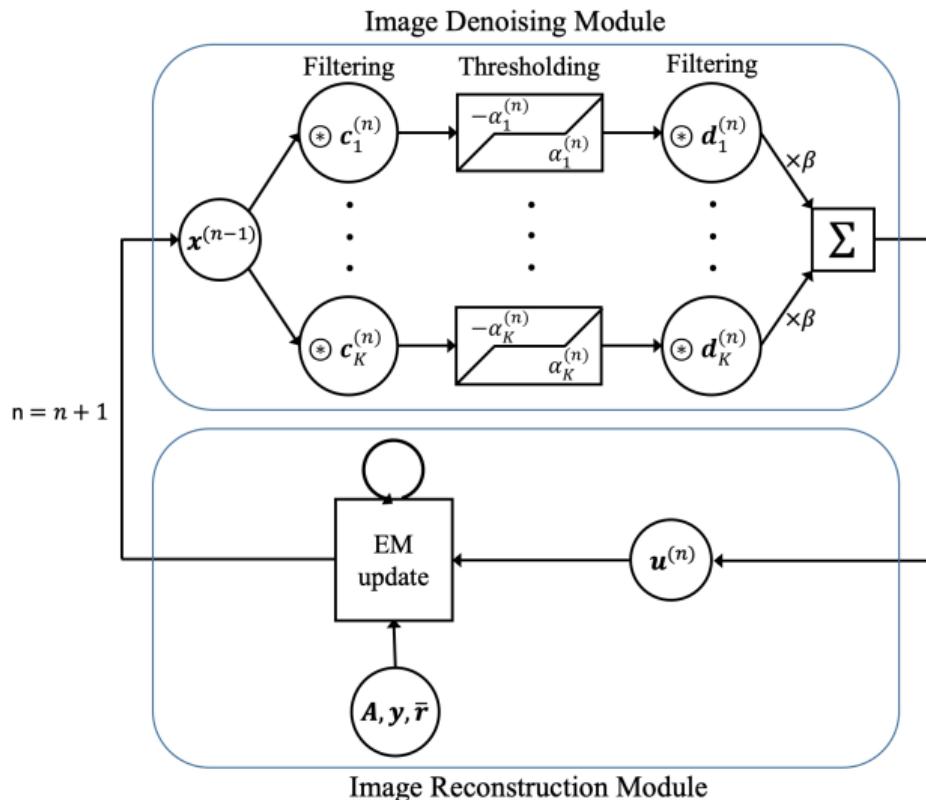
Table: Evaluation results on regularizers with β value obtaining highest CNR and lowest RMSE

	Iteration #	Time (Sec)	AR-Hot Lesion	AR-Liver	CNR	RMSE
EM	50	46	89.4	86.9	5.0	12.9
PDHG-TV	200	209	68.2	86.0	8.9	7.7
ADMM-NLM	200	2,907	71.0	84.7	7.0	9.2
BCD-NET	200 (20×10)	233	96.5	88.8	17.5	5.9

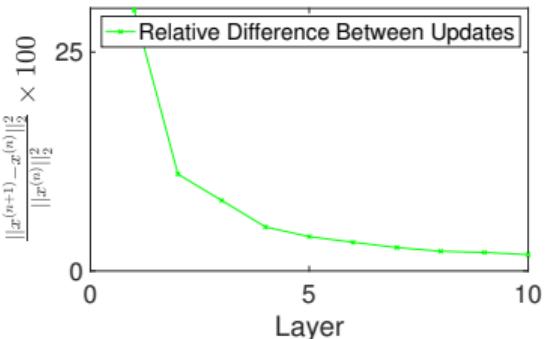
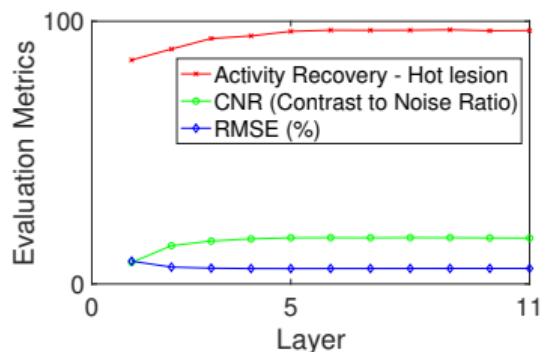
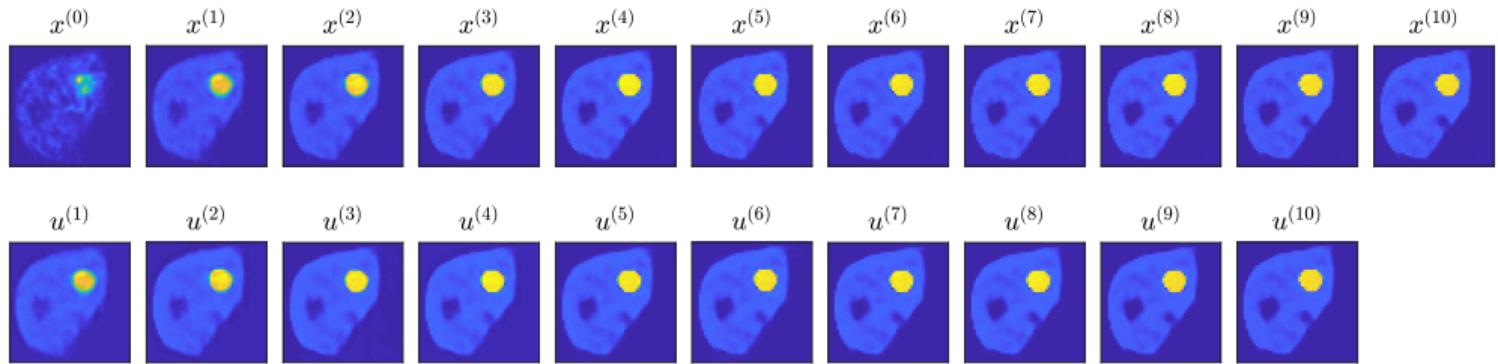
Profile comparison



BCD-Net notation reminder



BCD-Net: images and evaluation results at each layer



BCD-Net: comparison between single image denoising network

- Many related works are based on the framework composed of single image denoising (deep) network (e.g., U-Net) as a post-reconstruction processing, however, this single denoising framework has a potential **not** to fully recover the image (+ risk of over-fitting).

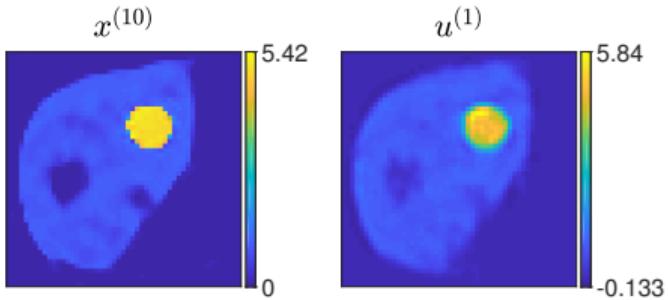
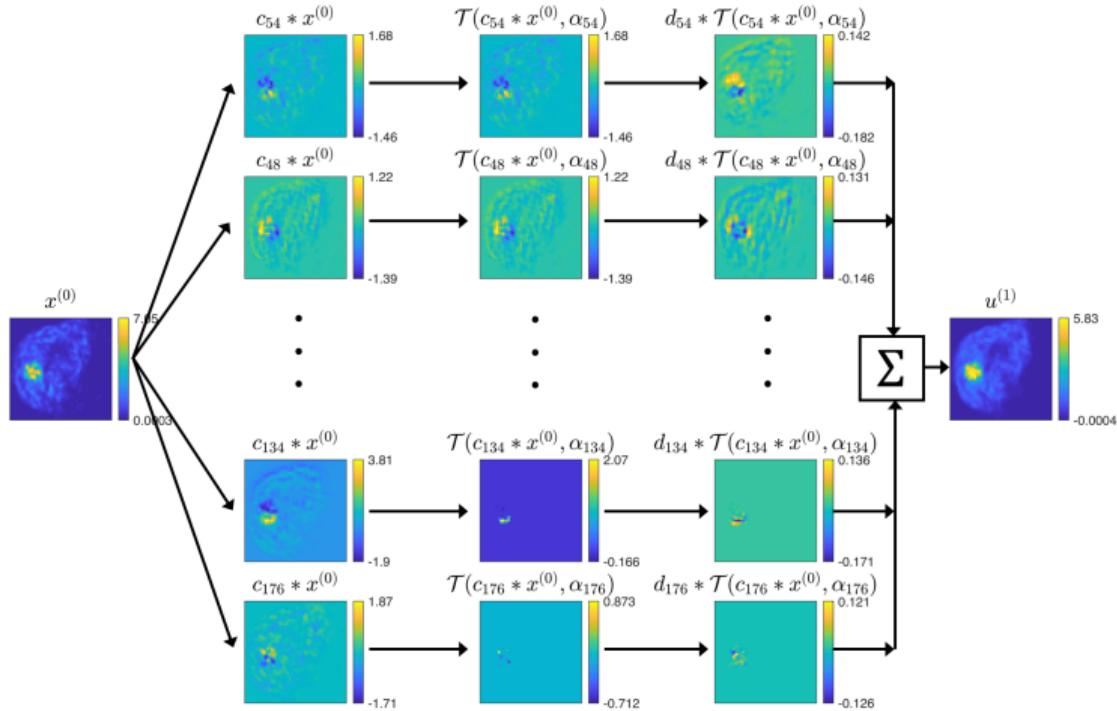


Table: Evaluation results on $x^{(10)}$ and $u^{(1)}$

	AR-Hot Lesion	AR-Liver	CNR	RMSE
$x^{(10)}$	96.5	88.8	17.5	5.9
$u^{(1)}$	89.4	86.3	15.0	6.3

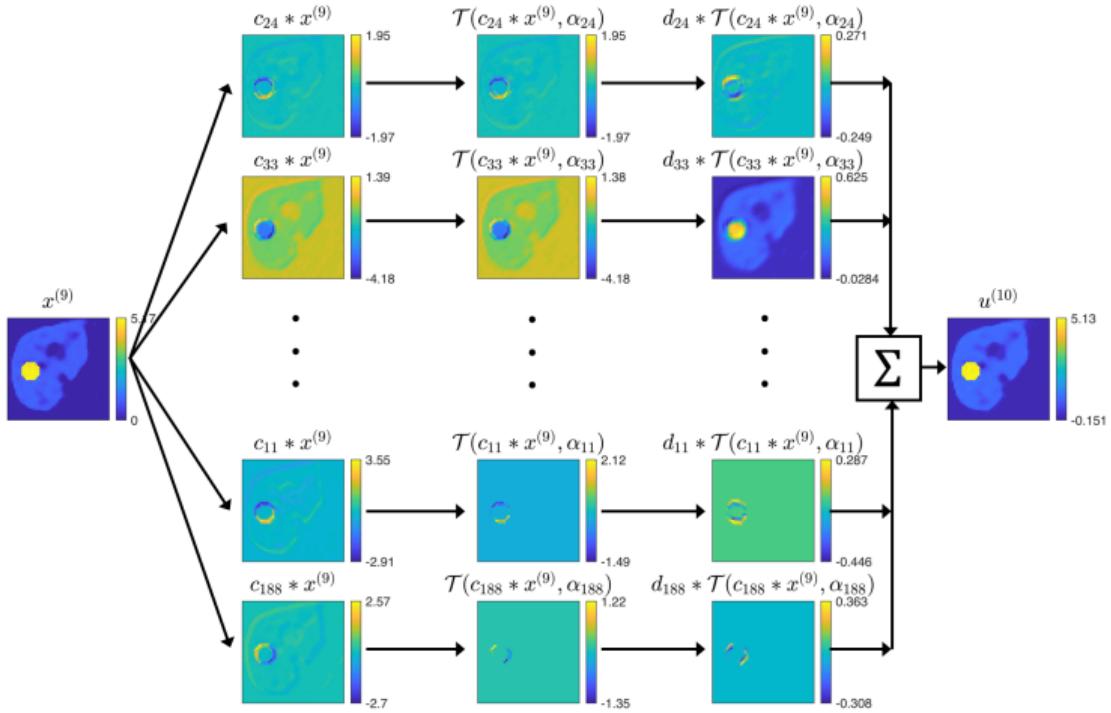
BCD-Net: convolutional filters and thresholding analysis

- Visualization of steps in $d_k^{(1)} * \mathcal{T}(c_k^{(1)} * x^{(0)}, \alpha_k^{(1)})$ with ascending order of thresholdings



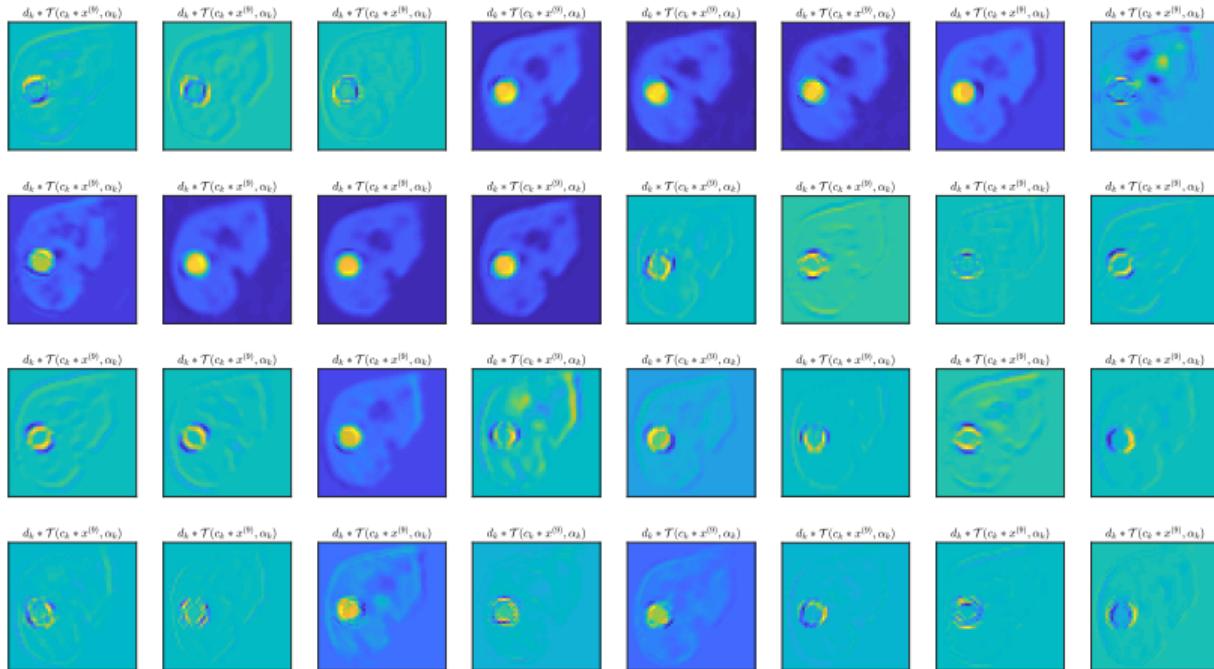
BCD-Net: convolutional filters and thresholding analysis

- Visualization of steps in $d_k^{(10)} * \mathcal{T}(c_k^{(10)} * x^{(9)}, \alpha_k^{(10)})$ with ascending order of thresholdings



BCD-Net: convolutional filters and thresholding analysis

- Visualization of $d_k^{(10)} * \mathcal{T}(c_k^{(10)} * x^{(9)}, \alpha_k^{(10)})$ with ascending order of thresholdings



Summary, Future work & Acknowledgement

- Non-trained regularizers had a trade-off between noise and recovery accuracy, whereas BCD-Net improved activity recovery for a hot sphere and reduced noise at the same time.
- BCD-Net improved CNR and activity recovery by 96.6% (150.0%) and 41.5% (35.9%) compared to PDHG-TV (ADMM-NLM) regularized reconstruction.
- Robustness to noise-level (count-level).
- Adaptive regularization parameter selection.
- Train and test on more diverse data including measured data.
- Thorough comparison between single denoising network framework.
- We acknowledge Se Young Chun (UNIST) for providing NLM regularization codes.
- We acknowledge Zhengyu Huang (UMich) for providing Pytorch codes to train the image denoising network.
- This work is supported by NIH-NIBIB grant R01EB022075

Thank You

Slides will be available at anytime here:

<https://limhongki.github.io>