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Research article

Predictors of radiation dose for CT pulmonary angiography in pregnancy across a multihospital integrated healthcare network

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ABSTRACT

Purpose: There is a large range of published effective radiation dose for CTPA during pregnancy. The purpose of our study is to determine the mean effective radiation dose and predictors of mean effective radiation dose for CTPA in pregnant patients across a multihospital integrated healthcare network.

Methods: This retrospective study evaluates pregnant women who had a CTPA as the first primary advanced imaging test for evaluation of PE in a multihospital integrated healthcare network from January 2012-April 2017. Patient and CT-related data were obtained from the electronic health record and Radimetrics server (Radimetrics Inc, Bayer). DLP was recorded and effective radiation dose in mSv was determined using a conversation factor of 0.014 $mSv \cdot mGy^{-1} \cdot cm^{-1}$. Patient size was determined by water equivalent diameter. Bivariate and multivariate analysis were performed for effective radiation dose based on patient and CT factors.

Results: In the 534 CTPA exams, the mean effective radiation dose was 3.96 mSv. Bivariate analysis showed significant differences in radiation dose by trimester, $p = 0.042$: first trimester 4.52 mSv, second trimester 3.73 mSv, and third trimester 3.95 mSv. Multivariable analysis demonstrated CTPA during first trimester, increasing mAs, kVp, scan length, patient size, and use of mAs modulation, as well as decreasing pitch, to be predictive of higher effective radiation dose.

Conclusion: Mean effective radiation dose was on the lower end of published studies. Trimester was a statistically significant predictor of effective radiation dose when accounting for known predictors of radiation dose.

1. Introduction

Pregnant patients have a tenfold increase in developing venous thromboembolism compared to non-pregnant patients because of their hypercoagulable state [1]. As such, pulmonary embolism (PE) is one of the most common causes of death in pregnancy [2]. Mortality from PE can be as high as 30% when untreated but decreases to less than 1% when treated [3]. Evaluation of PE in pregnancy is complicated by physiologic changes of pregnancy mimicking the symptoms of PE and poor performance of clinical prediction rules and d-dimer that are often used in non-pregnant patients [4,5]. Often, advanced imaging with CT pulmonary angiography (CTPA) or lung scintigraphy (LS) is needed during pregnancy as these are the only tests to directly image for PE. However, there is controversy in the existing literature regarding which is the better advanced imaging modality during pregnancy, as these tests increase the risk of radiation, including cancer to the mother and fetus, and do not perform as well in pregnancy [6].

The available guidelines for evaluation of PE in pregnancy identified by a recent systematic review demonstrate a preference for LS over CTPA because of a similar fetal radiation dose but larger maternal CTPA dose (4–18 mSv) compared to LS maternal dose (1–2.5 mSv) [7–9]. There are limited studies evaluating CTPA radiation dose in pregnancy and a recent study of 75 patients reported CTPA radiation dose in pregnancy of less than 1 mSv, suggesting the maternal dose of the two modalities may be more similar than previously estimated and the CTPA fetal dose could potentially be lower than the LS dose [10].

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Known predictors of CT radiation dose include patient size and CT settings, such as scan length, iterative reconstruction, and radiation dose settings such as automatic exposure control, kVp, and mA [11–15]. Limited data however is known about clinical predictors of CTPA radiation dose in pregnancy. Thus, the purpose of our study is to determine the mean effective radiation dose and predictors of mean effective radiation dose for CTPA in pregnant patients across a multihospital integrated healthcare network. The hypothesis of the study is that when accounting for known predictors of radiation dose (patient size and CT settings), the radiation dose will not depend on other demographic data.

2. Materials and methods

2.1. Study cohort

This retrospective study evaluated consecutive pregnant patients across a multihospital integrated healthcare network between January 2012 and April 2017 who had CTPA as the primary advanced imaging modality for evaluation of PE. Patients with a LS prior to CTPA in the same pregnancy were excluded because repeat advanced imaging can lead to deviations from standard acquisition techniques based on the initial indeterminate test. For patients with multiple CTPA in the same pregnancy, only the first CTPA was used. Patients with multiple CTPA in the same study were excluded. Pregnancy status was confirmed based on ultrasound, physician/nursing written note of a known pregnancy, or written language in the radiology order history specifying known pregnancy. Patients with early pregnancy, positive beta HCG but no visualized pregnancy by ultrasound, were included. Patients in which pregnancy could not be confirmed and post-partum patients were excluded. Finally, only patients with available radiation dose data were included.

2.2. Image acquisition

CTPA studies across our large health institution were performed on GE (Discovery, CT750 HD, Optima CT660, Revolution EVO, Brightspeed, Lightspeed 16, Lightspeed Plus, Lightspeed VCT), Philips (Brilliance 64), Siemens (SOMATOM Definition AS, SOMATOM Definition Edge), and Toshiba (Aquilion ONE) scanners, with iterative reconstruction. The median tube voltage, collimation, and slice thickness were 120 kVp, 40 mm, 0.625 mm respectively. mAs modulation and abdominal shielding were performed per site protocol.

2.3. Data collection

Studies were performed with approval from the institutional review board with waiver of informed consent. Patient's medical records were obtained by searching the radiology information system (RIS) for patients with CTPA and positive pregnancy status indicated by the clinician in the examination order. CT-related data from CTPA acquisition were obtained via the Radimetrics server (Radimetrics Inc, Bayer), and did not include scout, localizers, or timing sequences. DLP was recorded and effective radiation dose in mSv was determined using a conversation factor of 0.014 $mSv \cdot mGy^{-1} \cdot cm^{-1}$ [16]. CT continuous variables included mean mAs, pitch, total exam scan length, scan length ratio, and patient size. Patient size was estimated by water equivalent diameter (WED), with calculation automated by Radimetrics as has been previously discussed [17,18]. Scan categorical variables included kVp and mAs modulation.

Patient age was evaluated as a continuous variable. Categorical patient variables included race, trimester, study priority, and patient class. Race included Asian, black, white, other, or unknown. Trimester was classified as first (early pregnancy through week 13), second (weeks 14–26), third (week 27–42), or unknown gestational age. Study priority included routine, STAT/urgent, or other. Patient class was categorized as emergency department, inpatient, or outpatient.

2.4. Statistical analysis

Effective radiation dose was evaluated as a continuous variable. Bivariate analysis was performed with *t*-test and ANOVA for categorical predictors of effective radiation dose and with correlation for continuous predictors. Multivariable linear regression with all continuous and categorical variables was used to predict effective radiation dose in patients. All analyses were performed using SAS Version 9.4, with $p < 0.05$ considered statistically significant.

3. Results

3.1. Demographics

534 patients were included in this study, with an average age 29.9 ± 5.8 years. All patients are female, with 10% (56/534) Asian, 27% (145/534) black, 36% (192/534) white, 25% (133/534) other, and 1% (8/534) unknown. 45% (238/534) of patients were scanned in the third trimester, 33% (178/534) in the second trimester, and 13% (69/534) in the first trimester. 78% (416/534) of cases were ordered STAT/urgent and 22% (118/534) of cases were routine. 73% (390/534) of patients were emergency department, 21% (110/534) inpatients, and 6% (34/534) outpatients (Table 1).

3.2. CT technique

The mean WED was 271.4 ± 30.3 mm, mean scan length 288.6 ± 37.0 mm, mean tube current 162.5 ± 81.2 mAs, and mean pitch 1.2 ± 0.2; 81% (431/534) had mAs modulation and 19% (103/534) had no mAs modulation; 140 kVp was used for 10% (55/534) of patients, 120 kVp for 81% (431/534) of patients, 100 kVp for 8% (44/534) of patients, and 80 kVp for 1% (4/534) of patients (Table 1).

Table 1
Study and patient characteristics (N = 534).

Patient Characteristics	Mean ± Standard Deviation n (%)
Average age	29.9 ± 5.8
Patient size (WED), mm	271.4 ± 30.3
Scan length, mm	288.6 ± 37.0
Mean mAs	162.5 ± 81.2
Pitch	1.2 ± 0.2
Race	
Asian	56 (10%)
Black	145 (27%)
White	192 (36%)
Other	133 (25%)
Unknown	8 (1%)
Trimester	
1st	69 (13%)
2nd	178 (33%)
3rd	238 (45%)
Unknown	49 (9%)
Priority	
Routine	118 (22%)
STAT/Urgent	416 (78%)
Patient Class	
Emergency Department	390 (73%)
Inpatient	110 (21%)
Outpatient	34 (6%)
mAs Modulation	
True	431 (81%)
False	103 (19%)
kVp	
80	4 (1%)
100	44 (8%)
120	431 (81%)
140	55 (10%)

Table 2
Mean effective dose by patient factor categorical and continuous variables.

Patient Characteristics	Radiation Dose (mSv)	p-Value
All patients	3.96 ± 1.97	
Categorical Variables		
Race		0.002
Asian	3.58	
Black	4.46	
White	3.98	
Other	3.61	
Unknown	3.04	
Trimester		0.042
1st	4.52	
2nd	3.73	
3rd	3.95	
Unknown	4.04	
Priority		0.094
Routine	4.19	
STAT/Urgent	3.89	
Patient Class		0.395
Emergency Department	3.89	
Inpatient	4.18	
Outpatient	4.00	
mAs Modulation		< 0.001
True	3.75	
False	4.84	
kVp		< 0.001
80	1.32	
100	2.38	
120	3.93	
140	5.67	

Continuous Variables	Correlation	p-Value
Average age	0.032	0.4602
Patient size	0.506	< 0.001
Scan length	0.178	< 0.001
Mean mAs	0.777	< 0.001
Pitch	0.038	0.382

3.3. Bivariate analysis for predictors of mean radiation dose

The mean radiation dose was 3.96 mSv. Bivariate analysis showed statistical differences in radiation dose by race (3.58 mSv for Asian, 4.46 mSv for black, 3.98 mSv for white, 3.61 mSv for other, $p = 0.002$), trimester (4.52 mSv for first trimester, 3.73 mSv for second trimester, and 3.95 mSv for third trimester, $p = 0.042$), mAs modulation (3.75 mSv for modulation, 4.84 mSv for no modulation, $p < 0.001$), and kVp (1.32 mSv for 80 kVp, 2.38 mSv for 100 kVp, 3.93 mSv for 120 kVp, and 5.67 mSv for 140 kVp, $p < 0.001$) Moreover, there was a positive correlation for mean effective radiation dose with patient size ($p < 0.001$), scan length ($p < 0.001$), and mean mAs ($p < 0.001$) (Table 2).

3.4. Bivariate analysis of variables by trimester

There were no significant differences in trimester by study priority ($p = 0.0696$), use of mAs modulation ($p = 0.2563$), kVp ($p = 0.2661$), average age ($p = 0.3495$), patient size ($p = 0.4382$), or mean mAs ($p = 0.5439$). There were differences in trimester by race ($p = 0.0372$), patient class ($p < 0.001$), scan length ($p = 0.0372$) and pitch (0.0348). (Table 3)

3.5. Bivariate analysis of variables by race

There were no significant differences in race by study priority ($p = 0.1749$), patient class ($p = 0.3181$), use of mAs modulation ($p = 0.2155$), and patient age ($p = 0.0557$) by race. There were significant differences in race by trimester ($p = 0.0372$), kVp ($p < 0.001$), patient size ($p = 0.0101$), scan length ($p = 0.0088$), mean mAs ($p = 0.0154$), and pitch ($p < 0.001$). (Table 3)

3.6. Multivariable analysis for predictors of mean radiation dose

Multivariable analysis demonstrated first trimester CTPA, mean mAs, kVp, patient size, scan length, pitch, and mAs modulation to be predictive of effective radiation dose. Higher effective radiation dose was observed with first trimester scanning ($p = 0.0152$); increased mean mAs, kVp, patient size, and scan length ($p < 0.001$); decreased pitch ($p < 0.001$); and absence of mAs modulation ($p < 0.001$). There were no statistically significant relationships between radiation dose and age, race, study priority, or patient class (Table 4).

4. Discussion

Our study found a mean effective radiation dose of 3.96 mSv for CTPA in evaluating for PE in pregnant patients, and this dose varied significantly by trimester when accounting for known predictors of radiation dose. Prior literature has established that CTPA with conventional examination parameters delivers an average radiation dose ranging from 1 mSv to 14 mSv for the diagnosis of PE in the general population [19,20]. However, few studies have investigated radiation dose during pregnancy and a broad range of values exists for estimated maternal exposure, possibly reflecting heterogeneity in the protocols and equipment as well as differences in fetal size and age at the time of exposure. The New Zealand College of Obstetricians/ Gynecologists [21] and the American College of Radiology [22] estimate lower radiation doses for CTPA ranging from 1.6 to 6 mSv and 1–10 mSv respectively, while the American Thoracic Society/Society of Thoracic Radiology (ATS/STR) [8,9], and the Working Group in Women's Health of the Society of Thrombosis and Haemostasis (GTH) [23] suggest higher maternal whole-body effective doses at 4–18 mSv and 7–70 mSv, respectively. Based on these results, our reported dose falls in the lower end of the range currently reported by the existing literature. A recent analysis of 45 CTPA studies found a radiation dose in pregnancy of less than 1 mSv at the expense of higher noise [10]. This sub 1 mSv radiation dose was achieved with 100 kVp, 80 mAs, scanned from 1 cm above aortic arch to inferior sternum. A modality that offers promise for evaluation of pulmonary embolism in pregnancy is MRI as it has no patient radiation dose [24]. However, its clinical utility is not fully understood and as such is not considered as a primary advanced imaging modality by guidelines for evaluating PE in pregnancy. Further, this may change with improving techniques and protocols and additional research.

We confirmed known predictors for radiation dose that have been reported in prior studies, demonstrating that increasing kVp, mAs, patient size, scan length, decreasing pitch, and absence of mAs modulation were predictive of increased effective radiation dose. Radiation dose increases exponentially with tube energy (kVp) due to increased efficiency of photon production for a fixed exposure time [25], and is directly proportional to photon flux, increasing linearly with the tube current (mA) [26]. Greater patient size generally requires increased radiation technique to provide appropriate image quality [27]. Additionally, greater scan length is also associated with higher dose [28]. On the other hand, increasing pitch decreases the patient dose because it minimizes risk of over-scanning [25]. mAs modulation also decreases radiation dose by targeting tube current to adapt to different attenuation characteristics of specific body regions, increasing mAs for more attenuating areas and decreasing mAs for less attenuating areas to improve image quality [29]. A radiologist paying attention to using a scan protocol optimized for dose is important when it comes to imaging a pregnant patient. To this end, optimal technique should include low mA, kVp, iterative reconstruction, dose modulation, and minimized scan range.

Most importantly though, when adjusting for these predictors above in our multivariable linear regression model, we showed that a first

Table 3
Categorical and continuous variables by trimester and race.

Patient Characteristics	1st trimester N = 69	2nd trimester N = 178	3rd trimester N = 238	Unknown trimester N = 49	p	Asian N = 56	Black N = 145	White N = 192	Other N = 141	p
Categorical Variables										
Race					**0.0372**					NA
Asian	1 (1.4%)	24 (13.5%)	26 (10.9%)	5 (10.2%)		NA	NA	NA	NA	
Black	30 (43.5%)	47 (26.4%)	53 (22.3%)	15 (30.6%)		NA	NA	NA	NA	
White	23 (33.3%)	61 (34.3%)	92 (38.7%)	16 (32.7%)		NA	NA	NA	NA	
Other	15 (21.7%)	46 (25.8%)	67 (28.2%)	13 (26.5%)		NA	NA	NA	NA	
Trimester					NA					**0.0372**
1st	NA	NA	NA	NA		1 (1.8%)	30 (20.7%)	23 (12%)	15 (10.6%)	
2nd	NA	NA	NA	NA		24 (42.9%)	47 (32.4%)	61 (31.8%)	46 (32.6%)	
3rd	NA	NA	NA	NA		26 (46.4%)	53 (36.6%)	92 (47.9%)	67 (47.5%)	
Unknown	NA	NA	NA	NA		5 (8.9%)	15 (10.3%)	16 (8.3%)	13 (9.2%)	
Priority					0.0696					0.1749
Routine	16 (23.2%)	35 (19.7%)	49 (20.6%)	18 (36.7%)		10 (17.9%)	41 (28.3%)	41 (21.4%)	26 (18.4%)	
STAT/Urgent	53 (76.8%)	143 (80.3%)	189 (79.4%)	31 (63.3%)		46 (82.1%)	104 (71.7%)	151 (78.6%)	115 (81.6%)	
Patient Class					**< 0.001**					0.3181
Emergency Department	62 (89.9%)	148 (83.1%)	141 (59.2%)	39 (79.6%)		39 (69.6%)	111 (76.6%)	132 (68.8%)	108 (76.6%)	
Inpatient	7 (10.1%)	26 (14.6%)	68 (28.6%)	9 (18.4%)		11 (19.6%)	27 (18.6%)	44 (22.9%)	28 (19.9%)	
Outpatient	0 (0%)	4 (2.2%)	29 (12.2%)	1 (2%)		6 (10.7%)	7 (4.8%)	16 (8.3%)	5 (3.5%)	
mAs Modulation					0.2563					0.2155
True	52 (75.4%)	145 (81.5%)	190 (79.8%)	44 (89.8%)		43 (76.8%)	113 (77.9%)	153 (79.7%)	122 (86.5%)	
False	17 (24.6%)	33 (18.5%)	48 (20.2%)	5 (10.2%)		13 (23.2%)	32 (22.1%)	39 (20.3%)	19 (13.5%)	
kVp					0.2661					**< 0.001**
80	2 (2.9%)	1 (0.6%)	1 (0.4%)	0 (0%)		0 (0%)	1 (0.7%)	0 (0%)	3 (2.1%)	
100	7 (10.1%)	18 (10.1%)	17 (7.1%)	2 (4.1%)		0 (0%)	5 (3.4%)	13 (6.8%)	26 (18.4%)	
120	51 (73.9%)	141 (79.2%)	194 (81.5%)	45 (91.8%)		48 (85.7%)	123 (84.8%)	157 (81.8%)	103 (73%)	
140	9 (13%)	18 (10.1%)	26 (10.9%)	2 (4.1%)		8 (14.3%)	16 (11%)	22 (11.5%)	9 (6.4%)	
Continuous Variables										
Average age	29.13	29.6	30.4	30.2	0.3495	29.7	29.3	30.8	29.5	0.0557
Patient size	273.8	271.5	276.2	272.1	0.4382	264.9	280.0	272.9	272.8	**0.0101**
Scan length	299.7	289.2	285.0	287.8	**0.0372**	275.9	289.8	292.7	285.3	**0.0088**
Mean mAs	167.9	155.8	166.5	160.0	0.5439	165.0	179.6	157.8	150.2	**0.0154**
Pitch	1.19	1.24	1.26	1.28	**0.0348**	1.31	1.28	1.23	1.20	**< 0.001**

Table 4
Multivariable linear regression model for all continuous and categorical predictors of effective radiation dose. For continuous variables, a positive estimate coefficient indicates increasing radiation dose with the predictor. For categorical variables, a positive estimate coefficient indicates increased radiation dose with the predictor compared to its reference group.

Patient Characteristics	Estimate Coefficient	p-Value
Age	0.00056276	0.9182
Patient Size (WED)	0.00714	< .0001
Scan length	0.01191	< .0001
Mean mAs	0.01677	< .0001
Pitch	−2.77047	< .0001
Asian Race[a]	0.01025	0.9310
Black Race[a]	0.09958	0.2627
White Race[a]	0.08125	0.3185
1st Trimester[b]	0.25264	0.0152
3rd Trimester[b]	−0.04620	0.5308
Unknown Trimester[b]	0.07088	0.5428
Routine Priority[c]	−0.02710	0.7373
Inpatient exam[d]	−0.04458	0.5810
Outpatient exam[d]	0.07418	0.5758
Mean mAs * mAs modulation	0.00967	< .0001
mAs modulation[e]	−1.14482	< .0001
120 kVp[f]	1.93457	< .0001
140 kVp[f]	1.34215	< .0001

[a] Reference Group: Other/Unknown.
[b] Reference Group: 2nd trimester.
[c] Reference Group: STAT/urgent.
[d] Reference Group: Emergency department exam.
[e] Reference Group: No mAs modulation.
[f] Reference Group: 80 kVp and 100 kVp.

trimester CTPA scan was predictive of higher effective radiation dose. The precise reason for our variation in CTPA dose by trimester is currently unclear and warrants further evaluation and confirmation in future studies. It is possible this is related to a smaller sample size of patients scanned in the first trimester. In the bivariate analysis trimester varied significantly by race, patient class, scan length, and pitch. First trimester has the greatest percent of black patients, the most patients scanned in the emergency department, the highest scan length and the lowest pitch. While it may be true that there is a selection bias in terms of protocols and patient size by trimester, our multivariable regression analysis takes into account patient size and multiple protocol settings including scan length, mean mAs, pitch, mAs modulation, and kVp. In fact, all of these variables were highly significant in the multivariable model which should account for trimester. After adjusting by those factors, trimester is still significant in the final regression model.

This is not the first study to find that radiation doses vary by trimester (Table 5) [30,31]. This however is the first study to evaluate radiation dose when controlling for confounding factors.

Our radiation trends by trimester differ compared to prior studies. It is possible that these findings are not reproducible and external validation while controlling for other key variables is needed. One prior study evaluated 34 CTPA in pregnancy with an average maternal effective radiation dose of 9.8 mSv and found the lowest effective dose in the first trimester and the highest effective dose in the third trimester [30]. Another study evaluated 30 CTPA in pregnancy with an average maternal effective radiation dose of 21.02 mSv and found the lowest effective dose in the third trimester and the highest effective dose in the second trimester [31]. Interestingly, this study found that the maternal breast dose was highest in the third trimester and the lowest in the second trimester while the study found the fetal dose was highest in the second trimester and the lowest fetal dose was third trimester. Trimester is extremely important in determining fetal absorbed dose and risk of malignancy. Fetal absorbed dose depends in part on the mass of the fetus at the time of exposure, which is greatest in the third trimester, and the relative position of the fetus relative to the thorax, with closer position related to higher doses. For the same absorbed dose, the risk to

Table 5
Comparison of published maternal radiation doses.

Study	N	Overall	1st trimester	2nd trimester	3rd trimester	Significant difference between trimesters
Current study	534	3.96 mSv	4.52 mSv	3.73 mSv	3.95 mSv	Yes
Astani et al., [31]	30	21.02 mSv	21.07 mSv	21.26 mSv	20.74 mSv	Not calculated
Jordan et al., 2015 [30]	34	9.8 mSv	9.0 mSv	9.5 mSv	9.7 mSv	Not calculated

the fetus in terms of organogenesis and malignancy is the greatest early in pregnancy and approaches risks observed in a young pediatric population in the third trimester [32,33].

Age, race, study priority, and patient class were not statistically significant in predicting higher effective radiation dose. Radiation dose varied significantly by race in the bivariate analysis but not the multivariable analysis. In the bivariate analysis black patients had the highest radiation dose. There were several variables that varied significantly by patient race including trimester, kVp, patient size, scan length, mean mAs, and pitch. Race was not a significant factor in the multivariable analysis as it was dominated by these variables that remained significant in the multivariable analysis. Black patients had the highest average patient size which may be why those patients also had the highest scan length and mean mAs. While there were significant differences of kVp by race, it was in fact Asian patients that had the highest kVp. Interestingly, black patients were more likely to be scanned during the first trimester.

There are several limitations of this study. This is a retrospective study from a single health system, where scans were performed with non-uniform techniques. The non-uniform technique is a weakness because there are fewer scans for each setting however it is a strength of this study as it allows a wide range of scanners and protocols to be tested to identify the combination of hardware and scan protocols that was the most dose efficient. Also, radiation dose was compared without accounting for image quality. Further, sample bias was present in that only patients with available radiation dose data were included in the study, and technical factors such as scout, localizers, or timing sequences were not accounted for. Despite such limitations, this does reflect real-world experience with a large sample size over a span of multiple years that has practical implications for guiding patient management.

5. Conclusion

Mean effective radiation dose was on the lower end of published studies. Trimester was a statistically significant predictor of effective radiation dose when accounting for known predictors of radiation dose.

IRB statement

This research was performed with IRB approval and waiver of informed consent.

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Author Agreement/Declaration

All named authors have read and approved the final version of the manuscript being submitted. The article is original, with no portion under consideration for publication elsewhere or previously published.

Declaration of Competing Interest

Stuart Cohen was a consultant for Infervision June to August 2019. There are no other financial disclosures or conflicts of interest for the project.

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