

参赛队员姓名：刘宇慧

中学：北京市十一学校

省份：北京

国家/地区：北京

指导教师姓名：周政 窦向梅

指导教师单位：中国科学院生物物理所
北京市十一学校

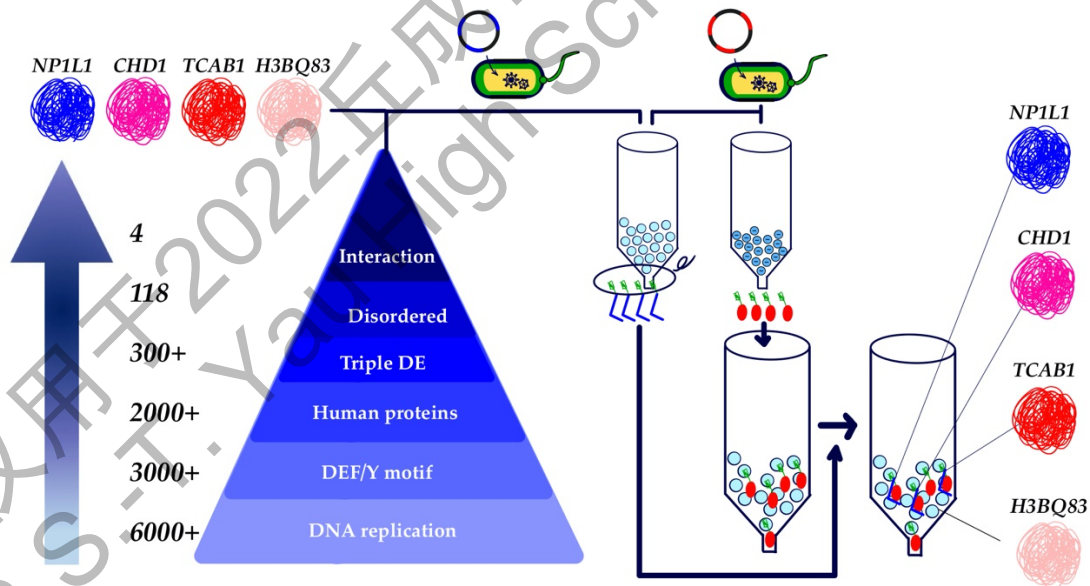
论文题目：A simple, effective approach to
screen and identify H2A-H2B binding proteins

A simple, effective approach to screen and identify H2A-H2B binding proteins.

Yuhui Liu

Abstract

Histone binding proteins regulate histone metabolism and play important roles in multiple biological processes that are linked to human diseases. Here we developed an in silico approach to screen and identified human histone H2A-H2B binding proteins. Target proteins are selected from the protein database and screened based on protein characteristics, which include specific histone binding motifs, protein folding tendency, and overall charges. Then, the binding between H2A-H2B and selected proteins is predicted by AlphaFold2, a computational protein structure prediction method, and further validated by pulldown experiments. Using this approach, we screened the DNA replication-associated proteins and demonstrated that NP1L1, CHD1, TCAB1, and H3BQ83 are H2A-H2B binding proteins. Collectively, this study reports a simple yet effective approach to identifying novel H2A-H2B binding proteins.



Keywords: Binding proteins, computer analysis, screening, identification, histones, binding affinity, pulldown experiment, DNA replication, H2A-H2B.

Contents

1. Introduction.....	4
A. Overview of H2A-H2B binding protein	4
B. Current research about H2A-H2B binding protein	6
C. Characteristics of H2A-H2B binding protein.....	8
2. Materials and Methods.....	10
A. Computer screening	9
B. Protein expression and purification	10
C. Protein affinity testing	11
3. Results	12
A. The computer predictions of DNA replication-associated protein	13
B. SDS-PAGE and data analysis for purified protein.....	14
C. Predicted protein and H2A-H2B binding affinity.....	15
4. Discussion	16
A. Comparison between computer analysis and experiment data	13
B. The sufficiency of the screening method	17
C. Method	18
5. Conclusion	19
References.....	20
Acknowledgments	25

1. Introduction

A. Overview of H2A-H2B binding protein

Nucleosomes are the basic unit of chromatin, which is the material basis of epigenetic control. Each nucleosome comprises a central histone octamer and a DNA strand surrounding that length in ~145 base pairs. The histone octamer contains two H2A-H2B heterodimers and one (H3-H4)₂ heterotetramer (Luger et al., 1997). (Figure 1A) Because of the condensed structure of histones and DNA (the structure of nucleosomes), the transcription, replication, repair, and other processing of DNA require the reassembling of nucleosomes. These modifications require specific complexes, which can be cataloged into histone chaperone and ATP-dependent chromatin remodeling complexes. Both contain particular recognizing binding regions inferred as binding proteins in this passage. In addition, the binding proteins of the H2A-H2B histone heterodimer will be called H2A-H2B binding proteins.

The H2A-H2B heterodimer contains a DNA binding region (DBR) and a histone binding region (HBR), interacting with the surrounding DNA strand and the H3-H4 histone, respectively. During DNA processing or epigenetic regulations, part of the complex will replace the DNA's position and interact with the DBR to expose the DNA (Figure 1B). Moreover, other parts of the complex may play a role in maintaining the original shape of the nucleosome by reinforcing the binding at the HBR or reassembling the nucleosome and maintaining the spatial arrangement of the genetic information after the process is finished (Huang et al., 2020). The H2A-H2B binding protein will primarily function in the binding along the DBR around the histone.

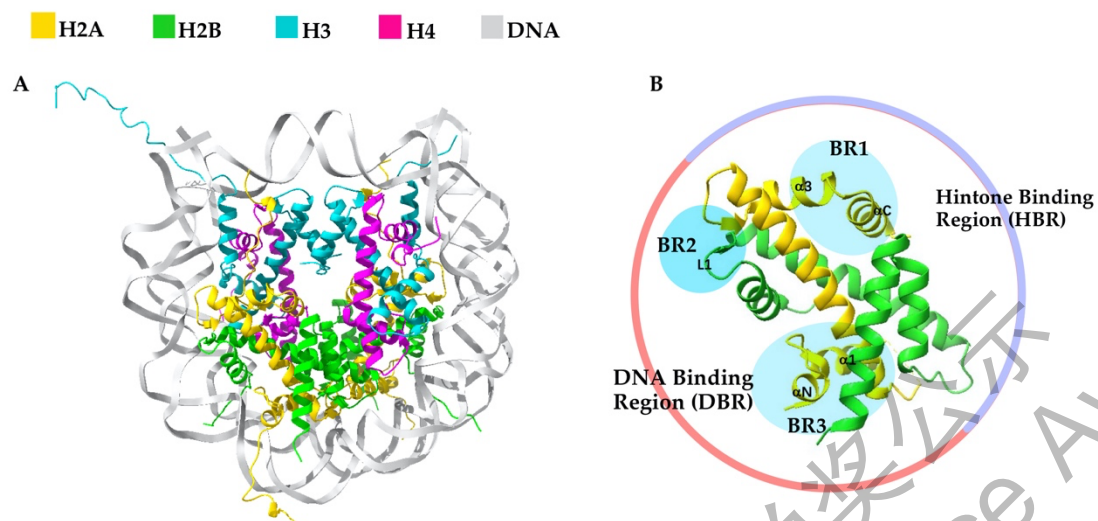


Figure 1 The structure of nucleosome and H2A-H2B dimer.

(A) nucleosome structure. The nucleosome structure is modified from PDB 1AO1 and the H2A-H2B structure. Histone and DNA are shown in cartoon and ribbon mode, respectively, and colored as illustrated. (B) H2A-H2B structure. The histone binding region (HBR, purple), DNA binding region (DBR, red), and corresponding secondary structure elements are labeled as indicated. The binding sites are marked in blue circles. The darker color indicates a more common binding.

B. Current research about H2A-H2B binding protein

Recent studies have found different nucleosome remodeling proteins and their binding protein, including the Chz1, ANP32e, YL1, and Swc5. The proteins play roles in transcription, DNA replication, and other chromosome remodeling processes.

Chz1

Chz1 is a histone chaperone that has been discovered to have the ability to bind H2A.Z¹-H2B dimer and may play a role in the H2A.Z exchanging process. (Liu et al., 2014) Studies have found out about the structure and sequences of Chz1 (Figure 2). The Chz1 is usually an intrinsically disordered protein but can form a stable heterotrimer when interacting with H2A.Z-H2B. The binding protein of Chz1 has two α -helices on each end and a long irregular chain in the middle. The N-terminal of the binding protein (sequencing 81-93 of the whole Chz1 protein) binds to the α 1 helix and L1 loop of H2A.Z. The long irregular chain in the middle (94-115) interacts with the α 2 helices of H2A.Z and the α 3 and α C helices of H2B. The C-terminal (116-132) binds to the α 2 and α 3 helices of H2A.Z (Zhou et al., 2008). The sequence of Chz1's binding protein has also shown the importance of recognizing the binding protein and the H2A.Z-H2B dimer, which is found to have rich D and E amino acids (Luk et al., 2007). Similar sequences have been found in other binding proteins.

YL1

The YL1 is a subunit of SRCAP², is critical in H2A.Z recognition, and can lead to transcriptional regulation (Xu M, 2021). The structure of YL1 has been found to rape the H2A.Z-H2B dimer and has three main binding sites. The first binding site is around the α C of H2A; the second is between the α 1 and α 2 helices of H2B, which is usually inferred as the H2B pocket; The third is around the H2A.Z's α 1 and α 2 (Figure 2). Moreover, the sequence of YL1 seems to follow the same pattern as Chz1 (Liang et al. 2016)

ANP32e

ANP32e has been found to bind the H2A.Z-H2B dimer specifically and contributes to the deposition of H2A.Z (Mao et al., 2014). This process can regulate the transcription

¹ histone H2A's variant, which is essential for specific genetic regulation and organism's development.

² SRCAP complex functioned through H2A.Z deposition to activate transcription of metabolic gene.

of DNA and influence DNA repair (Shin et al., 2018). The binding protein of ANP32e is at the C-terminal of ANP32e, and it contains a region rich in DE amino acids (Figure 2). The binding protein interacts with the L2 of H2A.Z and performs a firm binding (Obri et al., 2014).

Swc5

Swc5 is a subunit of the SWR complex³ and has been found to bind to H2A-H2B with its intrinsically disordered region. The mutation in Swc5 in the specific binding sequence can inhibit the nucleosome editing function of the SWR complex. The short helix of the binding protein can interact with the L2 in H2A and L1 in H2B (Figure 2). The short helix has the same sequence that contains D, E, F, and Y as the other binding protein (Huang et al., 2019).

Other binding proteins such as Nap1 (Steven et al., 2003), FACT(Bhakat & Ray, 2022), and APLF (Corbeski et al., 2018) have some similarities with the proteins stated above, most notably in the binding region and its binding sequence.

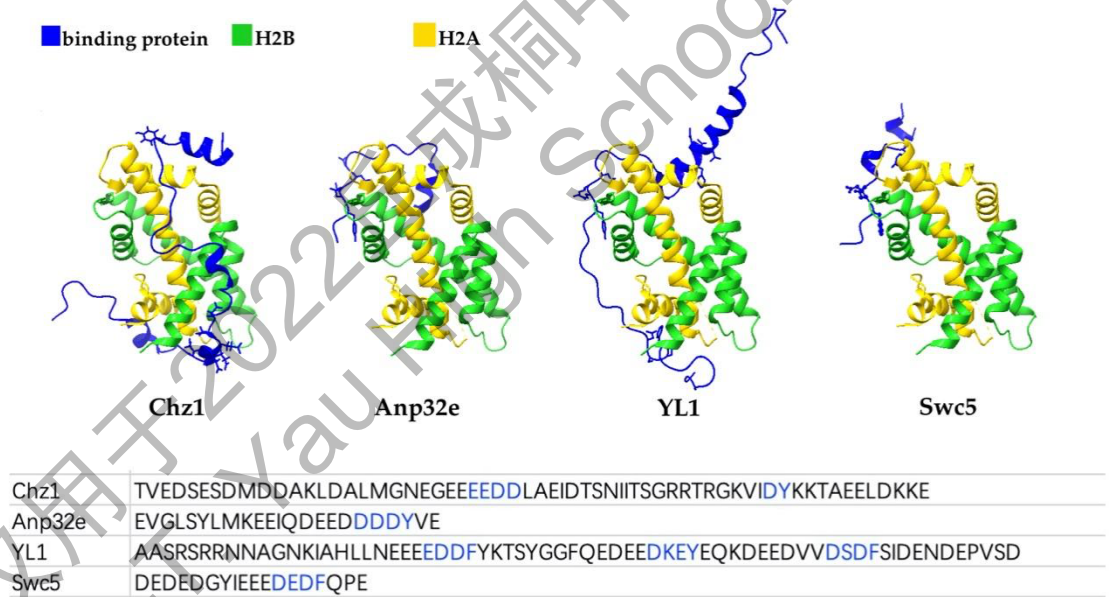


Figure 2 The binding proteins’ structure and interaction with H2A-H2B dimer.

The yellow colored ones are the H2A; the green colored ones are the H2B; the blue colored ones are the binding proteins discussed. The atoms shown are the sequences that have been labeled blue in the chart below, which are the DEF/Y motif.

³ SWR complex edits the histone composition of the nucleosome at promoters to facilitate transcription by replacing the two nucleosomal H2A-H2B dimers with H2A.Z-H2B dimers.

C. Characteristics of H2A-H2B binding protein

From the proteins shown above, we can find those binding proteins have specific characteristics in their structure and sequences.

The binding protein structure appears most likely intrinsically disordered (Warren & Shechter, 2017). The intrinsically disordered region (IDR) does not have a secondary structure and does not fold spontaneously into a single stable structure. Therefore, the flexibility and dynamics of the IDR are essential for histone binding.

Another structural characteristic of binding protein is that it contains three main binding sites, which are found according to the known histone binding proteins. In addition, the interaction at the three binding sites is most stable and plays a vital role in rapping the H2A-H2B dimer (Figure 1B). The first binding region (BR1) is at the α C and α 3 helices of H2A. The second binding region (BR2) is around the L1 of H2B and is the most common binding site found in most binding proteins. Finally, the third binding region (BR3) is near the α N helix and α 1 helix of H2A (Hammond et al., 2017). Although the BR1 and BR3 are not as widespread as BR2, the two locations also contribute to the firm and stable engagement between binding protein and H2A-H2B dimer.

The sequences of amino acids may also play a part in the binding process. The sequence at the three binding regions has got a DEF/Y motif, which suggests a D/E-rich region, and starting with a D/E amino acid (this D/E amino acid is at position 1), there will be another D/E amino acid at position 2 or 3, followed by an F or Y aromatic amino acid. In other words, the sequence should show a DXXDF or a DXDF pattern, where D and E can be converted to each other (Huang et al., 2020) (Figure 3). Moreover, the acidic nature, thus the continuous DE sequence, is used to bind H2A-H2B. The acidic amino acids tend to bind more tightly with the basic amino acid on the surface of H2A-H2B histone (Laskey et al., 1978). Through more research, another type of binding motif has also been found, which contains a W amino acid in the place of what was before known as F or Y. Further studies have demonstrated that the W amino acid is usually followed by a P amino acid (Mehrotra et al., 2010).

1	2	3	4	5
D	- X -	X -	D -	Φ
D	- X -	- -	D -	Φ

Figure 3 Possible sequences for the DEF/Y motif

The “D” in the figure suggests the acidic amino acids (D and E); the “X” suggests a random amino acid; and the “Φ” indicates the aromatic amino acids (F, Y, and W).

The correspondence of protein sequence and structure is critical for the binding ability of binding proteins. As stated above, the DEF/Y motif interacts with the three binding regions of H2A-H2B. Thus, the direction of binding proteins is also useful information when analyzing binding proteins. Theoretically, as long as the direction of binding is correlated with the position of the DEF/Y motif, the binding can be performed. However, all the binding proteins found so far demonstrate wrap H2A-H2B dimer counter-clockwise (meaning that the N-terminal is close to BR1 and C-terminal is close to BR3).

As we can see above, the structure and function of H2A-H2B binding proteins vary, and it is hard to find all of the binding proteins in a human's genome. Because of this, we wish to find a way to screen and identify the binding protein of H2A-H2B on a large scale and find the proteins that have been neglected by summarizing the features of binding proteins. Therefore, in this research, we have screened for the DNA replication performing protein to test our method of finding the H2A-H2B binding protein.

2. Materials and Methods

A. Computer screening

The first part of the protein screening process is done by computer analysis, narrowing the protein number down through the proteins' function, sequence, structure, and predicted interaction with the H2A-H2B dimer. The protein sequences that appear to have the most substantial possibility will later be tested through biological experiments.

Firstly, a program was used to search for DNA replication proteins in the UniProt database⁴. After that, each protein sequence is scanned to see if it contains the DEF/Y motif. Moreover, although some proteins are related to humans, they are only from viruses or bacteria that can infect humans, so we eliminated the non-human proteins. Because the protein number after the three steps above is still too significant for analysis, a triple D or E motif is added to filter out the proteins that are not acidic and is hard to bind with the histone. Finally, the qualified proteins are downloaded for the subsequent processes.

The UniProt database is then used to see the structure near the DEF/Y motif, and the sequences that are in the IDR are recorded in about 30 to 55 amino acids. There are three ways to record sequences: placing the DEF/Y motif in the N-terminal, the C-terminal, or the middle. The amino acids determine the way to record near the DEF/Y motif. In addition, the goal is to have more D/E acidic amino acids in the recorded sequence. If the acidic amino acid is evenly spread, we tend to place the DEF/Y motif near the N-terminal to have a higher possibility of getting a positive result in the latter interaction prediction screening. This is because the binding protein known all tend to rape the H2A-H2B dimer counter-clockwise, meaning the N-terminal of the binding protein is near the BR2, the most common and stable binding site.

The last part of computer screening uses alpha-fold (Jumper et al., 2021)(Evans et al., 2021) to predict the interaction between H2A-H2B dimers, and the result is then analyzed using ChimeraX (Goddard et al., 2017)(Pettersen et al., 2020). The two main characteristics of structural binding, its direction and the binding sites, are evaluated. First, the direction of the binding protein should be counter-clockwise, meaning that the N-terminal is around the BR1 and BR2 while the C-terminal is around the BR3. The second characteristic is if the DEF/Y motif is interacting near the three binding

⁴ <https://www.uniprot.org/>

sites. During the analysis, the BR2 is considered the most potent binding site, and the ones that do not bind to the BR2 with its DEF/Y motif are eliminated.

After the processes above, the protein sequences that are most likely to be binding proteins and interact with H2A-H2B dimer are chosen for the following experiment.

B. Protein expression and purification

Transformation. We modified the existing pET-28a-based plasmid, which encodes an N-terminal hexahistidine (His6) tag and thrombin protease cleavage site followed by a SUMO tag. Because the plasmids of the proteins chosen above are lyophilized, they are first centrifuged at 1200 RPM for 1 min, and 20 μ L TB buffer is added to dissolve the plasmids. The plasmids for H2A-H2B are already in the form of a solution and can be used without the procedure above. 5 μ L of each plasmid solution is added to the thawed E. coli BL21 (DE3) cells and incubated in the mixture on ice for 20min. The tube is then heat shocked in a 42 °C water bath for the 60s to 90s and incubated on ice for another 2min. 500 μ L nonantigenic LB culture medium are added to the plasmids and shaken at 37 °C 250 RPM for 30min to 60min. After incubation, 100 μ L of each mixture is spread on the selection plate with kanamycin and grown overnight.

Protein expression. The bacteria grown in the selection plate are moved to an 800mL liquid LB medium with kanamycin and chloromycetin and shaken at 25°C for 90min for the OD₆₀₀ to reach 0.6 to 0.8. 0.5mM of IPTG is then added to the medium, and the temperature is lowered to 15°C. The proteins are expressed overnight. The bacteria mixture is centrifuged at 4°C, 4000 RMP for 30min, and the sediment is collected.

Ni-NTA Purification. After the bacteria is harvested, it is resuspended using buffer A (10mM Tris 8.0, 2M NaCl, 20mM imidazole). The bacteria are then lysed through high pressure, and the mixture is centrifuged in a cryogenic superspeed centrifuge at 15000RMP for 90min, and the supernatant is collected. The nickel beads are first equilibrated using buffer A and then added to the supernatant to incubate at 4°C, mixing continuously for 90min. The mixture is then poured into a gravity-flow column and use buffer B (20mM Tris 8.0, 2M NaCl, 30mM imidazole) to wash off the miscellaneous protein. Coomassie brilliant blue (CBB) checks if the miscellaneous proteins have been washed completely. After that, buffer C (20mM Tris 8.0, 400mM NaCl, 250mM imidazole) is used for the elute. Again, CBB is used to check if all the target proteins have been collected.

Ion exchange chromatography for H2A-H2B. In this study, an automated HPLC (high performance liquid chromatography) system was used for purification. First, the nickel-purified protein was desalted and deimidazoled. Then the sample was loaded into the substantial cation exchange column and balanced with low salt according to the negative charge of the protein. The high salt was combined to gradually change the ion binding strength through the gradient salt mixing procedure and separate the target protein from the miscellaneous proteins. Finally, the proteins in the collection tubes were selected according to the elution peak.

C. Protein affinity testing

His-tag digestion. The proteinase thrombin is used to recognize and cut off his-tag through the thrombin site. The plasmid used for the protein expression contains a thrombin site between the his-tag and SUMO tag, which allows us to cut off the his-tag from the binding protein for the pulldown experiment. 4 μ L of thrombin is added to the purified binding protein, and the mixture is incubated overnight at 4°C.

His-tag elimination through Ni-NTA. The mixture is then incubated with the nickel beads as the procedure stated above and then poured into a gravity-flow column. Because the binding proteins that do not have his-tag will not be able to bind with nickel beads, while thrombin and the his-tags that have been cut off will stay on the beads, the flowthrough and wash are collected.

Pull-down experiment. The H2A-H2B is first incubated with nickel beads in buffer A for 120min at 4°C. 50 μ L of the his-tag-H2A-H2B beads are then incubated with the binding protein (secondary protein) for another 120min. The mixture is washed with buffer B (20mM Tris 8.0, 2M NaCl, 30mM imidazole) to test the binding affinity of the two proteins. After that, buffer D (20mM Tris 8.0, 300mM NaCl, 250mM imidazole) is used for the elute. The mixture is then centrifuged, and the supernatant is run through the SDS-PAGE. Proteins were visualized by staining with CBB.

3. Results

A. The computer predictions of DNA replication-associated protein

These are the number of proteins remaining after each stage of the screening process: there are more than 6000 proteins that are associated with DNA replication, and more than 3000 of them contain the DEF/Y motif. After eliminating the non-human protein, the number decreases to about 2000+, and only about 300 of them show a strong acidity. 118 protein sequence is in the IDR. After analyzing the interaction between the predicted protein and H2A-H2B dimer, four binding proteins were selected for further experiments.

CHD1

The first protein is CHD1, which has been identified as an ATP-dependent chromatin-remodeling factor that functions as a substrate recognition component of the transcription regulatory histone acetylation complex (Flanagan et al., 2005)(Sims et al., 2007). It has also been found to regulate DNA replication negatively. Moreover, it is required to maintain a specific chromatin configuration across the genome and associate histone deacetylase activity. There have already been studies suggesting that CHD1 can bind with histone H3. Human CHD1 double chromodomains are involved in targeting the lysine 4-methylated histone H3 tail recognition (Sims et al., 2005). Although the sequence found in the previous study is not the same as the sequence corresponding to the interaction with H3, the predicted structure still shows a high possibility that CHD1 can bind H2A-H2B dimer. The binding protein of CHD1 interacts with the BR2 and BR3 of the H2A-H2B dimer through its “DEDW” motif and its “ESDY” motif, respectively (Figure 3).

NP1L1

The second binding protein is NP1L1, which has been studied to be a histone chaperone that participates in the nuclear import of H2A-H2B and nucleosome assembly (referred to as Nap1 in the passage above). In addition, it engages in the control of DNA-templated processes such as replication and DNA damage repair (Venkatesh & Workman, 2015). It has already been found that the C-terminal acidic domain of Nap1 contributes to its stability of histone binding (Andrews et al., 2008). We have predicted the interaction between NP1L1 and H2A-H2B dimer from the computer analysis and screening. The “DDDY” motif and the “DPDY” motif bind with the BR2 and BR3. The binding protein sequence of Nap1 has already been found before, and it is highly

conserved (only a few amino acids longer) to the sequence found in our computer screening (Ohtomo et al., 2016).

TCAB1

TCAB1 is an RNA chaperone that maintains the telomere structure (Chen et al., 2018). Other studies suggest that it is an essential component of the telomerase holoenzyme complex, which participates in the replication of chromosome termini that elongates telomeres in most eukaryotes (Venteicher et al., 2009). In addition, it can recruit the ubiquitin ligase RNF8 to break the DNA and promote both homologous recombination and non-homologous end joining (Henriksson et al., 2014). The predicted interaction between TCAB1 and the H2A-H2B dimer shows a nicely raped shape with BR2, which contains an “ETEF” sequence (Figure 3).

H3BQ83

This protein has not been studied much, but it has been indicated to be essential in controlling DNA replication and maintaining replication fork stability (Zody et al., 2006). The predicted structure of H3BQ83 has shown a BR1 and BR2 in the interaction with H2A-H2B, which is the only protein found in the screening process to have BR1, giving it a possibility to be H2A.Z-H2B binding protein (Figure 3).

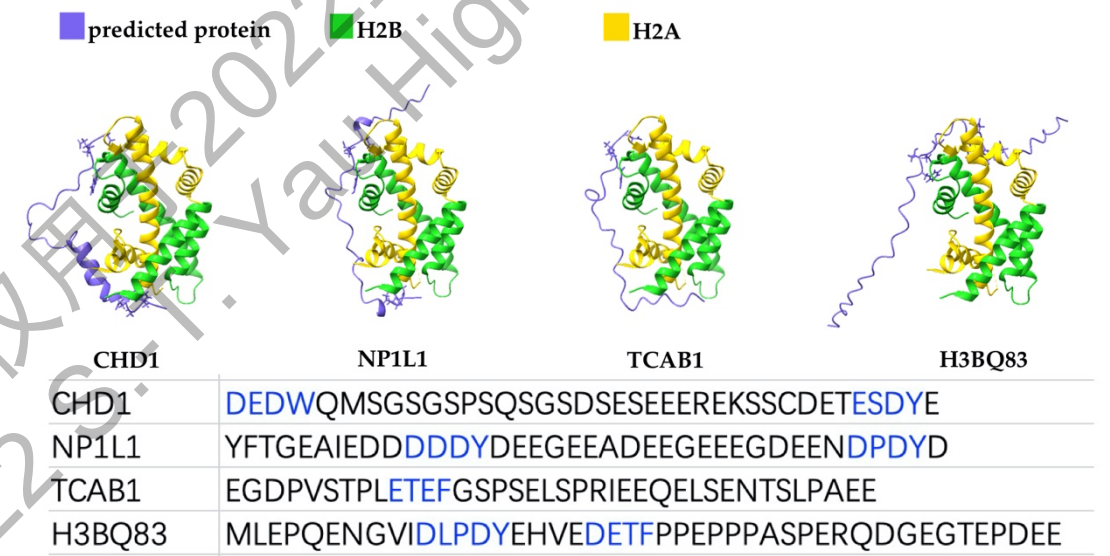


Figure 4 The structural interaction between predicted proteins and H2A-H2B.

Colored as illustrated, and the atoms shown are the sequences that have been labeled blue in the chart below, which are the DEF/Y motif.

B. SDS-PAGE and data analysis for purified protein

After being purified, the predicted proteins and H2A-H2B dimers went through SDS-PAGE and Coomassie blue staining. All of the five proteins have been shown to express, and they appear to be of a high degree of purity.

The proteins had a high expression in the condition provided, according to the first protein that had been purified, NP1L1. Although some of the target protein is lost in flowthrough and wash, there are still enough proteins remaining on the beads to be collected for the later experiment. The result for NP1L1 protein has two bands, but because beta-mercaptoethanol is not added when running the SDS-PAGE, the disulfide bond may change the protein's size. Nevertheless, indicated by the size of the two bands, which shows a twofold relationship, the purification is still convincing. Moreover, the pure H2A-H2B proteins, meaning that there is only one band from the gel, are collected for the later experiment. Most of the bands after the ion exchange chromatography have shown a high purity and high yield. Finally, the remaining three proteins, CHD1, TCAB1, and H3BQ83, have also shown to be expressed and purified.

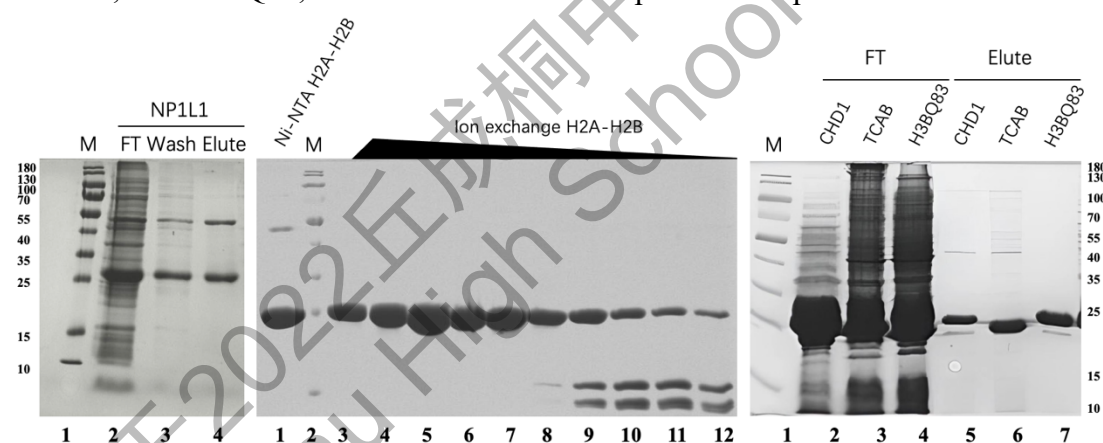


Figure 5 SDS-PAGE gel for binding protein and H2A-H2B.

(A) Coomassie-stained gel for NP1L1 purification. "M" stands for 100kDa marker; FT is flowthrough (the protein solution that directly goes through Ni-beads gravitational column); and Elute indicates the elution (the washed-off purified protein). (B) The purification of H2A-H2B, both Ni-NTA purification and ion exchange chromatography. The 3 to 12 lines indicate the collections of protein during ion exchange chromatography, and the 3 to 8 lines (having a high purity) are stored for the latter experiment. (C) Coomassie-stained gel for the purification of CHD1, TCAB, and H3BQ83. Notifications are the same as in (A).

C. Predicted protein and H2A-H2B binding affinity

The proteins have been tested through a pulldown experiment, and the Coomassie-stained gel has shown a positive result for both proteins. The H2A-H2B dimers are attached to nickel beads by his-tag, and the binding proteins are attached through the firmly binding between them and H2A-H2B dimers. SUMO is used for negative control because all proteins are purified through the SUMO⁵ system and contain a SUMO tag. Thus, the negative control is able to eliminate the possibility that SUMO binds H2A-H2B dimer.

From the gel, we are able to prove that all proteins do have a binding interaction with H2A-H2B (Figure 6). Although the size of the binding proteins and the H2A-H2B dimer is very close to the same because the amount of H2A-H2B dimer is conserved, the binding affinity of the binding protein can still be indicated. The negative control shows a clear band with only H2A-H2B, suggesting the accuracy of the data. NP1L1, TCAB1, H3BQ83, and CHD1 all have a greater amount of protein present in the gel. This can prove that they do have a binding interaction. Moreover, NP1L1 has been tested in a previous study suggesting its binding affinity (Hideaki et al., 2016).

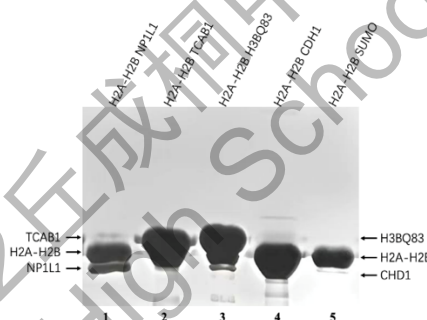


Figure 6 Coomassie-stained gel for pulldown experiment.

The purified binding proteins NP1L1, TCAB1, H3BQ83, and CHD1, were incubated with his-tag-H2A-H2B fusion protein bound to nickel beads. Bound proteins were separated by 12% SDS-PAGE and stained by Coomassie. Bindings of NP1L1, TCAB1, H3BQ83, and CHD1 with H2A-H2A dimer were shown, respectively.

⁵ Used to help the production of proteins.

4. Discussion

A. Comparison between computer analysis and experiment data

The result of the computer analysis and biological experiment have been summarized (Table 1). All of the proteins predicted by computer analysis to bind with H2A-H2B have also shown binding affinity in the biological experiment.

The proteins had confirmed different characteristics of binding protein characteristics that are summarized in this research. In this study, the IDR and DEF/Y motif has been considered to be essential elements for H2A-H2B binding. The triple DE motif has effectively narrowed the range of proteins from the acidity characteristic. All the predicted binding proteins matched these characteristics, and previous studies have shown their importance. The correspondence of computer analysis and experiment confirmed the incommensurability of deletion of these screening conditions.

The binding features are the most visualized screening process and have shown the binding affinity of each predicted binding protein by the structural calculation of alpha-fold technology. Because of the limited time, quantitative research like Isothermal Titration Calorimetry (ITC) has not been done, and the binding intensity cannot be tested. However, alpha-fold analysis help to eliminate the low probability results, establishing a clear screening strategy based on the interaction between binding protein and H2A-H2B dimer. The BR2, previously detected as the most common binding site, can be predicted by alpha-fold technology. The other two binding sites, the BR1 and BR3, may have also increased the affinity of H2A-H2B attachment.

In future research, quantitative research can supplement the alpha-fold technology to see how much more significant interaction is provided when BR1 or BR3 is present.

B. The sufficiency of the screening method

The human proteome is massively huge, and the ones related to histone modification are enormous. This screening method used the proteins that function in DNA replication as a sample containing about 5000 proteins. These 5000 proteins are screened and narrowed down into four protein sequences that have been predicted by this method to have the ability to bind H2A-H2B dimer. All predicted proteins display H2A-H2B binding ability, proving the sufficiency of the screening method.

The core of the method is that a standard characteristic of binding protein has been reasonably summarized. Reducing the work to find new binding proteins. For example, the CHD1 has previously been shown to bind with histone H3 and has also been found, in this case, to bind H2A-H2B. Moreover, other proteins that have been neglected can also be found using this method. H3BQ83 is an example of a protein that has not been put into attention, but from the pulldown experiment, it has been shown to bind with H2A-H2B, and its BR1 is also a strong suggestion that it may be an H2A.Z chaperone responsible for the exchange of H2A and H2A.Z.

Summary of computer analysis and biological experiment results

process		NP1L1	CHD1	TCAB1	H3BQ83
Computer screening features	DEF/Y motif	+	+	+	+
	IDR	+	+	+	+
	Triple DE motif	+	+	+	+
	BR1	-	-	-	+
	BR2	+	+	+	+
	BR3	+	+	-	-
	Counter-clockwise	+	+	+	+
Biological experiment		+	+	+	+

Table 1 the “+” indicates a positive result, “-” indicates a negative result.

C. Method optimization

To increase simplicity and sufficiency, we have designed certain optimizations, which increase the silico screening process and give more standardized criteria in the future.

First of all, the identification of protein IDR in this study was purely manual, and the structure of the sequence position given in the database was screened by visual observation. This process takes a long time and is less accurate than computer calculation. Therefore, an alternative to the manual screening method is very important. SlimSearch database provides conditions for the optimization of IDR identification (Krystkowiak & Davey, 2017). The website has a section called "Disordered Score Cut Off." If the score is greater than 0.4, the protein is considered to be IDR. In this way, the screening efficiency can be improved.

Moreover, quantitative analysis of the binding strength of binding protein can further help us clarify the importance of each feature of binding protein in the screening process. The screening features satisfied by binding proteins with higher binding strength can be considered more important, while some features satisfied by predicted proteins that are found to be false positives after identification may be considered not important. Therefore, we can assign points to different features according to their importance. For example, BR2, which has been identified as the most common binding site in previous studies and has shown positive results in numerous subsequent screenings, could be assigned a point of 50. However, BR1 may also be positive if it is not satisfied, but meeting BR1 can enhance the binding strength of the binding protein. Therefore, BR1 can be assigned 20 points. Finally, the predicted protein with the highest point will be considered to have the highest possibility of being binding protein. The points can make the screening process more standardized and reduce bias.

5. Conclusion

This research developed an approach to screening and identification of H2A-H2B binding proteins. The previous researches about this type of protein vary in structure and function, making the identification of binding protein verbose. Six features of the binding proteins have been summarized in this study to develop a simple and effective method to fix this problem.

The H2A-H2B binding proteins have been found to have a DEF/Y motif and are present in IDR with high acidity. Their interactions with the H2A-H2B histone dimer have been found to have three main binding sites. All the characteristics stated above are included in this study to screen the binding proteins. The pulldown experiment is used to verify the computer screening process and identify the binding proteins. The data from the in silico analysis and the experiment are consistent. NP1L1, CHD1, TCAB1 and H3BQ83 are identified as binding proteins.

More studies can be further conducted to improve the present screening process, such as automatic IDR identification and quantitative experiment for binding affinity.

References

Andrews, A. J., Downing, G., Brown, K., Park, Y.-J., & Luger, K. (2008). A thermodynamic model for NAP1-histone interactions. *Journal of Biological Chemistry*, 283(47), 32412–32418. <https://doi.org/10.1074/jbc.m805918200>

Bhakat, K. K., & Ray, S. (2022). The facilitates chromatin transcription (FACT) complex: Its roles in DNA repair and implications for cancer therapy. *DNA Repair*, 109, 103246. <https://doi.org/10.1016/j.dnarep.2021.103246>

Chen, L., Roake, C. M., Freund, A., Batista, P. J., Tian, S., Yin, Y. A., Gajera, C. R., Lin, S., Lee, B., Pech, M. F., Venteicher, A. S., Das, R., Chang, H. Y., & Artandi, S. E. (2018). An activity switch in human telomerase based on RNA conformation and shaped by TCAB1. *Cell*, 174(1). <https://doi.org/10.1016/j.cell.2018.04.039>

Corbeski, I., Dolinar, K., Wienk, H., Boelens, R., & van Ingen, H. (2018). DNA repair factor APLF acts as a H2A-H2B histone chaperone through binding its DNA interaction surface. *Nucleic Acids Research*, 46(14), 7138–7152. <https://doi.org/10.1093/nar/gky507>

Dronamraju, R., Ramachandran, S., Jha, D. K., Adams, A. T., DiFiore, J. V., Parra, M. A., Dokholyan, N. V., & Strahl, B. D. (2017). Redundant functions for NAP1 and CHZ1 in H2A.Z deposition. *Scientific Reports*, 7(1). <https://doi.org/10.1038/s41598-017-11003-8>

Evans, R., O'Neill, M., Pritzel, A., Antropova, N., Senior, A., Green, T., Židek, A., Bates, R., Blackwell, S., Yim, J., Ronneberger, O., Bodenstein, S., Zielinski, M., Bridgland, A., Potapenko, A., Cowie, A., Tunyasuvunakool, K., Jain, R., Clancy, E., ... Hassabis, D. (2021). Protein complex prediction with AlphaFold-Multimer. <https://doi.org/10.1101/2021.10.04.463034>

Flanagan, J. F., Mi, L.-Z., Chruszcz, M., Cymborowski, M., Clines, K. L., Kim, Y., Minor, W., Rastinejad, F., & Khorasanizadeh, S. (2005). Double Chromodomains cooperate to recognize the methylated histone H3 tail. *Nature*, 438(7071), 1181–1185. <https://doi.org/10.1038/nature04290>

Goddard, T. D., Huang, C. C., Meng, E. C., Pettersen, E. F., Couch, G. S., Morris, J. H., & Ferrin, T. E. (2017). UCSF ChimeraX: Meeting modern challenges in visualization and analysis. *Protein Science*, 27(1), 14–25. <https://doi.org/10.1002/pro.3235>

Hammond, C. M., Strømme, C. B., Huang, H., Patel, D. J., & Groth, A. (2017). Histone chaperone networks shaping chromatin function. *Nature Reviews Molecular Cell Biology*, 18(3), 141–158. <https://doi.org/10.1038/nrm.2016.159>

Henriksson, S., Rassoolzadeh, H., Hedström, E., Coucoravas, C., Julner, A., Goldstein, M., Imreh, G., Zhivotovsky, B., Kastan, M. B., Helleday, T., & Farnebo, M. (2014). The scaffold protein WRAP53 β orchestrates the ubiquitin response critical for DNA double-strand break repair. *Genes & Development*, 28(24), 2726–2738. <https://doi.org/10.1101/gad.246546.114>

Huang, Y., Dai, Y., & Zhou, Z. (2020). Mechanistic and structural insights into histone H2A–H2B chaperone in chromatin regulation. *Biochemical Journal*, 477(17), 3367–3386. <https://doi.org/10.1042/bcj20190852>

Huang, Y., Sun, L., Pierrakeas, L., Dai, L., Pan, L., Luk, E., & Zhou, Z. (2020). Role of a DEF/Y motif in histone H2A–H2B recognition and nucleosome editing. *Proceedings of the National Academy of Sciences*, 117(7), 3543–3550. <https://doi.org/10.1073/pnas.1914313117>

Jumper, J., Evans, R., Pritzel, A., Green, T., Figurnov, M., Ronneberger, O., Tunyasuvunakool, K., Bates, R., Židek, A., Potapenko, A., Bridgland, A., Meyer, C., Kohl, S. A., Ballard, A. J., Cowie, A., Romera-Paredes, B., Nikolov, S., Jain, R., Adler, J., ... Hassabis, D. (2021). Highly accurate protein structure prediction with alphafold. *Nature*, 596(7873), 583–589. <https://doi.org/10.1038/s41586-021-03819-2>

Krystkowiak, I., & Davey, N. E. (2017). SLiMSearch: A framework for proteome-wide discovery and annotation of functional modules in intrinsically disordered regions. *Nucleic Acids Research*, 45(W1). <https://doi.org/10.1093/nar/gkx238>

Laskey, R. A., Honda, B. M., Mills, A. D., & Finch, J. T. (1978). Nucleosomes are assembled by an acidic protein which binds histones and transfers them to DNA. *Nature*, 275(5679), 416–420. <https://doi.org/10.1038/275416a0>

Liang, X., Shan, S., Pan, L., Zhao, J., Ranjan, A., Wang, F., Zhang, Z., Huang, Y., Feng, H., Wei, D., Huang, L., Liu, X., Zhong, Q., Lou, J., Li, G., Wu, C., & Zhou, Z. (2016). Structural basis of H2A.Z recognition by SRCAP chromatin-remodeling subunit YL1. *Nature Structural & Molecular Biology*, 23(4), 317–323. <https://doi.org/10.1038/nsmb.3190>

Liu, H., Luo, K., Zhou, Z., Mu, Y., & Wan, Y. (2014). Histone chaperone CHZ1 facilitates the disfavouring property of SPT16 to H2A.Z-containing genes in

saccharomyces cerevisiae. *Biochemical Journal*, 460(3), 387–397.
<https://doi.org/10.1042/bj20140186>

Luger, K., Mäder, A. W., Richmond, R. K., Sargent, D. F., & Richmond, T. J. (1997). Crystal structure of the nucleosome core particle at 2.8 Å resolution. *Nature*, 389(6648), 251–260. <https://doi.org/10.1038/38444>

Luk, E., Vu, N.-D., Patteson, K., Mizuguchi, G., Wu, W.-H., Ranjan, A., Backus, J., Sen, S., Lewis, M., Bai, Y., & Wu, C. (2007). CHZ1, a nuclear chaperone for histone H2AZ. *Molecular Cell*, 25(3), 357–368. <https://doi.org/10.1016/j.molcel.2006.12.015>

Mao, Z., Pan, L., Wang, W., Sun, J., Shan, S., Dong, Q., Liang, X., Dai, L., Ding, X., Chen, S., Zhang, Z., Zhu, B., & Zhou, Z. (2014). ANP32E, a higher eukaryotic histone chaperone directs preferential recognition for H2A.Z. *Cell Research*, 24(4), 389–399. <https://doi.org/10.1038/cr.2014.30>

McBryant, S. J., Park, Y.-J., Abernathy, S. M., Laybourn, P. J., Nyborg, J. K., & Luger, K. (2003). Preferential binding of the histone (H3-H4)₂ tetramer by NAP1 is mediated by the amino-terminal histone tails. *Journal of Biological Chemistry*, 278(45), 44574–44583. <https://doi.org/10.1074/jbc.m305636200>

Mehrotra, P. V., Ahel, D., Ryan, D. P., Weston, R., Wiechens, N., Kraehenbuehl, R., Owen-Hughes, T., & Ahel, I. (2011). DNA repair factor APLF is a histone chaperone. *Molecular Cell*, 41(1), 46–55. <https://doi.org/10.1016/j.molcel.2010.12.008>

Obri, A., Ouarrhni, K., Papin, C., Diebold, M.-L., Padmanabhan, K., Marek, M., Stoll, I., Roy, L., Reilly, P. T., Mak, T. W., Dimitrov, S., Romier, C., & Hamiche, A. (2014). ANP32E is a histone chaperone that removes H2A.Z from chromatin. *Nature*, 505(7485), 648–653. <https://doi.org/10.1038/nature12922>

Ohtomo, H., Akashi, S., Moriwaki, Y., Okuwaki, M., Osakabe, A., Nagata, K., Kurumizaka, H., & Nishimura, Y. (2016). C-terminal acidic domain of histone chaperone humannap1 is an efficient binding assistant for histone H2A-H2B, but not H3-H4. *Genes to Cells*, 21(3), 252–263. <https://doi.org/10.1111/gtc.12339>

Pettersen, E. F., Goddard, T. D., Huang, C. C., Meng, E. C., Couch, G. S., Croll, T. I., Morris, J. H., & Ferrin, T. E. (2020). UCSF chimeraX: Structure visualization for researchers, educators, and developers. *Protein Science*, 30(1), 70–82. <https://doi.org/10.1002/pro.3943>

Shin, H., He, M., Yang, Z., Jeon, Y. H., Pfleger, J., Sayed, D., & Abdellatif, M. (2018). Transcriptional regulation mediated by H2A.Z via ANP32E-dependent inhibition of protein phosphatase 2A. *Biochimica Et Biophysica Acta (BBA) - Gene Regulatory Mechanisms*, 1861(5), 481–496. <https://doi.org/10.1016/j.bbagr.2018.03.002>

Sims, R. J., Chen, C.-F., Santos-Rosa, H., Kouzarides, T., Patel, S. S., & Reinberg, D. (2005). Human but not yeast CHD1 binds directly and selectively to histone H3 methylated at lysine 4 via its tandem chromodomains. *Journal of Biological Chemistry*, 280(51), 41789–41792. <https://doi.org/10.1074/jbc.c500395200>

Sims, R. J., Millhouse, S., Chen, C.-F., Lewis, B. A., Erdjument-Bromage, H., Tempst, P., Manley, J. L., & Reinberg, D. (2007). Recognition of trimethylated histone H3 lysine 4 facilitates the recruitment of transcription postinitiation factors and pre-mrna splicing. *Molecular Cell*, 28(4), 665–676. <https://doi.org/10.1016/j.molcel.2007.11.010>

Venkatesh, S., & Workman, J. L. (2015). Histone exchange, chromatin structure and the regulation of transcription. *Nature Reviews Molecular Cell Biology*, 16(3), 178–189. <https://doi.org/10.1038/nrm3941>

Venteicher, A. S., Abreu, E. B., Meng, Z., McCann, K. E., Terns, R. M., Veenstra, T. D., Terns, M. P., & Artandi, S. E. (2009). A human telomerase holoenzyme protein required for cajal body localization and telomere synthesis. *Science*, 323(5914), 644–648. <https://doi.org/10.1126/science.1165357>

Warren, C., & Shechter, D. (2017). Fly fishing for histones: Catch and release by histone chaperone intrinsically disordered regions and acidic stretches. *Journal of Molecular Biology*, 429(16), 2401–2426. <https://doi.org/10.1016/j.jmb.2017.06.005>

Xu, M., Yao, J., Shi, Y., Yi, H., Zhao, W., Lin, X., & Yang, Z. (2021). The SRCAP chromatin remodeling complex promotes oxidative metabolism during prenatal heart development. *Development*, 148(8). <https://doi.org/10.1242/dev.199026>

Zody, M. C., Garber, M., Sharpe, T., Young, S. K., Rowen, L., O'Neill, K., Whittaker, C. A., Kamal, M., Chang, J. L., Cuomo, C. A., Dewar, K., FitzGerald, M. G., Kodira, C. D., Madan, A., Qin, S., Yang, X., Abbasi, N., Abouelleil, A., Arachchi, H. M., ... Nusbaum, C. (2006). Analysis of the DNA sequence and duplication history of human chromosome 15. *Nature*, 440(7084), 671–675. <https://doi.org/10.1038/nature04601>

Acknowledgments

I am indebted to my two instructors, Dr. Zheng Zhou and Dr. Xiangmei Dou, and my two senior apprentices, Mr. Wencang Huang and Mr. Xin Yang. They taught me how to purify proteins and do pulldown experiments and helped me to design this research. Dr. Zheng Zhou helped me clarify the research direction and helped me decide on the topic according to my ability. My instructors acted as gatekeepers throughout the research process and instructed me through my paper writing. Moreover, all of them taught me the spirit of doing scientific research. I also want to thank my parents and friend who supported me during my research and comforted me when the experiment failed.

仅用于2022丘成桐中学科学奖
2022 S.-T. Yau High School Science Awards